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UNIVERSITY OF CALIFORNIA

Los Angeles

**The Development of a Low-Cost Motion Capture
System for Quantitative Clinical Assessments**

A dissertation submitted in partial satisfaction
of the requirements for the degree
Doctor of Philosophy in Mechanical Engineering

by

Julia Kathryn Nichols

2016

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ABSTRACT OF THE DISSERTATION

The Development of a Low-Cost Motion Capture System for Quantitative Clinical Assessments

by

Julia Kathryn Nichols

Doctor of Philosophy in Mechanical Engineering

University of California, Los Angeles, 2016

Professor Vijay Gupta, Chair

Orthopaedic surgery is currently a field that is reactive, rather than proactive. A movement screening tool could help identify individuals at risk for anterior cruciate ligament (ACL) injury before injury occurs and decrease the long term risk of osteoarthritis (OA). At present, accurate movement monitoring systems are prohibitive in cost and size to be practical and accessible to the general population. Current commercially available low-cost and more accessible systems lack the accuracy needed for clinical relevance.

To address these limitations, we have developed more accurate Low-Cost Movement Assessment Systems (LCMAS). We enhanced the retroreflective marker detection capabilities for the Microsoft Kinect depth camera (LCMAS-Single) and applied kinematic and kinetic calculations to the skeleton generated from the Microsoft Kinect2 depth camera (LCMAS-2).

Next, we laid out a detailed test-retest reliability study utilizing intraclass correlation coefficients (*ICC*), smallest detectable differences (*SDD*), Bland-Altman plots, minimal clinically important difference (*MCID*), and root mean squared (*RMS*) difference to assess the performance of our low-cost systems relative to the gold standard Vicon system for detecting kinematic and kinetic metrics asso-

ciated with knee injury risk. Our study encompassed the evaluation of the drop vertical jump (DVJ), double leg squat (DLS), and single leg squat (SLS). This methodology can be applied to evaluating any new system of measurement to the corresponding industry gold standard system.

Our LCMAS-Single and LCMAS-2 have repeatable measures and *SDD* smaller than the *MCID* values from the scientific literature between at-risk and normal populations for six and eight metrics, respectively. These metrics include hip angle, knee angle, knee moment, and center of mass position. This outcome enables the use of both systems as screening tools for ACL injury risk and rehabilitation.

Finally, we evaluate our envisioned clinical utility by implementing a literature based algorithm to assess combined motion and again compare the low-cost systems to the industry gold standard with a test-retest reliability study.

We have demonstrated the potential for a clinically-relevant, accurate, low-cost movement assessment tool that can revolutionize orthopaedic medicine by shifting the focus from reactionary to preventative.

The dissertation of Julia Kathryn Nichols is approved.

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*To Ken Jurkowski . . .
his support, encouragement,
and HOURS of proof reading
made this work possible*

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Chapter 1 and 5 contain some language that was used in several grant proposals.

Chapters 3 and 4 consist of a paper and accompanying supplementary material that has been submitted for publication, co-authored by Oliver O'Reilly, PhD [90]. Both Nichols and O'Reilly contributed to the writing of this article and supplementary material.

Some of the Dual Depth Camera data and language in Chapter 7 were presented at the Orthopaedic Research Society Annual Conference 2015 [91].

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PRESENTATIONS

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Part I

Background

CHAPTER 1

Introduction

1.1 Motivation

In order to complete my Ph.D. training and gain the knowledge to analyze and assess human movement, I sought out a Biomechanics research group at University of California, San Francisco (UCSF). I collaborated with the UCSF Department of Orthopaedic Surgery and the UC Berkeley (UCB) Department of Mechanical Engineering on research that involves assessing and quantitatively monitoring movement in 3-dimensions for injury risk and recovery on a widely accessible platform. In the future, I hope to expand this work into a broader scope of applications, including evaluations in clinical practice, physical and occupational therapy, ergonomics, and sports. I am especially excited to work on a highly clinically relevant project and be able to improve patients' movement, function, and quality of life.

My background in elite athletics has provided insight and piqued my interest in helping others in the field of Biomechanics. Anterior cruciate ligament (ACL) injury is particularly widespread. I am personally motivated to explore reducing ACL injury rates as several of my immediate family members have been afflicted, and females are 4-6 times more likely to suffer an ACL injury [3].

1.2 Terminology and Anatomy

To understand and the interdisciplinary work presented in this dissertation, it is important to be familiar with terminology and anatomy relating to the human body. This section presents an overview of this material.

1.2.1 Anatomical Planes and Directions

Three primary orthogonal planes are associated with the body, Figure 1.1. Terminology according to Moses et al. [77]:

Anatomical Planes:

Median (sagittal) plane - a vertical plane that divided the body into left and right halves;

Frontal (coronal) plane - a vertical plane oriented at 90° to the median plane that divides the body into front (anterior) and back (posterior) sections;

Horizontal (transverse or axial) plane, which divides the body into upper (superior) and lower (inferior) sections;

Descriptive Terms:

Anterior (ventral) - towards the front of the body;

Posterior (dorsal) - towards the back of the body;

Superior (cranial) - towards the head;

Inferior (caudal) - towards the feet;

Medial - towards the midline of the body;

Lateral - away from the midline of the body;

Proximal - toward the point of origin, root, or attachment of the structure;

Distal - away from the point of origin, root, or attachment of the structure;

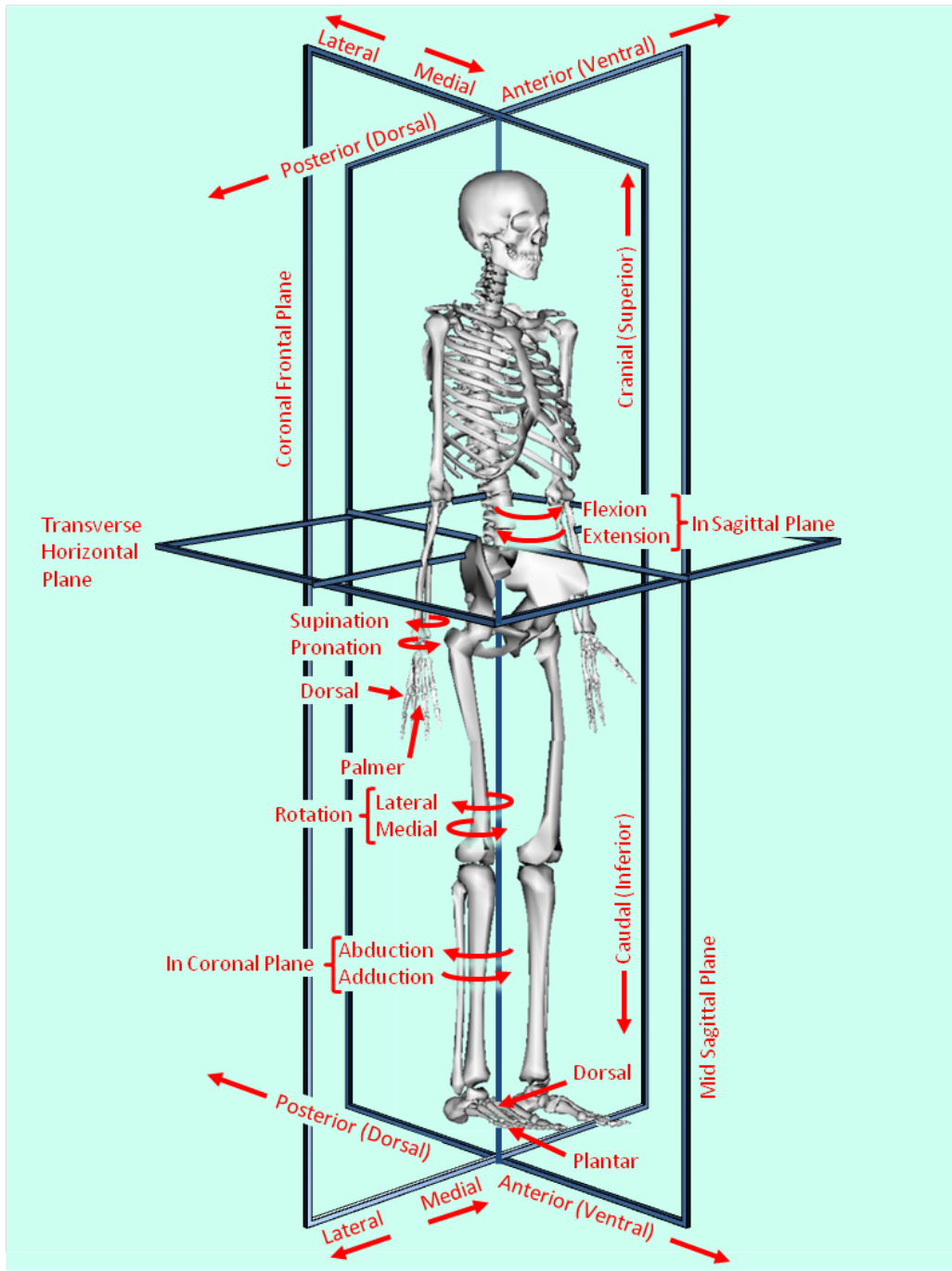


Figure 1.1: *Schematic of the anatomical position with anatomical planes and traditional terminology. Based on Chaffin and Andersson [23, Figure 4.1, p. 80]. Image was composed using OpenSim [31].*

1.2.2 Kinematic Conventions

General terms for movement according to Chaffin and Andersson [23]:

Flexion - Movement involving the bending of a joint whereby the angle between the bones is diminished; the opposite of extension (except at shoulder);

Extension - The position of the joints of the extremities and back when one stands at rest, or the direction of motion that tends to restore this position; the opposite of flexion;

Adduction (varus) - Motion toward the midline. Decreases the angle between a limb and the sagittal plane;

Abduction (valgus) - Motion away from the midline. Increases the angle between a limb and the sagittal plane.

In addition, Moses et al. [77] describe:

Medial (internal) rotation - turns the anterior surface medially or inward;

Lateral (external) rotation - turns the anterior surface laterally or outward;

Supination - lateral rotation of the limb (e.g. the palm starts the movement facing down and ends the movement facing up);

Pronation - medial rotation of the limb (e.g. the palm starts the movement facing up and ends the movement facing down);

Inversion - movement of the foot so that the sole faces medially;

Eversion - movement of the foot so that the sole faces laterally.

The standard anatomical position and traditional terminology are illustrated in Figure 1.1. Specific joint terminology is illustrated in Figure 1.2.

These terms all apply to the clinical description of motion. In motion capture joint angles are interpreted as a series of three rotations to transform from a segment coordinate system on one side of the joint to the segment coordinate

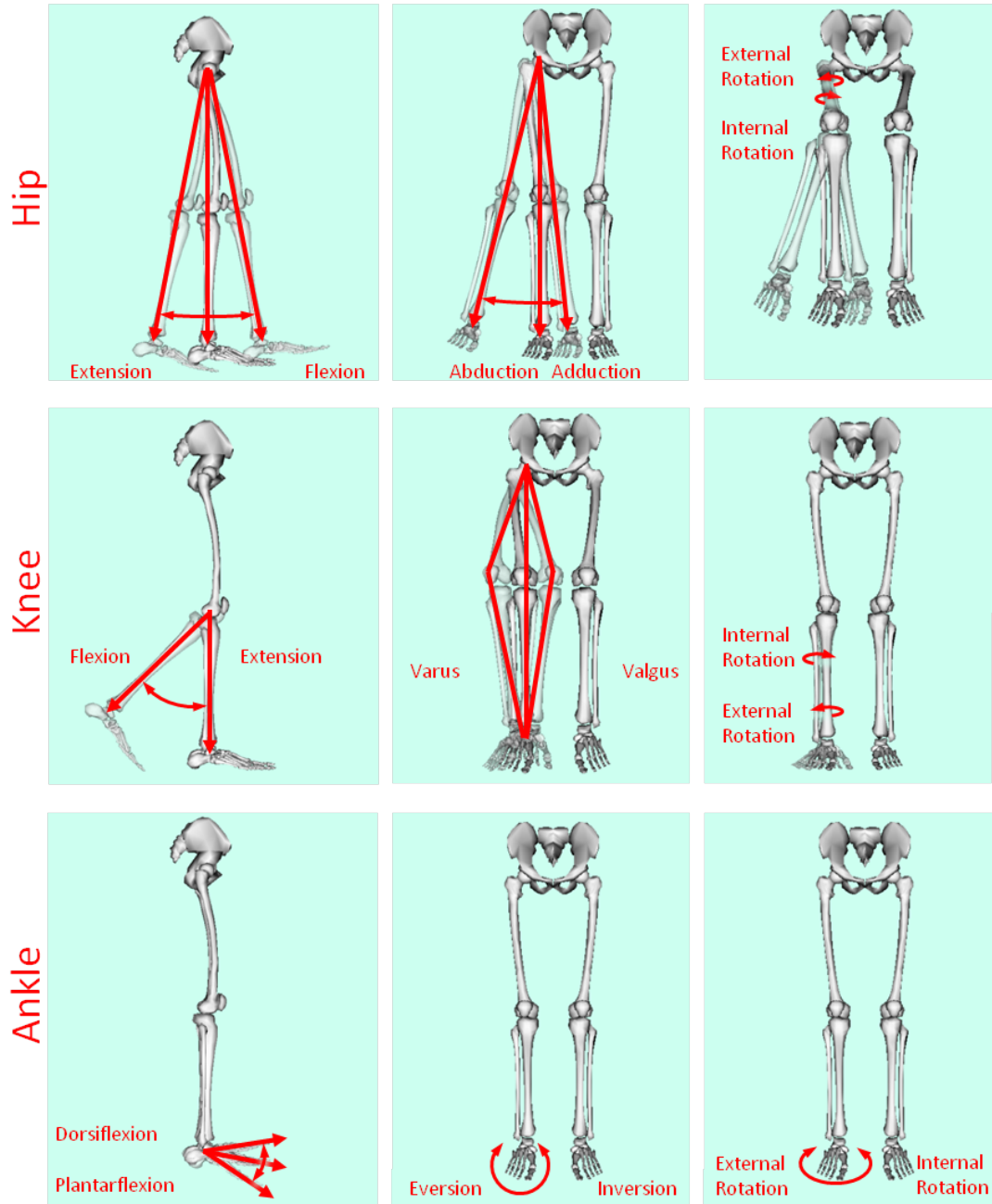


Figure 1.2: *Kinematic Motions of the hip, knee, and ankle. Based on Chaffin and Andersson [23, Figure 4.4, p. 86]. Images were composed using OpenSim [31].*

system on the other side of the joint. The joint coordinate system and angles are explained in more detail in Chapters 3 and 4. It is also important to note

that there is some translation present in joints. The techniques dealt with in this dissertation do not broach this aspect of joint movement. The interested reader is directed to start with Grood and Suntay [45] who include translational degrees of freedom between limb segments.

1.2.3 Anatomy of the Knee

According to Chaffin and Andersson [23, pp. 15, 44, 45]:

Ligaments and tendons are dense connective tissues similar in morphology and function. Ligaments connect bone to bone, providing stability at joints, while tendons attach muscles to bone, transmitting forces from the muscles....

A joint is a union of two or more bones. ... [In] synovial joints... there is no tissue between the articular (joint) surfaces... Most joints are synovial...

Many joints have discs of fibrocartilage to protect and support them. Examples are the menisci of the knee joint, which serve to distribute load and protect the articular cartilage.

The four bones in the synovial knee joint are the femur, tibia, fibula, and patella. Four major ligaments of the knee are the anterior cruciate ligament (ACL), the posterior cruciate ligament (PCL), the medial (or tibial) colateral ligament (MCL), and the lateral (or fibular) colateral ligament (LCL).

Details and function of ligaments and menisci are listed in Table 1.1 and pictured in Figure 1.3.

Table 1.1: *Select major structures of the knee joint based on information from Moses et al. [77, p. 530].*

Structure	Attachment	Movement limited	Comments
MCL	Medial epicondyle of femur to medial condyle and shaft of tibia	Limits extension, hyperflexion, and lateral flexion	Deeper fibers are firmly attached to medial meniscus
LCL	Lateral epicondyle of femur to lateral surface of head of fibula	Limits hyperextension (is relaxed in flexion)	Separated from lateral meniscus by tendon of popliteus
ACL	Anterior part of intercondylar area of tibia; extends superiorly, posteriorly, and laterally to posterior part of medial side of lateral condyle of femur	Limits extension, lateral rotation, and posterior slipping of tibia on femur	Slack when the knee is fully flexed, and taut when the knee is fully extended
PCL	Posterior part of intercondylar area of tibia; extends superiorly, and medially to anterior part of lateral surface of medial condyle of femur	Taut in full flexion and lateral rotation, limits posterior slipping of tibia on femur	In the weightbearing flexed knee, it stabilizes the femur
Medial meniscus	Anterior end attaches to anterior intercondylar area of tibia; posterior end attached to posterior intercondylar area	Deepens the medial condyle of the tibia	Crescent-shaped and firmly adherent to the deep surface of tibial collateral ligament
Lateral meniscus	More freely movable, through the posterior meniscomfemoral ligament, it is attached to the medial condyle of the femur	Deepens the lateral condyle of the tibia	Nearly circular, separated from the fibular collateral ligament

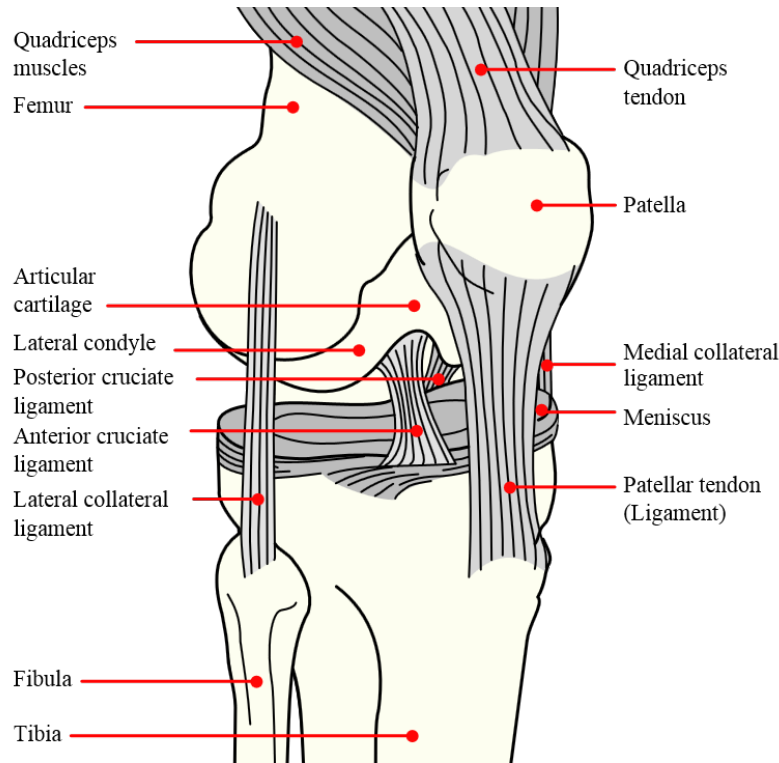


Figure 1.3: *Schematic of bones, major ligaments, and menisci of the right knee joint, anterior lateral view. Image obtained from the public domain.*

1.2.4 Musculature of the Lower Extremities

The prior section discussed passive joint stabilizers. In this section we discuss muscles, the active joint stabilizers. According to Chaffin and Andersson [23, pp. 26,88]:

Skeletal muscle constitutes almost 50% of the body weight. There are several hundred muscles within the body, each with special function. In general, they all serve to generate moments about the joints... Muscles are attached to bone by tendons and cross one or several joints. They are under the direct control of the voluntary nervous system, sometimes referred to as the somatic nervous system. The

unique property of muscle is that it can contract. When contraction is initiated through the nervous system, the muscle either shortens, producing a movement at the joint, or contracts without shortening, providing stability...

When the muscle is extremely shortened, it cannot produce a useful amount of tension. If gravity or tissue compression causes resistance to extreme rotation of a body segment, then joint motion can be limited by the diminished force capacities of the muscles. When a muscle acts about only one joint, the described limitation to joint motion is not great. Unfortunately, many joints are spanned by two-joint muscles, and thus the mobility at one joint depends to some degree on the position of an adjacent joint.

A compilation of lower extremity muscles and their respective functions are listed in Table 1.2. For a more comprehensive list and description of lower extremity muscles, the interested reader is referred to an anatomy text book such as Moses et al. [77].

Table 1.2: *Action of major muscle groups on the hip and knee. Based on Bartel et al. [5, Table 1.2, p. 13].*

Joint	Action	Muscles/Muscle Groups
Hip	Flexion	Illiopus, psoas major
	Extension	Hamstrings, gluteus maximus
	Abduction	Abductors (gluteus minimus, gluteus medius, etc.)
	Adduction	Adductors (adductor magnus, adductor longus, etc.)
Knee	Flexion	Hamstrings, gastrocnemius
	Extension	Quadriceps femoris

Note: Hamstrings consist of three different muscles (semitendinosus, semimembranosus, and biceps femoris);
 Quadriceps consists of four different muscles (rectus femoris, vastus lateralis, vastus medialis, and vastus intermedius).

1.3 Anterior Cruciate Ligament Injury Incidence and Prevalence

One in 3000 individuals in the US sustain an ACL injury, accounting for 100,000 injuries annually [33]. Seventy percent of these injuries are due to non-contact mechanisms [44], with kinematic abnormalities suggested to be an important root cause of these injuries [6, 87]. Long-term studies on ACL-reconstructed patients show that 10-15 years after surgery, 50% to 70% of these patients develop knee osteoarthritis (OA) [119]. Furthermore, the patients with post-traumatic knee OA are, on average, 15 to 20 years younger than patients with primary knee OA. Thus, ACL injury is serious, wide-spread, and has potentially preventable kinematic profiles.

1.4 Injury Mechanism and Neuromuscular Retraining

Knee injury risk is influenced by both extrinsic and intrinsic factors. Extrinsic factors include the sports competition level, physical and visual perturbations, bracing, equipment, playing surface. Intrinsic risk factors include age, gender, anatomy, prior injury, neuromuscular control, and biomechanical patterns [33, 49].

Some terminology according to Swanik et al. [114] and references therein include:

Proprioception refers to conscious and unconscious appreciation of joint position, while *kinesthesia* is the sensation of joint motion or acceleration [78]. These signals are transmitted to the spinal cord via afferent (sensory) pathways. The efferent (motor) response to sensory information is termed *neuromuscular control* [56].

Of the intrinsic factors we recognize the potential to impact neuromuscular

control to improve active stiffness and biomechanical patterns. According to Hewett et al. [49] studies that look at neuromuscular control include those that investigate antagonist-agonist relationships [50, 51, 111, 123], lower extremity muscle activation patterns [8, 54, 73, 128], decreased proprioception [61, 105, 106], imbalanced medial-lateral muscle firing patterns [37, 65, 68, 72, 82, 102], and increased fatigue [92, 123]. Some studies look at biomechanical patterns that attempt to identify kinematic and kinetic differences that elevate injury risk. In their review article Hewett et al. [49] included several examples including center of mass relative to base of support [115], sagittal and frontal plane mechanics [30, 37, 50], side-to-side imbalances in neuromuscular strength, flexibility, and coordination [7, 50, 65], increased ACL strain [39, 58, 69, 72], increased ankle eversion [38], valgus collapse [12, 48, 58], increased hip internal rotation and decreased hip muscle activation [9, 66, 72], and knee internal and external rotation motion and torques [76].

An example of combined kinematic motions, defined as dynamic valgus [50], is a theory of deficiencies in neuromuscular control that increase ACL injury risk, Figure 1.4.

While many knee injury risk factors are not modifiable, multiple studies have demonstrated that improving neuromuscular control of muscles (including those listed in Table 1.2) can improve ACL injury risk [26, 86, 88], [21, 35] via [44], [47, 71, 89] via [46] and symptoms of knee OA [109]. However, a primary challenge in reducing injury rates is determining the proper algorithm to identify at-risk individuals so they can be enrolled in neuromuscular training programs [44].

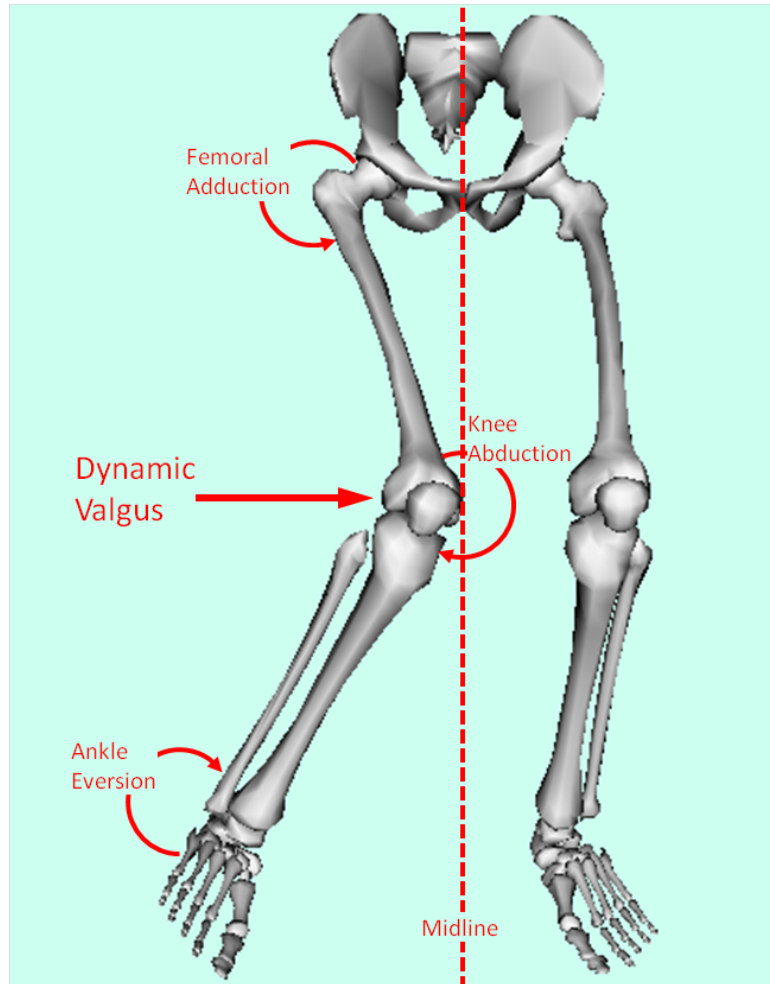


Figure 1.4: *Combined kinematic motions resulting in dynamic valgus [50]. Image was composed using OpenSim [31].*

1.5 Maneuvers and Literature Values for Detecting Deficiencies

Measures of function and disability include performance-based clinical assessments, such as the double leg squat (DLS), single leg squat (SLS), and drop vertical jump (DVJ).

During these maneuvers, trained clinicians can visualize certain lower extremity movements that suggest neuromuscular deficits and increase injury potential.

Joint kinematics, kinetics, and muscular activation can be quantified by using laboratory-based screening tools such as motion capture and electromyographic (EMG) systems. Several studies [13, 17, 29, 42, 50, 52, 83, 84, 85, 120, 126, 129] have used these assessment exercises and tools for evaluating movement deviations.

Another metric, popular in gait studies exploring fall mechanisms, is the dynamic balance metric of displacement of center of mass relative to base of support [127]. We believe that this metric could also be interesting to measure in relation to ACL injury risk screening.

1.5.1 Double Leg Squat

The double leg squat (DLS) is the least demanding of the screening tasks discussed here. For the DLS, the participant is asked to stand with their feet parallel and shoulder-width apart, then perform squats by bending the knees while keeping the back straight, and to bend the knees no further than was comfortable, while attempting to keep their heels in contact with the ground [116], Figure 1.5.

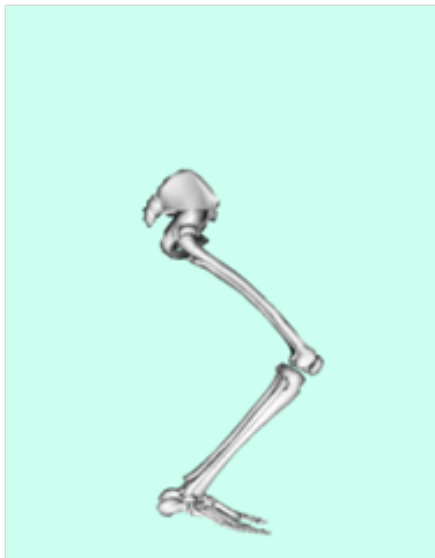


Figure 1.5: *Double leg squat. Image was composed using OpenSim [31].*

1.5.2 Single Leg Squat

A more demanding maneuver is the single leg squat (SLS), Figure 1.6. The SLS allows independent examination of the right and left lower extremities and is a popular evaluation maneuver for ACL studies [29, 52, 120, 126, 129]. To perform the SLS, the participant looks straight ahead and first stands on one leg with the opposite knee flexed to approximately 90° . Then the individual squats down, as far as they feel comfortable and without losing balance, on the weight-bearing limb in a slow and controlled manner. Finally, they complete the continuous motion by returning to the starting position.



Figure 1.6: *Single leg squat. Image was composed using OpenSim [31].*

1.5.3 Drop Vertical Jump

A higher impact and more demanding screening maneuver in studies, used by Hewett and Myer [50], is the drop vertical jump (DVJ), Figure 1.7. For the DVJ, the participant initially stands upright at rest on a 31 cm high box. They are instructed to drop off the box onto a horizontal surface and immediately perform

a maximum vertical jump, as if they were executing a basketball rebound. The stance/impact phase was defined as the participant’s initial contact with the force platform following the drop (Stage II), to the take-off for the maximum vertical jump (Stage IV). Other studies (e.g. Goerger, Padua et al. [42]) have used a similar jump landing (JL) maneuver.

1.5.4 Performance Metrics from Prior Studies

Performance metrics from prior studies in the scientific literature are presented in Tables 1.3 and 1.4. In these tables the first column contains a list of parameters sorted by type (e.g. Kinematic, Kinetic, Other), and then joint (e.g. hip, knee, ankle). The other major columns are headed by a letter that corresponds to a study in the scientific literature. In these columns mean values and either the standard deviation or the standard error of the mean for one or more of the metrics are presented for low injury risk and high injury risk groups. The definitions of these groups vary by study and are denoted in the Comparison row of these tables.

In order to evaluate a person performing the previously discussed maneuvers and draw meaningful conclusions, we look to prior studies reported in the scientific literature. According to Crossley [28], “The minimal clinically important difference quantifies the minimal difference that patients or practitioners consider clinically important and thus will indicate a relevant change in the patient’s symptoms.[2, 55]” We will take our minimal clinically important differences (MCID) to be the difference between mean values in the literature data for low injury risk and high injury risk groups. The MCID values associated with the metrics from prior studies are presented in a similar format in Tables 1.5 and 1.6.

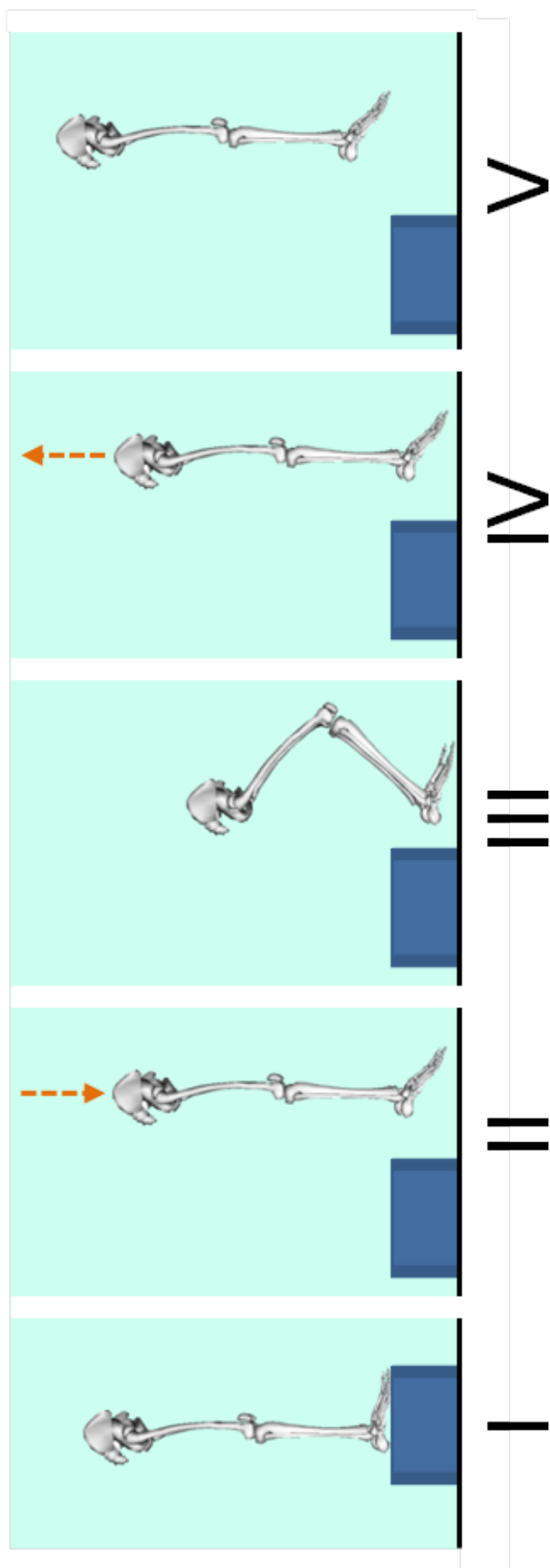


Figure 1.7: Schematic of the five stages of the drop vertical jump task. The stance phase starts at initial contact, Stage II, and ends at take-off, Stage IV. Images were composed using OpenSim [31].

Table 1.4: Studies highlighting metrics with significant differences between groups for double leg maneuvers. Note: $G[17]$, $H[50]$, $I[13]$, $J[42]$; patellofemoral pain (PFP); Functional Movement Screen (FMS); deep squat (DS); jump landing (JL); mean (M); standard deviation (SD); standard error of the mean (SEM); number of participants in each group (n).

Study	G			H			I			J		
	Injury	FMS injury screening	ACL	ACL	DVI	ACL	PFP	ACL	ACL	n=39	n=19	n=12
Maneuver	DS			n=9			n=309			n=40		
	M	SEM	M	SEM	M	SEM	M	SEM	M	SD	M	SD
Comparison	Group 1 - low performer											
	Group 3 - high performer											
	Uninjured											
	Injured											
	Control baseline											
	Control follow-up											
	ACL-R-UNINJ follow-up											
	ACL-R-INJ baseline											
	ACL-R-INJ follow-up											
	ACL-R-INJ follow-up											
Kinematic	Hip											
	Knee											
	Ankle											
	Hip											
	Knee											
	Side-to-side differences abduction moment											
	Peak anterior tibial shear force (%BW)											
	Vertical ground reaction force (N)											
	Vertical ground reaction force (%BW)											
	Stance time											
Kinetic	Peak Flexion Moment (Nm)											
	Peak External Rotation Moment (%BW·ht)											
	Peak Abduction Moment (Nm)											
	Peak Extension Moment (Nm)											
	Peak Extension Moment (%BW·ht)											
	Side-to-side differences abduction moment											
	Peak anterior tibial shear force (%BW)											
	Vertical ground reaction force (N)											
	Vertical ground reaction force (%BW)											
	Stance time											

Table 1.5: MCID values from studies highlighting metrics with significant differences between groups for single leg maneuvers.
Note: A[52], B[120], C[126], D[129], E[29], F[127]; patellofemoral pain (PFP); anterior knee pain (AKP); center of mass (COM); base of support (BOS).

Study	A			B			C			D			E			F		
	Injury	PFP	Screen	ACL	ACL	ACL	ACL	ACL	ACL	ACL	ACL	ACL	ACL	ACL	ACL	ACL	ACL	ACL
Maneuver	Parameter of Interest	SLS	SLS	SLS	SLS	SLS	SLS	SLS	SLS	SLS	SLS	SLS	SLS	SLS	SLS	SLS	SLS	SLS
		MCID	MCID	MCID	MCID	MCID	MCID	MCID	MCID	MCID	MCID	MCID	MCID	MCID	MCID	MCID	MCID	MCID
Kinematic	Hip																	
	ROM Adduction (deg)																	
	Adduction at max knee flexion (deg)		6.3															
	Flexion at max flexion Female-Control (deg)																	
	Flexion at max knee flexion (deg)																	
	ROM Flexion (deg)		7.5															
	ROM Extension (deg)																	
	External rotation at max flexion Male-Self (deg)																	
	External rotation at max flexion Female-Control (deg)																	
	ROM External rotation (deg)																	
Knee	Varus at max flexion Male-Self (deg)																	
	Varus at max flexion Female-Self (deg)																	
	Max Flexion Angle (deg)																	
	Flexion at max flexion Male-Self (deg)																	
	Flexion at max flexion Female-Control (deg)																	
	External rotation at max flexion Male-Self (deg)																	
	External rotation at max flexion Female-Control (deg)																	
	ROM Varus (deg)																	
	ROM Valgus (deg)																	
	ROM Dorsiflexion (deg)																	
Ankle	ROM Supination (deg)																	
	ROM Pronation (deg)																	
	ROM Lateral flexion (deg)																	
	Rectus femoris-area under the linear envelope (%MVC)																	
	Rectus femoris-maximum activation (%MVC)																	
	Anterior gluteus medius (ms)																	
	Posterior gluteus medius (ms)																	
	Forward displacement of COM relative to BOS (cm)																	
EMG																		
Other																		

Table 1.6: MCID values from studies highlighting metrics with significant differences between groups for double leg maneuvers.
Note: *G*[17], *H*[50], *I*[13], *J*[42]; patellofemoral pain (PFP); deep squat (DS); jump landing (JL).

Study		G		H		I		J	
		Screen	ACL	ACL	PFP/ACL	ACL	JL	ACL	JL
Injury	Maneuver	DS	DVJ	DVJ	JL	JL			
		MCID	MCID	MCID	MCID	MCID	MCID	MCID	MCID
Kinematic	Hip	IC Adduction Angle (deg)							
		Peak flexion (deg)	32.3						
	Knee	ROM Flexion (deg)	31.6						
		IC Abduction Angle (deg)		8.4					
		Max Abduction Angle (deg)		7.6					
		IC Varus (deg)						6.17	6.83
		Peak varus (deg)						8.72	6.20
		Peak valgus (deg)						6.35	
		Max Flexion Angle (deg)	46.0	10.5					
		ROM Flexion Angle (deg)	51.4						
		Peak internal rotation (deg)					7.92		
		ROM Dorsiflexion (deg)	8.4						
Kinetic	Hip	Peak Flexion Moment (Nm)		41.1					
		Peak Flexion Moment (%BW·ht)							0.118
		Peak External Rotation Moment (%BW·ht)			0.14				
		Peak Abduction Moment (Nm)		26.9					
	Knee	Peak Extension Moment (/M·ht)	0.182						
		Peak Extension Moment (%BW·ht)			0.02				0.065
		Peak anterior tibial shear force (%BW)							0.324
		Vertical ground reaction force (N)		208.3					
Other		Vertical ground reaction force (%BW)			0.3				

1.6 Addressing Current Limitations in Technology and Accessibility

Current assessment tools have major limitations. Clinical tests are subjective, difficult to implement, and lack of normative data for test results interpretation. Laboratory-based screening tools require dedicated facilities, trained personnel, and expensive equipment [81]. As a result, performance-based tests can be sensitive to neuromuscular deficits that create risk, but are difficult to implement on a wide scale.

In addition to laboratory-based functional assessment tools, other products, such as Wii Fit, Your Shape, and Kinect Sports, are highly accessible but lack the accuracy needed to reliably measure improvements in function and performance. Low-cost (\$150), commercially available depth cameras have attracted attention from the biomechanics community as a potential measurement tool for use in clinical and sports-related analysis of gait, posture, and human performance. Common brands of these depth cameras include the ASUS Pro and Microsoft Kinect, Figure 1.8.



Figure 1.8: *Depth cameras. Note: ASUS Pro (left) and Microsoft Kinect (right).*

Unfortunately, because built-in body position estimates are generated using statistical learning algorithms rather than direct measurements, they are insufficiently accurate to enable detailed biomechanical analyses, Figure 1.9. Current comparisons only evaluate slow large maneuvers [14] or limited kinematics [93, 113], and direct application of the raw 3D pose data lacks the accuracy to

be clinically relevant [57]. To overcome these limitations, we have developed computer vision enhancements and novel software tools that improve the way the depth camera acquires, processes, and interprets human movement data and enables the recognition of 3D human body position with low-cost commercially available depth cameras.



Figure 1.9: *Example of 3D pose estimation (skeleton) overlaid on RGB image captured from the Microsoft Kinect during a SLS maneuver.*

1.7 Significance

Orthopaedic surgery is currently a field that is reactive, rather than proactive. A movement screening tool could help identify at risk individuals before injury occurs and decrease the long term risk of OA. At present, accurate movement monitoring systems are prohibitive in cost and size to be practical and accessible to the general population. Current commercially available low-cost and more accessible systems lack the accuracy needed for clinical relevance. The result of this current study paves the way for a breakthrough in preventative medicine.

CHAPTER 2

Motion Capture

2.1 System Function

Our studies were conducted at the UCSF Human Performance Center (HPC). The space is calibrated prior to subject data capture. Forty-eight retro-reflective spherical markers, 14 mm in diameter, are positioned on the participant on key bony landmarks and laterally on limb segments in rigid clusters of four markers. Three-dimensional kinematic data were collected at 250 Hz by an infrared 10-camera system (Vicon, Oxford Metrics, UK). Kinetic data were collected at 1000 Hz by two embedded force platforms (AMTI, Watertown, MA USA). All data collection is synchronized. The position of passive retro-reflective markers within the collection volume is located using the multiple cameras and direct linear transformation (DLT) [1, 74, 101]. A static trial is captured for a reference posture and baseline participant metrics, including weight, followed by the capture of dynamic trials.

2.1.1 Marker Sets

Calibrations marker positions from the static standing trial were used to establish local coordinate systems for each segment (see Section 2.2.1). The relative position and orientation of tracking markers associated with each segment are also identified. These tracking markers are used to locate that segment's position and orientation during the dynamic trials. Marker sets with type and segment

association are pictured in Figure 2.1 and listed in Table 2.1.

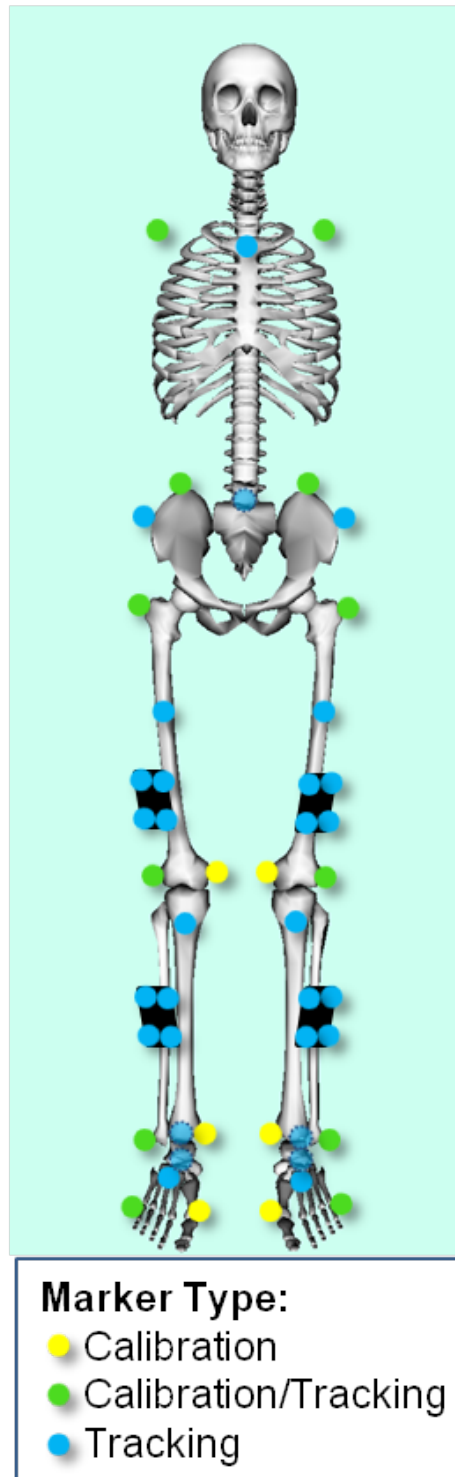


Figure 2.1: *Marker locations. Image was composed using OpenSim [31].*

Table 2.1: *Marker Names with locations and type of use in model.*

	#	Marker Name	Description	Segment	Type
T	1T	'AR'	Top of the T on the Participant's Right	Ground T	Reference
	2T	'CTop'	Top of the T in the center	Ground T	Reference
	3T	'AL'	Top of the T on the Participant's Left	Ground T	Reference
	4T	'CBot'	Bottom of the stem of the T	Ground T	Reference
P	1	'R_Acro'	Right acromion	Torso	Calibration/Tracking
	2	'SCJ'	Sternoclavicular Joint	Torso	Tracking
	3	'L_Acro'	Left acromion	Torso	Calibration/Tracking
	4	'R_IC'	Right iliac crest	Torso/Pelvis	Calibration/Tracking
	5	'L_IC'	Left iliac crest	Torso/Pelvis	Calibration/Tracking
	6	'R_GTro'	Right Greater Trochanter	Pelvis/Right Thigh	Calibration/Tracking
	7	'L_GTro'	Left Greater Trochanter	Pelvis/Left Thigh	Calibration/Tracking
	8	'R_ASIS'	Right Anterior-superior iliac spine	Pelvis	Tracking
	9	'L_ASIS'	Left Anterior-superior iliac spine	Pelvis	Tracking
	10	'R_Mid_Thigh'	Right Mid-Thigh	Right Thigh	Tracking
	11	'L_Mid_Thigh'	Left Mid-Thigh	Left Thigh	Tracking
	12	'R_PS_T'	Right Posterior-superior thigh	Right Thigh (cluster)	Tracking
	13	'R_PI_T'	Right Posterior-inferior thigh	Right Thigh (cluster)	Tracking
	14	'L_PS_T'	Left Posterior-superior thigh	Left Thigh (cluster)	Tracking
	15	'L_PI_T'	Left Posterior-inferior thigh	Left Thigh (cluster)	Tracking
	16	'R_AS_T'	Right Anterior-superior thigh	Right Thigh (cluster)	Tracking
	17	'R_AI_T'	Right Anterior-inferior thigh	Right Thigh (cluster)	Tracking
	18	'L_AS_T'	Left Anterior-superior thigh	Left Thigh (cluster)	Tracking
	19	'L_AI_T'	Left Anterior-inferior thigh	Left Thigh (cluster)	Tracking
	20	'R_Lat_Epi'	Right Lateral-epicondyl	Right Thigh/Right Shank	Calibration/Tracking
	21	'L_Lat_Epi'	Left Lateral-epicondyl	Left Thigh/Left Shank	Calibration/Tracking
	22	'R_Med_Epi'	Right Medial-epicondyl	Right Thigh/Right Shank	Calibration
	23	'L_Med_Epi'	Left Medial-epicondyl	Left Thigh/Left Shank	Calibration
	24	'R_TibTu'	Right Tibial-tuberosity	Right Shank	Tracking
	25	'L_TibTu'	Left Tibial-tuberosity	Left Shank	Tracking
	26	'R_PS_S'	Right Posterior-superior shank	Right Shank (cluster)	Tracking
	27	'R_PI_S'	Right Posterior-inferior shank	Right Shank (cluster)	Tracking
	28	'L_PS_S'	Left Posterior-superior shank	Left Shank (cluster)	Tracking
	29	'L_PI_S'	Left Posterior-inferior shank	Left Shank (cluster)	Tracking
	30	'R_AS_S'	Right Anterior-superior shank	Right Shank (cluster)	Tracking
	31	'R_AI_S'	Right Anterior-inferior shank	Right Shank (cluster)	Tracking
	32	'L_AS_S'	Left Anterior-superior shank	Left Shank (cluster)	Tracking
	33	'L_AI_S'	Left Anterior-inferior shank	Left Shank (cluster)	Tracking
	34	'R_Lat_Mal'	Right Lateral-malleolus	Right Shank/Right Foot	Calibration/Tracking
	35	'L_Lat_Mal'	Left Lateral-malleolus	Left Shank/Left Foot	Calibration/Tracking
	36	'R_Med_Mal'	Right Medial-malleolus	Right Shank/Right Foot	Calibration
	37	'L_Med_Mal'	Left Medial-malleolus	Left Shank/Left Foot	Calibration
	38	'R_5th_Met'	Right 5 th Metatarsal	Right Foot	Calibration/Tracking
	39	'L_5th_Met'	Left 5 th Metatarsal	Left Foot	Calibration/Tracking
	40	'R_Arch'	Right Arch	Right Foot	Tracking
	41	'L_Arch'	Left Arch	Left Foot	Tracking
	42	'R_1st_Met'	Right 1 st Metatarsal	Right Foot	Calibration
	43	'L_1st_Met'	Left 1 st Metatarsal	Left Foot	Calibration
P-Vicon	44	'R_PS_Heel'	Right Posterior-superior heel	Right Foot	Tracking
	45	'R_PI_Heel'	Right Posterior-inferior heel	Right Foot	Tracking
	46	'L_PS_Heel'	Left Posterior-superior heel	Left Foot	Tracking
	47	'L_PI_Heel'	Left Posterior-inferior heel	Left Foot	Tracking
	48	'L5_S1'	L5-S1	Pelvis	Tracking

2.2 Data Processing

The markers in the static and dynamic trials are labeled in Vicon Nexus software, Figure 2.2a, and run through a custom pipeline that exports the data for processing in Visual3D (C-Motion, Germantown, MD, USA). In Visual3D a series of custom pipelines start by importing the marker trajectory data, as well as center of pressure location, ground reaction force and free moment data from the synchronized force platforms.

In order to perform pose estimation, kinematics and kinetics, custom model files construct a rigid segment representation of the participant based on the bony landmark calibration markers, see Section 2.2.1. These rigid segments have mass and inertial properties based on Dempster’s body segment parameters and Hanavan’s frustum of right circular cones and elliptical cylinders, as well as individual coordinate systems [101], Figure 2.2b. From the static reference posture, the segment coordinate systems (or local coordinate systems) are oriented with the first axis (**X**, red) in the medial/lateral direction with the participant’s right as positive, the second axis (**Y**, green) is the anterior/posterior direction with anterior as positive, and the third axis (**Z**, blue) in the superior inferior direction with superior as positive. Three or more noncolinear tracking markers locate each segment’s position and orientation throughout the laboratory space. In our case, we have used a combination of individual markers and noncolinear clusters of markers attached to rigid plates as tracking markers. The light blue sphere is the composite center of mass for the model.

2.2.1 Segment Coordinate System Definitions

The segment coordinate system are pictured in Figure 2.3 and defined as follows:

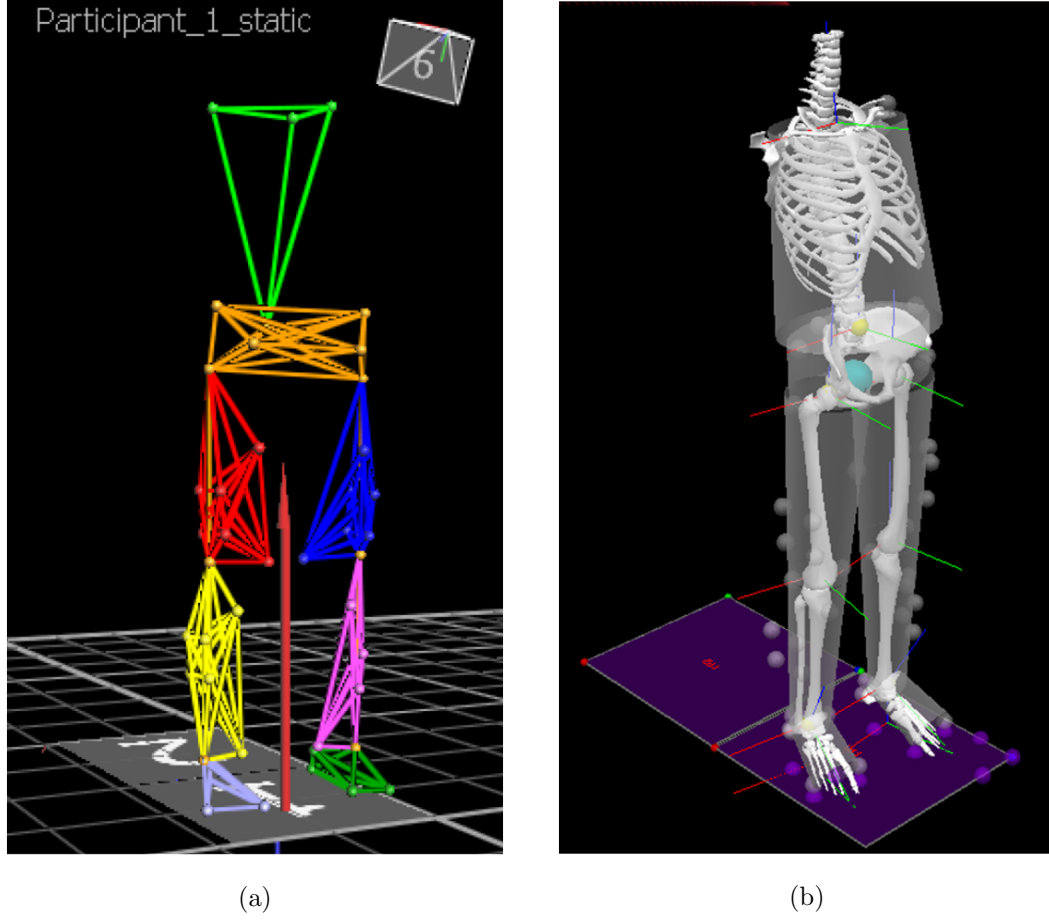


Figure 2.2: *Pictorial representations of motion capture models, (a) labeled markers from Vicon capture, and (b) segment visualization with frustum of right circular cones and coordinate systems in Visual3D.*

Torso

Using a least-squares fit, a segmental frontal plane is fit to the 2 acromion and 2 iliac crest markers. The inferior torso center is defined as the midpoint between the iliac crest markers. The superior torso center is defined as the midpoint between the acromion markers. Thus, the superior-inferior axis, $\mathbf{Z}_{Torso}$, is defined as passing between the inferior torso center and superior torso center on the segmental frontal plane, and points towards the superior direction. The anterior-posterior axis, $\mathbf{Y}_{Torso}$, is chosen to be normal to the segmental frontal plane and

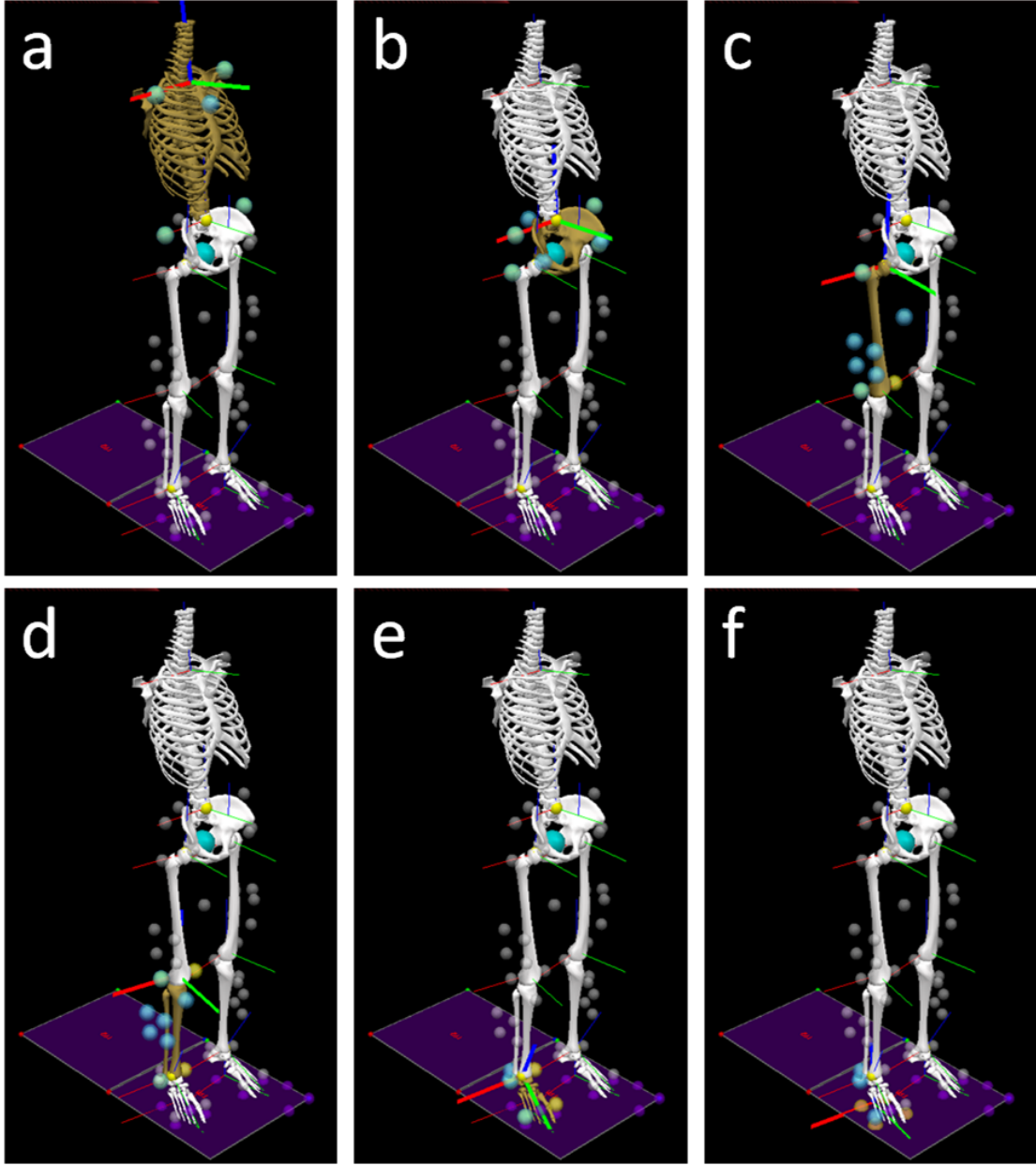


Figure 2.3: *Model segments visualizations in Visual3D: (a) torso; (b) pelvis; (c) right thigh; (d) right shank; (e) right foot; (f) right virtual foot.*

points towards the anterior direction. The medial-lateral axis, $\mathbf{X}_{Torso}$, is mutually perpendicular to $\mathbf{Y}_{Torso}$ and $\mathbf{Z}_{Torso}$, and is positive in (or points towards) the lateral direction for the right side.

Pelvis

Using a least-squares fit, the pelvis frontal plane is fit to the 2 iliac crest and 2 greater trochanter markers. The inferior pelvis center is defined as the midpoint between the greater trochanter markers. The superior pelvis center is defined as the midpoint between iliac crest markers. Thus, the superior-inferior axis, $\mathbf{Z}_{Pelvis}$, is defined as passing between the inferior pelvis center and superior pelvis center on the segmental frontal plane, and points towards the superior direction. The anterior-posterior axis, $\mathbf{Y}_{Pelvis}$, is chosen to be normal to the pelvis frontal plane and points towards the anterior direction. The medial-lateral axis, $\mathbf{X}_{Pelvis}$, is mutually perpendicular to $\mathbf{Y}_{Pelvis}$ and $\mathbf{Z}_{Pelvis}$, and is positive in (or points towards) the lateral direction for the right side.

Thigh

To elaborate further on the specification of the basis vectors, we next consider the thigh. A virtual point, “mid-trochanter”, is identified midway between the contralateral and ipsilateral greater trochanter markers. Using a least-squares fit, the femoral frontal plane is fit to the femoral medial and lateral epicondyle markers, the greater trochanter marker, and the “mid-trochanter” virtual point. The hip center is defined as the midpoint between the greater trochanter marker and “mid-trochanter” virtual point. The knee center is defined as the midpoint between femoral medial and lateral epicondyle markers. Thus, the superior-inferior axis, $\mathbf{Z}_{Thigh}$, is defined as passing between the hip center and knee center on the femoral frontal plane, and points towards the superior direction. The anterior-posterior axis, $\mathbf{Y}_{Thigh}$, is chosen to be normal to the femoral frontal plane and points towards the anterior direction. The medial-lateral axis, $\mathbf{X}_{Thigh}$, is mutually perpendicular to $\mathbf{Y}_{Thigh}$ and $\mathbf{Z}_{Thigh}$, and is positive in (or points towards) the lateral direction for the right side.

Shank

The corotational basis for the shank is specified by first fitting the tibial frontal plane to tibial medial and lateral malleolus markers, and femoral medial and lateral epicondyle markers. Again, a least-square fit is used. The ankle center is defined as the midpoint between tibial medial and lateral malleolus markers. The superior-inferior axis, $\mathbf{Z}_{Shank}$, is defined to pass between the knee center and ankle center on the tibial frontal plane and is positive in the superior direction. The anterior-posterior axis, $\mathbf{Y}_{Shank}$, is normal to the tibial frontal plane and is positive in the anterior direction. The medial-lateral axis, $\mathbf{X}_{Shank}$, is mutually perpendicular to $\mathbf{Y}_{Shank}$ and $\mathbf{Z}_{Shank}$ and is positive in the lateral direction for the right side.

Foot

For the Foot segment the coordinate system assignment is modified from the convention above to retain a coordinate system alignment in the neutral (static) posture. Using a least-squares fit, a segmental plane is fit to the medial and lateral malleolus markers and the 1st and 5th metatarsal markers. The distal toe center is defined as the midpoint between the metatarsal markers. The proximal ankle center is defined as the midpoint between malleolus markers. For neutral alignment, the anterior-posterior axis, $\mathbf{Y}_{Foot}$, is defined as passing between the ankle center and toe center on the segmental plane, and points towards the anterior direction. The superior-inferior axis, $\mathbf{Z}_{Foot}$, is chosen to be normal to the segmental plane and points towards the superior direction. The medial-lateral axis, $\mathbf{X}_{Foot}$, is mutually perpendicular to $\mathbf{Y}_{Foot}$ and $\mathbf{Z}_{Foot}$, and is positive in (or points towards) the lateral direction for the right side.

Virtual Foot

Virtual foot segments are also calculated using projections of the malleolus and

metatarsal markers onto the ground plane. The axis assignments are the same as in the Foot, simply substituting the projected markers for the actual markers.

2.2.2 Model Choice

Generally a six-degree-of-freedom (DOF) or Segment Optimization model is used where each segment has 6-DOF in space. The position and orientation of each segment is located by using a least squares fit of the tracking markers on that segment relative to the tracking markers in the standing static trial [101]. Some laboratories choose to employ the Inverse Kinematic (IK) or Global Optimization [70, 118] model where you can constrain the degrees of freedom of each segment. One method is to allow the parent pelvis segment 6-DOF and then constrain translation degrees of freedom on child segments.

For our Industry Gold Standard Data we have employed the 6-DOF model. The custom pipelines are set up to calculate and export marker locations, lower extremity (LE) joint angles, forces, and moments. Joint angles are calculated from the rotation between the proximal and distal coordinate system. Joint forces and moments are calculated using standard inverse dynamics, with the internal forces and internal moments reported in the proximal, distal, and joint coordinate system. In addition, the pipelines export the center of mass of the model and force plate data comprising of force, free moment, and center of pressure.

2.2.3 Sign Conventions

The sign conventions used with kinematic and kinetic metrics are based on right-handed segment coordinate systems and are listed in Table (2.2).

Table 2.2: *Sign conventions used with kinematic and kinetic metrics.*

Angles and Moments								
			Right			Left		
		Extension (X)	Adduction (Y)	Internal Rotation (Z)		Extension (X)	Adduction (Y)	Internal Rotation (Z)
Hip		-	+	+		-	-	-
Knee		+	+	+		+	-	-
Ankle		-	+	+		-	-	-

Forces								
			Right			Left		
		Lateral (X)	Anterior (Y)	Superior (Z)		Lateral (X)	Anterior (Y)	Superior (Z)
Hip		+	+	+		-	+	+
Knee		+	+	+		-	+	+
Ankle		+	+	+		-	+	+

2.2.4 Units and Normalization

Angles are reported in units of *degrees* and are obtained from the calculation of rotating from the coordinate system of the proximal segment to the coordinate system of the distal segment in a 1-2-3 sequence of Euler angles. Since angles are described as a combination of three rotations they cannot simply be added or subtracted for normalization. For the ankle we used the strategy of a virtual foot segment for the distal segment as described in Section 2.2.1. More details on rotations are covered in Chapters 3 and 4.

Forces are reported in units of N , as well as normalized to be dimensionless by dividing by participants mass (Kg) and gravity (m/s^2).

Moments are reported in units of Nm , as well as normalized to be dimensionless by dividing by participants mass (Kg), gravity (m/s^2), and leg length in (m). Leg length was chosen over height because 1) we are focusing on lower extremity mechanics, and 2) we could rely on metrics generated through motion capture from marker data.

2.2.5 Data Filtering

Originally we simply applied filtering to marker trajectory data. Due to marker dropout in our low-cost systems and the resultant impact on both the 6-DOF and IK models, we investigated other accepted practices. C-Motion maintains a well documented wiki on Visual3D. A suggested solution is to refrain from filtering data until after joint angles, moments, and forces are calculated and then filter these metrics [18]. We wanted to handle the Vicon data and the low-cost system data in the same fashion, so this filtering tactic is used in our analysis of the Vicon data.

In post processing, kinematic and kinetic metrics are filtered according to Winter’s analysis of residuals [122]. The residual, R , is evaluated at a range of cutoff frequencies, f_c , in the following calculation (2.1):

$$R(f_c) = \sqrt{\frac{1}{N} \sum_{i=1}^N (X_i - \hat{X}_i)^2} \quad (2.1)$$

Where f_c is the cutoff frequency of the bi-directional fourth-order zero-lag low-pass butterworth filter, N is the number of data points, X_i is the raw data of the i th sample, $\hat{X}_i$ is the filtered data of the i th sample.

Signal distortion and noise passing through the filter are balanced at the selected cutoff frequency, Figure 2.4. An analysis of residuals was performed using MATLAB (MathWorks, Natick, MA, USA) on kinematic and kinetic data. According to van den Bogert, all signals should be filtered with the same parameters

[18, 117]. We determined that our gold standard Vicon data be filtered at 12 Hz for kinematic and kinetic metrics.

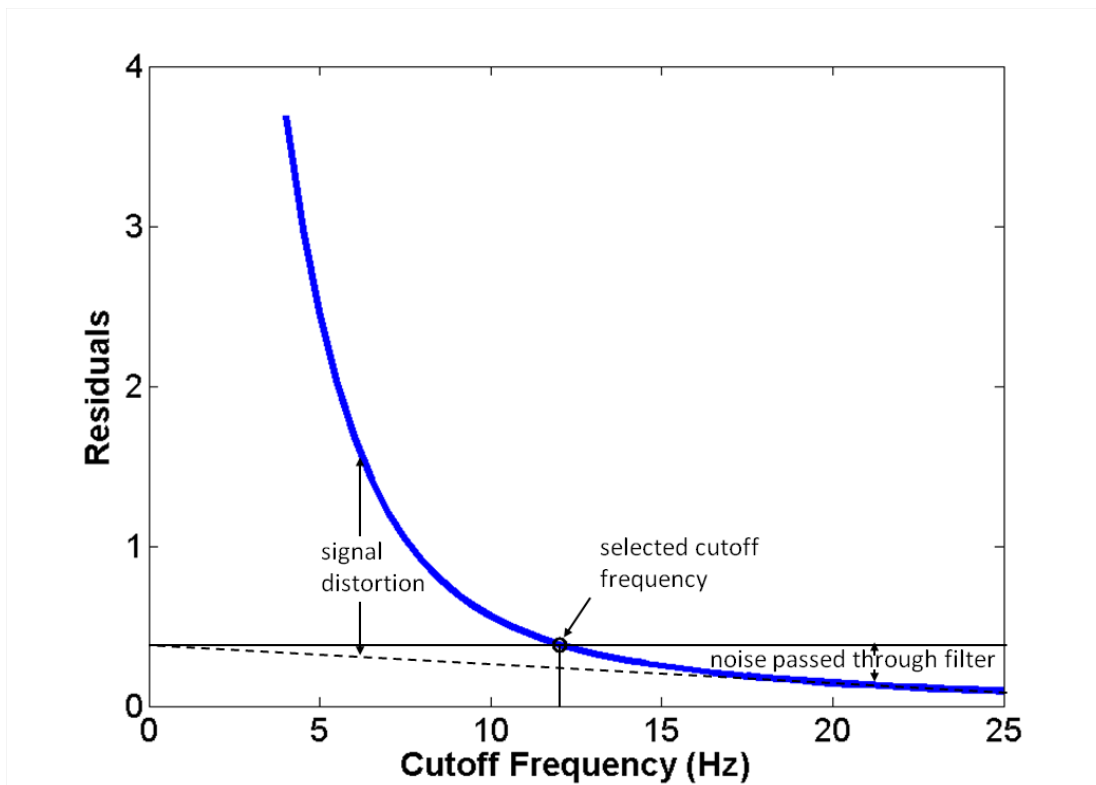


Figure 2.4: *Analysis of residuals to determine cutoff frequency in kinematic data filtering. Note: Here the example metric is Knee Flexion Angle in units of degrees.*

2.2.6 Repetition Identification

For the dynamic trials, we needed to define the beginning and end of each repetition. This definition is dependent on the type of maneuver. The DVJ starts with the participant standing on top of a 31 cm high box, not in contact with the force plates. For data segmentation, a repetition of a DVJ begins upon initial landing when the force plate signal exceeds 10 N and ends at the following takeoff when the force plate signal drops below 10 N. These values have been used in other studies [42, 50]. The signals from each force plate (right (R) and left (L)) are

separately identified and the starting (ON) events are tagged as RON and LON, while the end (OFF) events are tagged as ROFF and LOFF. For the DLS, SLSR, and SLSL maneuvers we cannot rely on the force plate signal to identify the beginning and ending events as the participant is in contact with the force plates for the entire series of repetitions. Instead we focused on the knee flexion angle and defined an ON event in a sample of our data. Then we used a pattern recognition algorithm within Visual3D to identify RON and LON, and the mirrored event to identify ROFF and LOFF. All tags were manually checked, with extraneous tags removed and missing tags added. In the SLS maneuvers only the active leg was tagged. For all exercises, these ON and OFF events are tagged in the capture timeline and apply to all metrics.

2.3 Limitations

At present, accurate movement monitoring systems are prohibitive in cost and size to be practical and accessible to the general population. The systems require many resources, including: space, money, personnel, time for data processing and for subject markering. These limitations make it difficult to develop a normative database or to be practical to be used for screening and assessing the general population. In addition, even these industry standard systems are subject to some level of error, including soft tissue artifact ranging from 20-31 mm when compared to invasive bone mounted pins [40] or small capture volume fluoroscopy [112]. Reischmidt et al. reported individual and mean root mean square (RMS) differences, as well as maximum differences, in joint angles at the knee [100] and ankle [99] between skin mounted and bone mounted markers for 3 and 5 participants, respectively. Mean values for RMS differences are presented in Table 2.3. All of these studies demonstrate the the limitations in current non-invasive motion capture and the resulting level of accuracy in kinematic and kinetic data.

Table 2.3: *Mean differences between knee [100] and ankle [99] angles derived from skin mounted and bone mounted markers locations for 3 and 5 participants, respectively.*

Knee rotation	Variable	Mean	Ankle rotation	Variable	Mean
Flexion/extension (X)	RMS Diff (deg)	5.3	Plantarflexion/dorsiflexion (X)	RMS Diff (deg)	4.6
	Max Diff (deg)	7.9		Max Diff (deg)	7.5
	RMS Diff (%)	20.8		RMS Diff (%)	14.1
	Max Diff (%)	30.9		Max Diff (%)	21.4
Adduction/abduction (Y)	RMS Diff (deg)	4.1	Inversion/eversion (Y)	RMS Diff (deg)	4.6
	Max Diff (deg)	6.6		Max Diff (deg)	7.5
	RMS Diff (%)	70.4		RMS Diff (%)	34.7
	Max Diff (%)	115.0		Max Diff (%)	56.4
Internal/external rotation (Z)	RMS Diff (deg)	4.4	Adduction/abduction (Z)	RMS Diff (deg)	3.6
	Max Diff (deg)	9.0		Max Diff (deg)	5.7
	RMS Diff (%)	63.6		RMS Diff (%)	51.2
	Max Diff (%)	129.2		Max Diff (%)	85.8

CHAPTER 3

Sets of Bases Vectors

This chapter, supplemental work to the following chapter Nichols and O'Reilly “Verifying the Equivalence of Representations of Joint Moment Vectors with Application to Biomechanical Motion Capture Data from a Drop Vertical Jump Task”, discusses the derivation of formulae describing the relationships between components for different representations of the same vector. The rotation between two of the featured bases is parameterized by a 1-2-3 set of Euler angles and the other two sets of featured bases are the Euler and dual Euler bases for this 1-2-3 set of Euler angles. For this choice of Euler angle parameterization, the relevant transformations are collected in Equations (3.13), (3.14), (3.15), and (3.16).

3.1 Introduction

In the subsequent chapter, Nichols and O'Reilly “Verifying the Equivalence of Representations of Joint Moment Vectors with Application to Biomechanical Motion Capture Data from a Drop Vertical Jump Task”, the moment vector is described using four different sets of basis vectors. In the interests of brevity many of the details on the derivations of the relationships between the resulting four sets of components that feature in this work were omitted. The purpose of this material is to present this relevant background. We start with a discussion of the rotation between the proximal and distal frames and then consider the parameterization of this rotation using a set of 1-2-3 Euler angles. Our motivation for this choice of angles is based on the seminal paper by Grood and Suntay [45] on the knee joint

and the joint coordinate system associated with the Euler angles is detailed in Section 3.4. The transformations between the components of a vector are collected in Equations (3.13), (3.14), (3.15), and (3.16).

The notation featured in our work is identical to that used in O'Reilly (2008) [95]. Arrays of real numbers are denoted by san-serif Roman letters, such as $\mathbf{R}$, $\mathbf{m}$, while vectors and tensors are denoted by bold-faced Roman letters, e.g., $\mathbf{g}_1$ and $\mathbf{R}$. For additional background on the Euler and dual Euler bases, the reader is referred to O'Reilly (2008) [95] and references therein. Biomechanical applications of this pair of bases can be found in multiple other works [27, 32, 34, 97].

3.2 The Rotation Between the Proximal and Distal Frames

It is convenient to define a fixed right-handed orthonormal basis for Euclidean space $\mathbb{E}^3$. This fixed basis $\{\mathbf{E}_1, \mathbf{E}_2, \mathbf{E}_3\}$ will serve as the laboratory fixed basis. Associated with the proximal body, we define an orthonormal, right-handed, basis that is fixed to the proximal body. This basis is denoted by $\{\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3\}$. A similar basis, fixed to the distal body, is denoted by $\{\mathbf{d}_1, \mathbf{d}_2, \mathbf{d}_3\}$. While separate rotations can be used to define the rotation of the proximal and distal bases vectors relative to the laboratory fixed basis, the rotation of interest here relates the proximal frame to the distal frame. This rotation is defined by a rotation tensor $\mathbf{R}$:

$$\mathbf{d}_i = \mathbf{R}\mathbf{p}_i, \quad (i = 1, 2, 3). \quad (3.1)$$

The tensor $\mathbf{R} = \sum_{i=1}^3 \mathbf{d}_i \otimes \mathbf{p}_i$ has several equivalent representations:

$$\mathbf{R} = \sum_{i=1}^3 \sum_{k=1}^3 R_{ik} \mathbf{p}_i \otimes \mathbf{p}_k = \sum_{i=1}^3 \sum_{k=1}^3 R_{ik} \mathbf{d}_i \otimes \mathbf{d}_k, \quad (3.2)$$

where $\otimes$ is the tensor product: $(\mathbf{a} \otimes \mathbf{b})\mathbf{c} = (\mathbf{b} \cdot \mathbf{c})\mathbf{a}$ for any vectors $\mathbf{a}$, $\mathbf{b}$ and $\mathbf{c}$. Given a vector $\mathbf{a}$ we can establish the following relationships between its compo-

nents in bases related by a rotation tensor $\mathbf{R}$:

$$\begin{bmatrix} \mathbf{a} \cdot \mathbf{p}_1 \\ \mathbf{a} \cdot \mathbf{p}_2 \\ \mathbf{a} \cdot \mathbf{p}_3 \end{bmatrix} = \mathbf{R} \begin{bmatrix} \mathbf{a} \cdot \mathbf{d}_1 \\ \mathbf{a} \cdot \mathbf{d}_2 \\ \mathbf{a} \cdot \mathbf{d}_3 \end{bmatrix}, \text{ where } \mathbf{R} = \begin{bmatrix} R_{11} & R_{12} & R_{13} \\ R_{21} & R_{22} & R_{23} \\ R_{31} & R_{32} & R_{33} \end{bmatrix}. \quad (3.3)$$

The inverse of the matrix $\mathbf{R}$ is its transpose: $\mathbf{R}^{-1} = \mathbf{R}^T$.

3.3 Euler Angle Parameterization of a Rotation

Among the 12 possible sets of Euler angle sequences of particular interest in the present work is the 1-2-3 set. For this set of Euler angles, the components of the rotation matrix $\mathbf{R}$ can be defined as the product of three simple rotations:

$$\begin{aligned} \mathbf{R}^T &= \begin{bmatrix} R_{11} & R_{21} & R_{31} \\ R_{12} & R_{22} & R_{32} \\ R_{13} & R_{23} & R_{33} \end{bmatrix} \\ &= \begin{bmatrix} \cos(\gamma) & \sin(\gamma) & 0 \\ -\sin(\gamma) & \cos(\gamma) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos(\beta) & 0 & -\sin(\beta) \\ 0 & 1 & 0 \\ \sin(\beta) & 0 & \cos(\beta) \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\alpha) & \sin(\alpha) \\ 0 & -\sin(\alpha) & \cos(\alpha) \end{bmatrix}. \end{aligned} \quad (3.4)$$

That is the Euler angle sequence is a rotation of α about $\mathbf{p}_1$ followed by a rotation about a vector $\mathbf{d}_2'$ through an angle β and a rotation of γ about $\mathbf{d}_3$, Figure 3.1. The three vectors we have just mentioned form the Euler basis:

$$\begin{aligned} \mathbf{g}_1 &= \mathbf{p}_1, \\ \mathbf{g}_2 &= \mathbf{d}_2' = \cos(\alpha)\mathbf{p}_2 + \sin(\alpha)\mathbf{p}_3, \\ \mathbf{g}_3 &= \mathbf{d}_3 = \cos(\beta)\mathbf{d}_3' + \sin(\beta)\mathbf{d}_1' \\ &= \sin(\beta)\mathbf{p}_1 - \sin(\alpha)\cos(\beta)\mathbf{p}_2 + \cos(\alpha)\cos(\beta)\mathbf{p}_3. \end{aligned} \quad (3.5)$$

Because $\mathbf{g}_1 \cdot \mathbf{g}_3 = \sin(\beta)$, the Euler basis is typically not orthogonal.

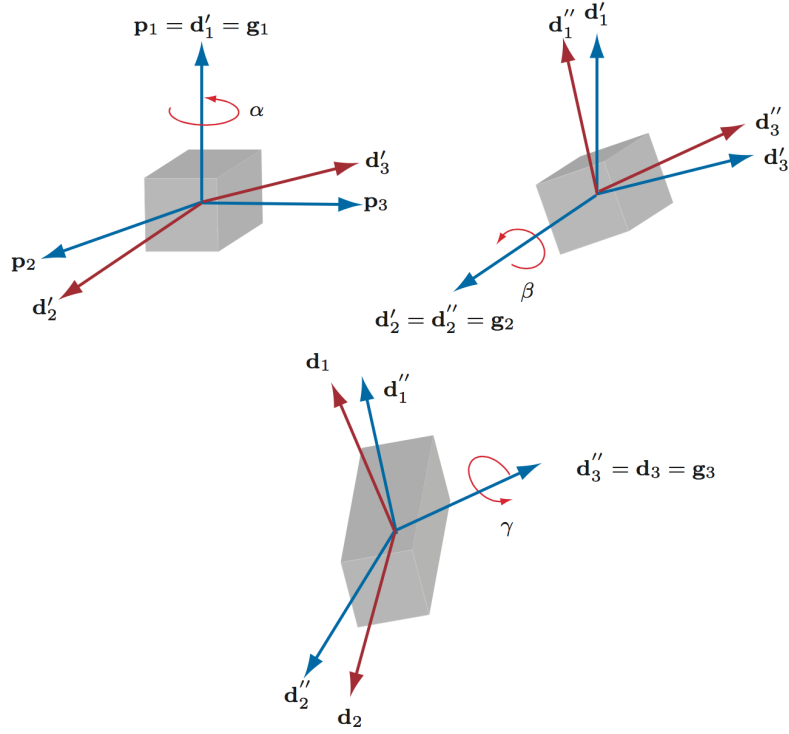


Figure 3.1: The 1-2-3 Euler angle rotation sequence for the rotation tensor $\mathbf{R} = \sum_{k=1}^3 \mathbf{d}_k \otimes \mathbf{p}_k$. Here, $\mathbf{d}'_i$ and $\mathbf{d}''_i$ are the intermediate basis vectors following the respective rotation by α about $\mathbf{p}_1$ and β about $\mathbf{d}'_2$. The third rotation γ completes the transformation from $\mathbf{p}_k$ to $\mathbf{d}_k$.

We can express the Euler basis in terms of the proximal or distal bases vectors:

$$\begin{aligned}
 \begin{bmatrix} \mathbf{g}_1 \\ \mathbf{g}_2 \\ \mathbf{g}_3 \end{bmatrix} &= \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\alpha) & \sin(\alpha) \\ \sin(\beta) & -\sin(\alpha)\cos(\beta) & \cos(\alpha)\cos(\beta) \end{bmatrix} \begin{bmatrix} \mathbf{p}_1 \\ \mathbf{p}_2 \\ \mathbf{p}_3 \end{bmatrix} \\
 &= \begin{bmatrix} \cos(\beta)\cos(\gamma) & -\cos(\beta)\sin(\gamma) & \sin(\beta) \\ \sin(\gamma) & \cos(\gamma) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \mathbf{d}_1 \\ \mathbf{d}_2 \\ \mathbf{d}_3 \end{bmatrix}. \quad (3.6)
 \end{aligned}$$

These transformations are useful when relating components of a vector that is expressed in different bases.

The dual Euler basis vectors are defined using the Euler basis vectors by the following nine equations:

$$\mathbf{g}^i \cdot \mathbf{g}_k = \delta_k^i, \quad (i = 1, 2, 3), \quad (k = 1, 2, 3). \quad (3.7)$$

Here δ_k^i is the Kronecker delta: $\delta_k^i = 1$ if $i = k$ and is otherwise zero. For example, $\delta_2^2 = 1$ and $\delta_1^3 = 0$. Solving the equations $\mathbf{g}^i \cdot \mathbf{g}_k = \delta_k^i$ for $\mathbf{g}^i$, we find that

$$\mathbf{g}^1 = \frac{1}{g} (\mathbf{g}_2 \times \mathbf{g}_3), \quad \mathbf{g}^2 = \frac{1}{g} (\mathbf{g}_3 \times \mathbf{g}_1), \quad \mathbf{g}^3 = \frac{1}{g} (\mathbf{g}_1 \times \mathbf{g}_2), \quad (3.8)$$

where

$$g = (\mathbf{g}_1 \times \mathbf{g}_2) \cdot \mathbf{g}_3. \quad (3.9)$$

Expressing these results in terms of the proximal and distal bases for the 1-2-3 set of Euler angles, we find that $g = \cos(\beta)$ and

$$\begin{aligned} \begin{bmatrix} \mathbf{g}^1 \\ \mathbf{g}^2 \\ \mathbf{g}^3 \end{bmatrix} &= \begin{bmatrix} 1 & \sin(\alpha) \tan(\beta) & -\cos(\alpha) \tan(\beta) \\ 0 & \cos(\alpha) & \sin(\alpha) \\ 0 & -\sin(\alpha) \sec(\beta) & \cos(\alpha) \sec(\beta) \end{bmatrix} \begin{bmatrix} \mathbf{p}_1 \\ \mathbf{p}_2 \\ \mathbf{p}_3 \end{bmatrix} \\ &= \begin{bmatrix} \sec(\beta) \cos(\gamma) & -\sec(\beta) \sin(\gamma) & 0 \\ \sin(\gamma) & \cos(\gamma) & 0 \\ -\tan(\beta) \cos(\gamma) & \tan(\beta) \sin(\gamma) & 1 \end{bmatrix} \begin{bmatrix} \mathbf{d}_1 \\ \mathbf{d}_2 \\ \mathbf{d}_3 \end{bmatrix}. \end{aligned} \quad (3.10)$$

With some additional work, we find that

$$\begin{aligned} \begin{bmatrix} \mathbf{g}_1 \\ \mathbf{g}_2 \\ \mathbf{g}_3 \end{bmatrix} &= \begin{bmatrix} 1 & 0 & \sin(\beta) \\ 0 & 1 & 0 \\ \sin(\beta) & 0 & 1 \end{bmatrix} \begin{bmatrix} \mathbf{g}^1 \\ \mathbf{g}^2 \\ \mathbf{g}^3 \end{bmatrix}, \\ \begin{bmatrix} \mathbf{g}^1 \\ \mathbf{g}^2 \\ \mathbf{g}^3 \end{bmatrix} &= \begin{bmatrix} \sec^2(\beta) & 0 & -\sec(\beta) \tan(\beta) \\ 0 & 1 & 0 \\ -\sec(\beta) \tan(\beta) & 0 & \sec^2(\beta) \end{bmatrix} \begin{bmatrix} \mathbf{g}_1 \\ \mathbf{g}_2 \\ \mathbf{g}_3 \end{bmatrix}. \end{aligned} \quad (3.11)$$

A graphical summary of these results can be found in Figure 3.2.

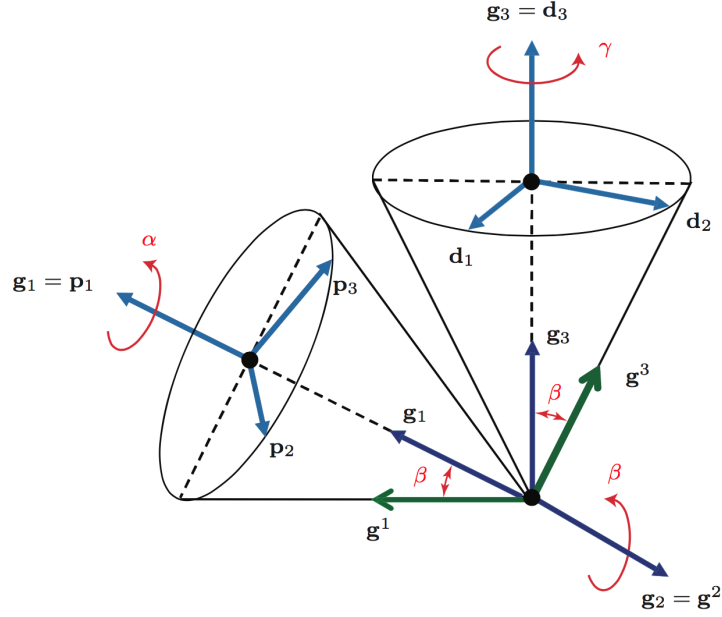


Figure 3.2: Graphical representation of the Euler $\{\mathbf{g}_1, \mathbf{g}_2, \mathbf{g}_3\}$ and dual Euler $\{\mathbf{g}^1, \mathbf{g}^2, \mathbf{g}^3\}$ basis vectors and their relationships with the proximal $\{\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3\}$ and distal $\{\mathbf{d}_1, \mathbf{d}_2, \mathbf{d}_3\}$ basis vectors, where α - β - γ are a set of 1-2-3 Euler angles. Explicit expressions for these vectors can be found in Equation (3.6). In this figure $\beta > 0$.

3.4 The Joint Coordinate System

In a joint coordinate system, two of the Euler basis vectors are identified with axes through bony landmarks on the proximal and distal bodies. For the knee joint shown in Figure 3.3, Grood and Suntay [45] identify $\mathbf{g}_1 = \mathbf{p}_1$ by stating the following: “In the femur, the body fixed axis is chosen so that rotations about it correspond to the clinical motion of flexion-extension.” For the axis $\mathbf{g}_3 = \mathbf{d}_3$ that represents the internal-external rotation axis, they note that this axis “is located so it passes midway between the two intercondylar eminences proximally and through the center of the ankle distally.” The floating axis $\mathbf{g}_2$, that represents the adduction-abduction axis, is mutually perpendicular to $\mathbf{g}_3$ and $\mathbf{g}_1$. We note that

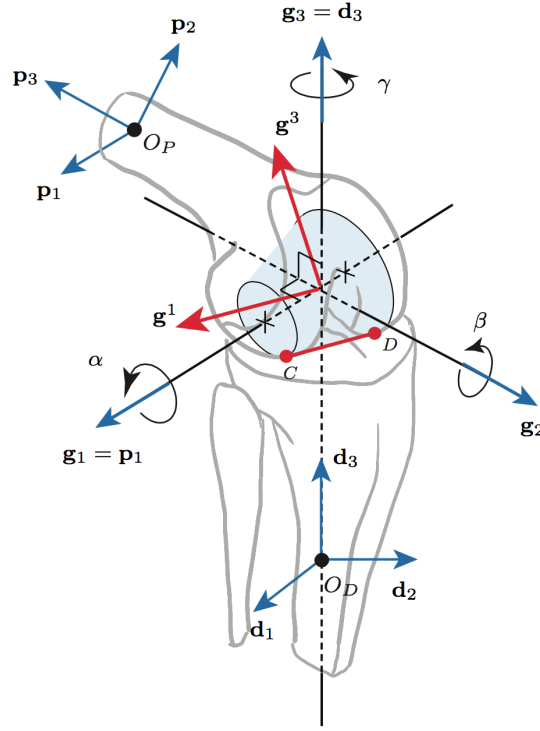


Figure 3.3: *Schematic of the right knee joint showing the proximal $\{\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3\}$ and distal $\{\mathbf{d}_1, \mathbf{d}_2, \mathbf{d}_3\}$ bases which corotate with the femur and tibia, respectively. The Euler $\{\mathbf{g}_1, \mathbf{g}_2, \mathbf{g}_3\}$ and dual Euler $\{\mathbf{g}^1, \mathbf{g}^2, \mathbf{g}^3\}$ basis vectors associated with the rotation of this joint when it is parameterized using a set of 1-2-3 Euler angles ($1 = \alpha, 2 = \beta, 3 = \gamma$ as in Grood and Suntay (1983) [45]) and the condyles C and D are also shown. This figure is adapted from O'Reilly (2013) [97].*

Grood and Suntay's discussion refers to bony landmarks identified with bi-planar X-rays to establish segment coordinate systems [45]. How to initially define these segment coordinate systems (e.g., $\mathbf{p}_k, \mathbf{d}_k$) within a motion capture laboratory remains an interesting question in biomechanics research. The specification of segment coordinate systems is not uniform in the literature and the exploration of various representations is outside the scope of this work. For the example data presented in Chapter 4, our choice of bases is outlined in Chapter 2.2.1.

3.5 Components of a Vector

Given a vector $\mathbf{A}$, we can express the vector in a variety of representations:

$$\begin{aligned}
 \mathbf{A} &= A_1 \mathbf{p}_1 + A_2 \mathbf{p}_2 + A_3 \mathbf{p}_3 \\
 &= a_1 \mathbf{d}_1 + a_2 \mathbf{d}_2 + a_3 \mathbf{d}_3 \\
 &= A_E^1 \mathbf{g}_1 + A_E^2 \mathbf{g}_2 + A_E^3 \mathbf{g}_3 \\
 &= A_{E1} \mathbf{g}^1 + A_{E2} \mathbf{g}^2 + A_{E3} \mathbf{g}^3.
 \end{aligned} \tag{3.12}$$

With the help of Equations (3.3), (3.4), (3.10), and (3.11), we can arrive at the relationship between the components in these representations:

$$\begin{aligned}
 \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix} &= \begin{bmatrix} R_{11} & R_{21} & R_{31} \\ R_{12} & R_{22} & R_{32} \\ R_{13} & R_{23} & R_{33} \end{bmatrix} \begin{bmatrix} A_1 \\ A_2 \\ A_3 \end{bmatrix} \\
 &= \begin{bmatrix} \cos(\beta) \cos(\gamma) & \sin(\gamma) & 0 \\ -\cos(\beta) \sin(\gamma) & \cos(\gamma) & 0 \\ \sin(\beta) & 0 & 1 \end{bmatrix} \begin{bmatrix} A_E^1 \\ A_E^2 \\ A_E^3 \end{bmatrix} \\
 &= \begin{bmatrix} \sec(\beta) \cos(\gamma) & \sin(\gamma) & -\tan(\beta) \cos(\gamma) \\ -\sec(\beta) \sin(\gamma) & \cos(\gamma) & \tan(\beta) \sin(\gamma) \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} A_{E1} \\ A_{E2} \\ A_{E3} \end{bmatrix}, \tag{3.13}
 \end{aligned}$$

and

$$\begin{aligned}
\begin{bmatrix} A_1 \\ A_2 \\ A_3 \end{bmatrix} &= \begin{bmatrix} R_{11} & R_{12} & R_{13} \\ R_{21} & R_{22} & R_{23} \\ R_{31} & R_{32} & R_{33} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix} \\
&= \begin{bmatrix} 1 & 0 & \sin(\beta) \\ 0 & \cos(\alpha) & -\sin(\alpha)\cos(\beta) \\ 0 & \sin(\alpha) & \cos(\alpha)\cos(\beta) \end{bmatrix} \begin{bmatrix} A_E^1 \\ A_E^2 \\ A_E^3 \end{bmatrix} \\
&= \begin{bmatrix} 1 & 0 & 0 \\ \sin(\alpha)\tan(\beta) & \cos(\alpha) & -\sin(\alpha)\sec(\beta) \\ -\cos(\alpha)\tan(\beta) & \sin(\alpha) & \cos(\alpha)\sec(\beta) \end{bmatrix} \begin{bmatrix} A_{E_1} \\ A_{E_2} \\ A_{E_3} \end{bmatrix}. \quad (3.14)
\end{aligned}$$

Of particular interest is to determine the components A_{E_k} given the components in the distal and proximal bases. These relations can be obtained from Equations (3.13) and (3.14) by standard matrix manipulations:

$$\begin{aligned}
\begin{bmatrix} A_{E_1} \\ A_{E_2} \\ A_{E_3} \end{bmatrix} &= \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\alpha) & \sin(\alpha) \\ \sin(\beta) & -\sin(\alpha)\cos(\beta) & \cos(\alpha)\cos(\beta) \end{bmatrix} \begin{bmatrix} A_1 \\ A_2 \\ A_3 \end{bmatrix} \\
&= \begin{bmatrix} \cos(\beta)\cos(\gamma) & -\cos(\beta)\sin(\gamma) & \sin(\beta) \\ \sin(\gamma) & \cos(\gamma) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix}. \quad (3.15)
\end{aligned}$$

We also note that the components $\mathbf{A} \cdot \mathbf{g}_k$ and $\mathbf{A} \cdot \mathbf{g}^i$ are related by a transformation that is not invertible when the Euler angles are singular (that is, when $\beta = \pm \frac{\pi}{2}$):

$$\begin{aligned}
\begin{bmatrix} A_E^1 \\ A_E^2 \\ A_E^3 \end{bmatrix} &= \begin{bmatrix} \sec^2(\beta) & 0 & -\sec(\beta)\tan(\beta) \\ 0 & 1 & 0 \\ -\sec(\beta)\tan(\beta) & 0 & \sec^2(\beta) \end{bmatrix} \begin{bmatrix} A_{E_1} \\ A_{E_2} \\ A_{E_3} \end{bmatrix}, \\
\begin{bmatrix} A_{E_1} \\ A_{E_2} \\ A_{E_3} \end{bmatrix} &= \begin{bmatrix} 1 & 0 & \sin(\beta) \\ 0 & 1 & 0 \\ \sin(\beta) & 0 & 1 \end{bmatrix} \begin{bmatrix} A_E^1 \\ A_E^2 \\ A_E^3 \end{bmatrix}. \quad (3.16)
\end{aligned}$$

The transformation Equations (3.13), (3.14), (3.15), and (3.16) are the principal results in this Chapter.

CHAPTER 4

Verifying the Equivalence of Representations of Joint Moment Vectors with Application to Biomechanical Motion Capture Data from a Drop Vertical Jump Task

Biomechanics software programs, such as Visual3D, Nexus, Cortex, and OpenSim, have the capability of generating several distinct component representations for joint moments and forces from motion capture data. These representations include those for orthonormal proximal and distal coordinate systems and a non-orthogonal joint coordinate system. In this chapter, a method is presented to address the challenging problem of evaluating and verifying the equivalence of these representations. The method accommodates the difficulty that there are two possible sets of non-orthogonal basis vectors that can be used to express a vector in the joint coordinate system and is illuminated using motion capture data from a drop vertical jump task.

4.1 Introduction

The drop vertical jump task, Figure 4.1(a), has been championed by Hewett and Myer [50] as a method to assess susceptibility to anterior cruciate ligament (ACL) injury. They have identified knee abduction moment (KAM) during the stance phase, Stages II-IV, of this maneuver as a key predictor in ACL injury risk. The

KAM, which is a specific component of the knee joint moment vector $\mathbf{M}$, is featured in numerous other studies, including gait analysis research on degenerative knee joint diseases such as osteoarthritis. The moment $\mathbf{M}$ is not measured directly, rather estimates of certain components of $\mathbf{M}$ can be computed using kinematic and force plate data with the help of software packages such as Visual3D, Nexus, Cortex, and OpenSim.

Motivated by the desire to seek clinical relevant results, one can examine multiple representations for $\mathbf{M}$ and its components (see works, e.g., [103], [15], [125] and references therein). For instance, one can describe this vector using a basis fixed to the tibia, or a basis fixed to the femur, a laboratory fixed basis, or, dating to the seminal paper by Grood and Suntay [45] on the knee joint, it is also common to describe the components of $\mathbf{M}$ in terms of a joint coordinate system. If a set of Euler angles is used to describe the relative rotation provided by the joint, then each of the three joint coordinate axes can be placed in one-to-one correspondence with the axes used to define the Euler angles. This set of axes forms a set of non-orthogonal unit vectors $\{\mathbf{g}_1, \mathbf{g}_2, \mathbf{g}_3\}$ which is known as the Euler basis. In addition, associated with every set of Euler angles, a dual Euler basis $\{\mathbf{g}^1, \mathbf{g}^2, \mathbf{g}^3\}$ is also defined. Thus multiple sets of distinct basis vectors can be associated with a given joint including the orthonormal basis $\{\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3\}$ that corotates with the proximal body, the orthonormal basis $\{\mathbf{d}_1, \mathbf{d}_2, \mathbf{d}_3\}$ that corotates with the distal body, the Euler basis, and the dual Euler basis. By way of illustration, a representative example of the progression of the joint rotation (Euler) angles α (flexion-extension), β (adduction-abduction), and γ (internal-external rotation) through Stages II-IV of the jump maneuver is shown in Figure 4.1(b) and, following O'Reilly (2013) [97], the four aforementioned sets of basis vectors axes are sketched in Figure 4.1(c).

Software packages enable the output of multiple sets of components for $\mathbf{M}$. What is not apparent is how to check if the different sets of components are equiv-

alent. This situation is particularly the case when the user has limited access to the algorithms producing the representations. An additional complication, that has only been recently appreciated, arises because the joint coordinate system purports, not one, but two sets of non-orthogonal basis vectors: the Euler $\{\mathbf{g}_1, \mathbf{g}_2, \mathbf{g}_3\}$ and dual Euler $\{\mathbf{g}^1, \mathbf{g}^2, \mathbf{g}^3\}$ bases vectors. In this chapter, we present a straightforward method to check the equivalence of the various component representations and use experimental data from a drop vertical jump task as a demonstration. We also note that the results shown in this chapter are the first to explicitly demonstrate that knowledge of the dual Euler basis $\{\mathbf{g}^1, \mathbf{g}^2, \mathbf{g}^3\}$ is needed to reconstruct $\mathbf{M}$ from its joint coordinate system components provided by popular biomechanics software packages.

To make this work as widely accessible as possible, a detailed discussion of the transformations between the various set of basis vectors and components can be found in Chapter 3. We also note that the work by Grood and Suntay [45] prompted a series of related investigations and standardizations for other anatomical joints (see [4] and [124]). Consequently, many of the methods discussed in this chapter can be used with other anatomical joints such as the ankle, shoulder, and elbow joints.

4.2 Methods

4.2.1 Acquisition of Sets of Kinematic and Force Data

Movement data was used of an adult male participant, from a larger motion analysis study to monitor return-to-play criteria after ACL injury. The study was approved by University of California, San Francisco, Committee on Human Research (IRB 12-10253). Forty-eight retro-reflective spherical markers, 14 mm in diameter, were positioned on the participant on key bony landmarks and laterally on limb segments in rigid clusters of 4 markers. Three-dimensional kinematic

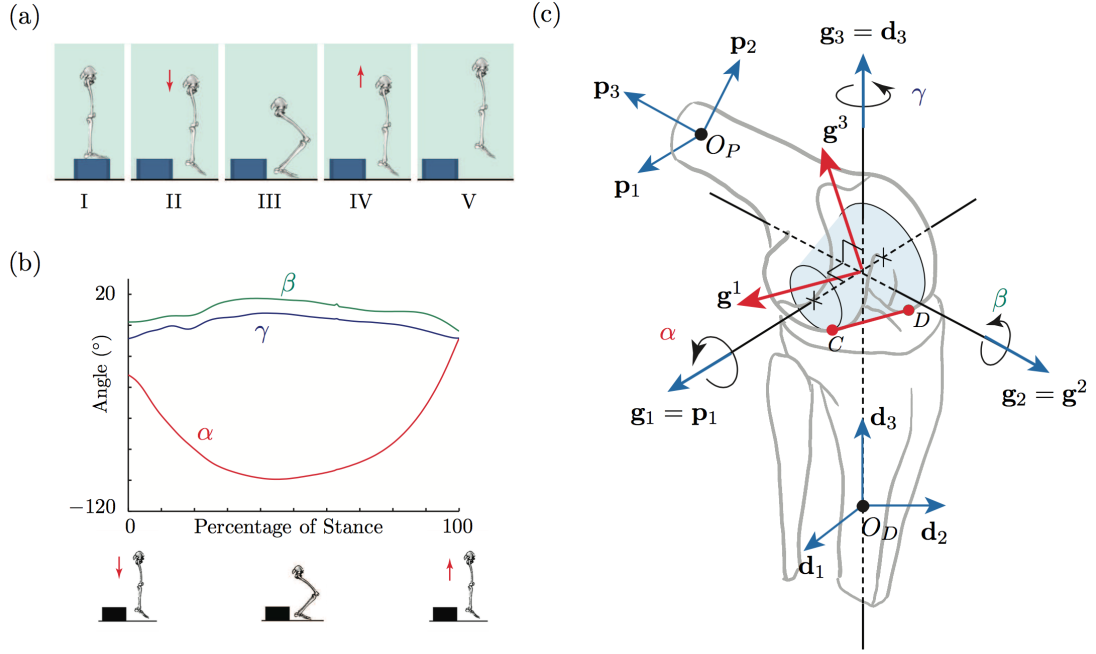


Figure 4.1: (a) Schematic of the five stages of the drop vertical jump task. (b) Variation in the right knee joint angles during a drop vertical jump task. The stance phase starts at initial contact, Stage II, and ends at take-off, Stage IV. (c) Schematic of the right knee joint showing the proximal $\{p_1, p_2, p_3\}$ and distal $\{d_1, d_2, d_3\}$ bases which corotate with the femur and tibia, respectively. The Euler $\{g_1, g_2, g_3\}$ and dual Euler $\{g^1, g^2, g^3\}$ basis vectors associated with the rotation of this joint when it is parameterized using a set of 1-2-3 Euler angles ($1 = \alpha$, $2 = \beta$, $3 = \gamma$ as in Grood and Suntay [45]) and the condyles C and D are also shown. The skeleton images were composed using OpenSim [31].

data were collected at 250 Hz by a 10-camera system (Vicon, Oxford Metrics, UK). Kinetic data were collected at 1000 Hz by two embedded force platforms (AMTI, Watertown, MA USA).

In order to define the reference posture, a static trial was first conducted. Next, data were collected from a participant performing a drop vertical jump as described by Hewett and Myer [50], sketched in Figure 4.1(a). The participant

initially stands upright at rest on a box. They are instructed to drop off the box onto a horizontal surface and immediately perform a maximum vertical jump, as if they were executing a basketball rebound. The stance/impact phase was defined as the participant's initial contact with the force platform following the drop, to the take-off for the maximum vertical jump. Kinematics for six-degree-of-freedom models of the thigh, shank, and foot along with force data from one of the force platforms were imported into Visual3D (C-Motion, Germantown, MD, USA). Marker position data was filtered using a 4th-order low-pass Butterworth filter with a cutoff frequency of 15 Hz. For this analysis, variables, including right knee joint angles and internal knee moment, calculated using the standard inverse dynamics in Visual3D, with components in the proximal, distal, and joint coordinate system (see Equations (4.4)_{1,2,4} below), were exported from Visual3D to MATLAB (MathWorks, Natick, MA, USA). The moment in question is an estimate of the moment $\mathbf{M}$ at the proximal end of the shank [101, pp. 161–164]. MATLAB, in conjunction with the methods discussed below, was used to check the equivalence of representations of the moment in different coordinate systems.

4.2.2 Definition of the Segment Coordinate Systems

Segment coordinate systems for the thigh and shank are shown in Figure 4.1(c) and we take this opportunity to clearly define the associated axes. Segment frontal planes and joint centers are defined using a model within the motion analysis software in conjunction with marker data.

First, for the thigh, the superior-inferior axis, $\mathbf{p}_3$, is defined as passing between the hip and knee centers on the femoral frontal plane, and points towards the superior direction. The anterior-posterior axis, $\mathbf{p}_2$, is chosen to be normal to the femoral frontal plane and points towards the anterior direction. The medial-lateral axis, $\mathbf{p}_1$, is mutually perpendicular to $\mathbf{p}_2$ and $\mathbf{p}_3$, and is positive in (i.e., points towards) the lateral direction for the right side.

The corotational basis for the shank is specified by first defining the superior-inferior axis, $\mathbf{d}_3$, to pass between the knee and ankle centers on the tibial frontal plane and is positive in the superior direction. The anterior-posterior axis, $\mathbf{d}_2$, is normal to the tibial frontal plane and is positive in the anterior direction. Paralleling the specification of $\mathbf{p}_1$, the medial-lateral axis, $\mathbf{d}_1$, is mutually perpendicular to $\mathbf{d}_2$ and $\mathbf{d}_3$ and is positive in the lateral direction for the right side.

The bases $\{\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3\}$ and $\{\mathbf{d}_1, \mathbf{d}_2, \mathbf{d}_3\}$ that have just been defined are right-handed. Thus, counterclockwise rotations are considered positive following the right-hand rule. Additional details on the specification of the distal and proximal bases sets can be found in Chapter 3.

4.2.3 Representations of Moments

We follow Grood and Suntay [45] and assume that a 1-2-3 set of Euler angles ($1 = \alpha$, $2 = \beta$, $3 = \gamma$) is being used to parameterize the rotation of the knee joint. As mentioned previously, α denotes the flexion-extension angle, β denotes the adduction-abduction angle, and γ denote the internal-external rotation. In addition, we have the following Euler and dual Euler basis sets, respectively:¹

$$\mathbf{g}_1 = \mathbf{p}_1, \quad \mathbf{g}_2 = \frac{\mathbf{d}_3 \times \mathbf{p}_1}{\|\mathbf{d}_3 \times \mathbf{p}_1\|}, \quad \mathbf{g}_3 = \mathbf{d}_3, \quad (4.1)$$

and

$$\begin{aligned} \mathbf{g}^1 &= \sec^2(\beta) \mathbf{g}_1 - \sec(\beta) \tan(\beta) \mathbf{g}_3, \\ \mathbf{g}^2 &= \mathbf{g}_2, \\ \mathbf{g}^3 &= -\sec(\beta) \tan(\beta) \mathbf{g}_1 + \sec^2(\beta) \mathbf{g}_3. \end{aligned} \quad (4.2)$$

It should be noted that $\mathbf{g}^1$ and $\mathbf{g}^3$ have no apparent clinical interpretations unlike $\mathbf{g}_1$ and $\mathbf{g}_3$ which are chosen to align with the flexion-extension axis and internal-external rotation axis, respectively, Figure 4.1(c). Additional details on the Euler

¹We tacitly assume that $\beta \neq \pm \frac{\pi}{2}$.

and dual Euler basis and their application to biomechanics can be found in multiple works (see [32, 34, 94, 96] and [97]).

The moment vector $\mathbf{M}$ has a variety of representations:

$$\begin{aligned}
\mathbf{M} &= M_1 \mathbf{p}_1 + M_2 \mathbf{p}_2 + M_3 \mathbf{p}_3 && \text{Proximal basis} \\
&= m_1 \mathbf{d}_1 + m_2 \mathbf{d}_2 + m_3 \mathbf{d}_3 && \text{Distal basis} \\
&= M_E^1 \mathbf{g}_1 + M_E^2 \mathbf{g}_2 + M_E^3 \mathbf{g}_3 && \text{Euler basis} \\
&= M_{E_1} \mathbf{g}^1 + M_{E_2} \mathbf{g}^2 + M_{E_3} \mathbf{g}^3. && \text{Dual Euler basis} \quad (4.3)
\end{aligned}$$

Explicit relationships between the four sets of basis vectors appearing in these representations can be found in Chapter 3. The interested reader is also referred to O'Reilly (2013) [97, Figure 1(c)] for a graphical representation of Equations (4.3)_{3,4}. The four sets of components in Equations (4.3) are determined by projecting $\mathbf{M}$ onto a specific basis vector:

$$M_k = \mathbf{M} \cdot \mathbf{p}_k, \quad m_k = \mathbf{M} \cdot \mathbf{d}_k, \quad M_E^k = \mathbf{M} \cdot \mathbf{g}^k, \quad M_{E_k} = \mathbf{M} \cdot \mathbf{g}_k, \quad (k = 1, 2, 3). \quad (4.4)$$

As we shall see below, the moment components in a joint coordinate system are typically reported in the literature are M_{E_1} , M_{E_2} and M_{E_3} . That is,

$$\begin{aligned}
M_{E_1} &= \mathbf{M} \cdot \mathbf{g}_1 = \mathbf{M} \cdot \mathbf{p}_1 = M_1, \\
M_{E_2} &= \mathbf{M} \cdot \mathbf{g}_2 = \mathbf{M} \cdot \left(\frac{\mathbf{d}_3 \times \mathbf{p}_1}{\|\mathbf{d}_3 \times \mathbf{p}_1\|} \right) = \mathbf{M} \cdot \mathbf{g}^2 = M_E^2, \\
M_{E_3} &= \mathbf{M} \cdot \mathbf{g}_3 = \mathbf{M} \cdot \mathbf{d}_3 = m_3.
\end{aligned} \quad (4.5)$$

However, in order to show that the resulting vector is equivalent to its counterpart expressed in the proximal and distal bases, we need to compute $M_{E_1} \mathbf{g}^1 + M_{E_2} \mathbf{g}^2 + M_{E_3} \mathbf{g}^3$. That is, knowledge of the Euler basis is sufficient to compute the components M_{E_k} of $\mathbf{M}$ in the joint coordinate system, but, in order to construct the moment vector from these components, the dual Euler basis is required.

It is straightforward to show that $\mathbf{M} \neq M_{E_1} \mathbf{g}_1 + M_{E_2} \mathbf{g}_2 + M_{E_3} \mathbf{g}_3$. Indeed,

using the identity, Equation (3.16), from the prior chapter, we find that

$$M_{E_1} = M_E^1 + \sin(\beta)M_E^3, \quad M_{E_3} = \sin(\beta)M_E^1 + M_E^3. \quad (4.6)$$

Thus, the difference in the components can be entirely attributed to the second Euler angle β . As mentioned in O'Reilly (2013) [97] for the knee joint this angle is small. For other joints, such as the shoulder, this is not the case but this angle still suffers from the “crosstalk” effect [34] which can lead to challenges in comparing representations of $\mathbf{M}$.

Concomitant with the representations for $\mathbf{M}$, related expressions for the magnitude $||\mathbf{M}||$ of $\mathbf{M}$ can be found by taking the inner (dot) product of this vector with itself and then taking the square root. After some rearranging, the resulting representations for $||\mathbf{M}||^2$ are

$$\begin{aligned} ||\mathbf{M}||^2 &= \mathbf{M} \cdot \mathbf{M} \\ &= M_1^2 + M_2^2 + M_3^2 \\ &= m_1^2 + m_2^2 + m_3^2 \\ &= (M_E^1)^2 + (M_E^2)^2 + (M_E^3)^2 + \underbrace{2(M_E^1 M_E^3) \sin(\beta)} \\ &= (M_{E_1})^2 + (M_{E_2})^2 + (M_{E_3})^2 \\ &\quad + \underbrace{((M_{E_1})^2 + (M_{E_3})^2) \tan^2(\beta) - 2(M_{E_1} M_{E_3}) \sec(\beta) \tan(\beta)}. \end{aligned} \quad (4.7)$$

The underbraced terms in these representations arise because of the non-orthogonality of the Euler and dual Euler basis vectors.

4.2.4 Signal Comparisons

In order to assess the equivalency of representations, software reported moment components M_k and m_k were used to provide estimates of M_{E_k} . The estimates for the components M_{E_k} obtained using M_k are denoted by B_{E_k} while the estimates for the components M_{E_k} obtained using m_k are denoted by b_{E_k} . The appropriate

transformations are obtained using Equation (3.15) in Chapter 3:

$$\begin{aligned} \begin{bmatrix} B_{E_1} \\ B_{E_2} \\ B_{E_3} \end{bmatrix} &= \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\alpha) & \sin(\alpha) \\ \sin(\beta) & -\sin(\alpha)\cos(\beta) & \cos(\alpha)\cos(\beta) \end{bmatrix} \begin{bmatrix} M_1 \\ M_2 \\ M_3 \end{bmatrix}, \\ \begin{bmatrix} b_{E_1} \\ b_{E_2} \\ b_{E_3} \end{bmatrix} &= \begin{bmatrix} \cos(\beta)\cos(\gamma) & -\cos(\beta)\sin(\gamma) & \sin(\beta) \\ \sin(\gamma) & \cos(\gamma) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} m_1 \\ m_2 \\ m_3 \end{bmatrix}. \end{aligned} \quad (4.8)$$

An *RMS* (evaluated at 1% of stance intervals) was calculated for each of the three components (B_{E_k} and b_{E_k}) and compared to M_{E_k} . In addition, the moment magnitude $\|\mathbf{M}\|$ was calculated using M_k and m_k using Equations (4.7)_{2,3} and compared to corresponding expression computed using the components M_{E_k} and Equation (4.7)₅. Finally, moment vectors, $\mathbf{M}$ constructed from Equations (4.3)_{1,2,4}, at 0% to 100% of stance in increments of 10% were all rotated into the proximal coordinate system and overlaid for qualitative comparison.

4.3 Results and Discussion

Knee joint angle components from one repetition of a drop vertical jump are presented in Figure 4.1(b) and used in with Equations (4.7, 4.8) to calculate the estimates $\|\mathbf{M}\|$, B_{E_k} , and b_{E_k} . Software produced moment components M_k , m_k and M_{E_k} for the drop vertical jump are shown in Figure 4.2(a,b,d). We find that the *RMS* differences between B_{E_k} and M_{E_k} are 0.0 Nm, 8.2×10^{-1} Nm, 3.1×10^{-5} Nm, and between b_{E_k} and M_{E_k} are 4.4×10^{-6} Nm, 8.2×10^{-1} Nm, 0.0 Nm, for the 1st, 2nd, and 3rd components, respectively. Moment magnitude from the software produced moment components M_k , m_k and M_{E_k} are displayed in Figure 4.3(a). The *RMS* difference between the $\|\mathbf{M}\|$ computed using M_k and M_{E_k} is 1.9×10^{-1} Nm, using m_k and M_{E_k} is 1.9×10^{-1} Nm, and using M_k and m_k is 4.4×10^{-6} Nm. Moment vectors, $\mathbf{M}$ constructed from the different bases, at increments of

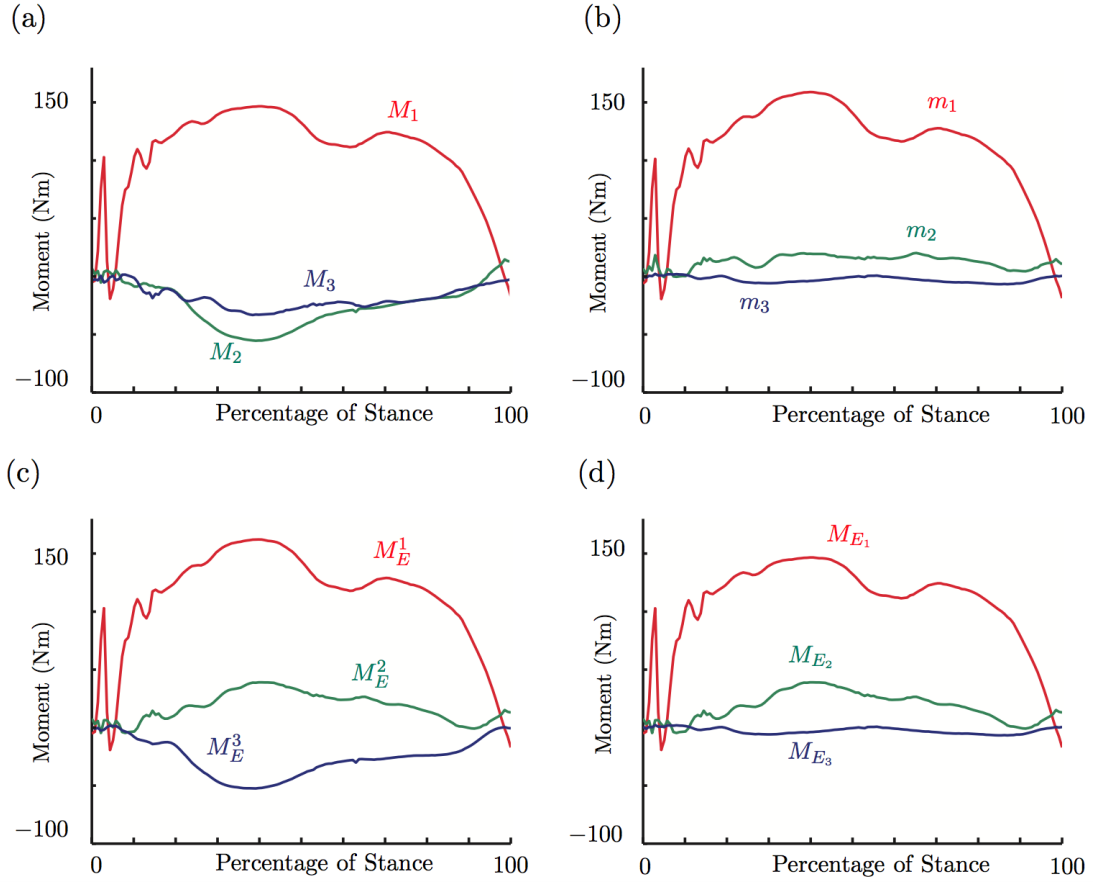


Figure 4.2: The moment vector $\mathbf{M}$ and four different representations of its components as a function of the percentage of the stance. (a) The components in the proximal basis $M_k = \mathbf{M} \cdot \mathbf{p}_k$, (b) the components in the distal basis $m_k = \mathbf{M} \cdot \mathbf{d}_k$, (c) the components $M_E^k = \mathbf{M} \cdot \mathbf{g}^k$ computed using (S.16)₁, and (d) the components in the joint coordinate system $M_{E_k} = \mathbf{M} \cdot \mathbf{g}_k$. As anticipated $M_{E_1} = M_1$ and $M_{E_3} = m_3$. The data shown in (a), (b), and (d) are imported directly from Visual3D.

10% were all rotated into the proximal coordinate system and overlaid in Figure 4.3(b). At each increment, the moment vectors visually align.

As mentioned earlier, KAM has been identified as a key indicator in ACL injury risk screening and knee osteoarthritis. This component of $\mathbf{M}$ is equivalent

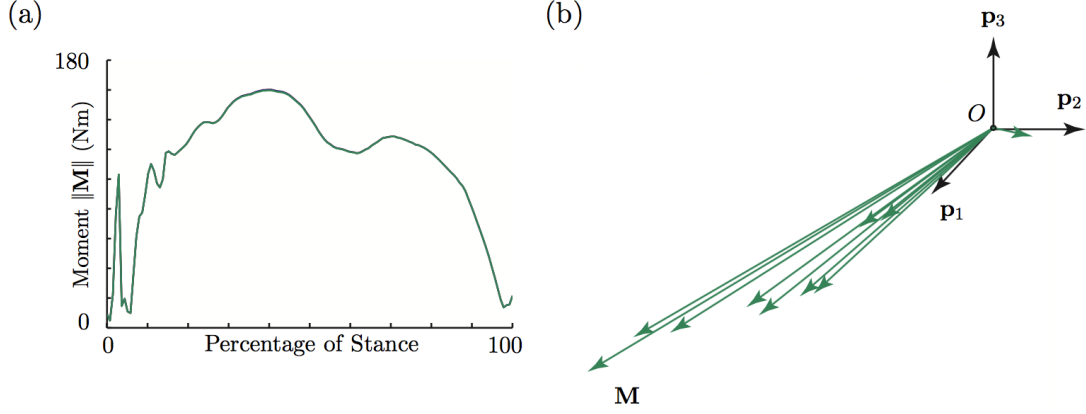


Figure 4.3: (a) Overlaid computations of the magnitude of the moment vector $\mathbf{M}$ using three representations from Equations (4.7)_{2,3,5} (i.e., the components in proximal, distal, and joint coordinate system representations). (b) The moment vectors $\mathbf{M}$, at each 10% of stance, obtained by reconstructing $\mathbf{M}$ from its components using Equations (4.3)_{1,2,4}, rotated into the proximal basis, and overlaid. The axes in this figure are not to scale.

in the Euler and dual Euler basis, $M_{E_2} = M_E^2$. It is difficult to conclude if M_{E_2} is correct from the exported signal data (Figure 4.2(a,b,d)). However, using rotated M_k and m_k signals allows us to compare moment vector components. The small *RMS* values for M_{E_2} confirm the similarity of the signals. Both exported signal data and *RMS* values demonstrate M_1 aligns with M_{E_1} and m_3 aligns with M_{E_3} , as expected since $\mathbf{p}_1 = \mathbf{g}_1$ and $\mathbf{d}_3 = \mathbf{g}_3$. Reconstructing these components in the proximal coordinate system in Figure 4.3(b) also aids in confirming the equivalence of these signals.

Further comparison of overall magnitude gives confidence that we have obtained complete signals. All magnitude comparisons yield small values of *RMS* difference. However in this example, erroneously omitting the underbraced terms in the determination of $\|\mathbf{M}\|$ (Equation (4.7)₅) increases the *RMS* error value by a factor of 22. This magnitude calculation is dependent on β due to the additional

terms introduced by the non-orthogonal dual Euler basis. In the case of the knee where β values are small, *RMS* error is also small. However, other joints such as the shoulder could see higher values of β thus making the understanding and inclusion of the dual Euler basis even more critical.

4.4 Conclusions

To properly verify signals from commercially available software and confidently report findings from experimental data, it is crucial to understand the relationships between the different coordinate systems used to present biomechanical data. In this chapter, a method has been presented to show how four distinct sets of moment components can be used to reconstruct the moment vector. Of the four distinct sets, we note that the commonly used moment components in a joint coordinate system (i.e., M_{E_k}) require the dual Euler basis both for the reconstruction of the moment vector, $\mathbf{M} = M_{E_1}\mathbf{g}^1 + M_{E_2}\mathbf{g}^2 + M_{E_3}\mathbf{g}^3$, and the accurate determination of its magnitude $||\mathbf{M}||$. The authors encourage the inclusion and use of the dual Euler basis in biomechanics education curriculum so that a more comprehensive understanding of the kinetic quantities described using the joint coordinate system can be achieved.

Part II

Low-Cost Motion Capture Systems

CHAPTER 5

Low-Cost Movement Assessment System - Kinect

5.1 System Function - Kinect

In the depth camera, beams of infrared light are cast across a scene, illuminating objects within the viewing volume, and a receiver picks up information about how far the light has traveled and builds a 3-dimensional (3D) depth map of objects within the volume, Figure 5.1. This technology is known as Structured-light 3D Scanning [36]. Raw data (2D infrared (IR) image, 3D depth map, and 3D estimated pose) streams from the depth camera continuously over the course of the maneuver at a frame rate up to 30Hz, Figure 5.2.

5.1.1 Measurement, Accuracy, and Resolution

Khoshelham and Elberink detailed the system function of the original Kinect camera and conducted an exploration into accuracy and resolution of the system [62]. The following is a summary of that information.

The original Kinect camera was released in November 2010. It is a triangulation sensor consisting of an IR laser emitter, an IR camera, and an RGB camera, Figure 5.3. A diffraction grating splits the IR beam into a speckle pattern, projected onto the volume of interest. The IR camera detects this pattern. The system compares this pattern to a reference pattern on a plane at a known dis-

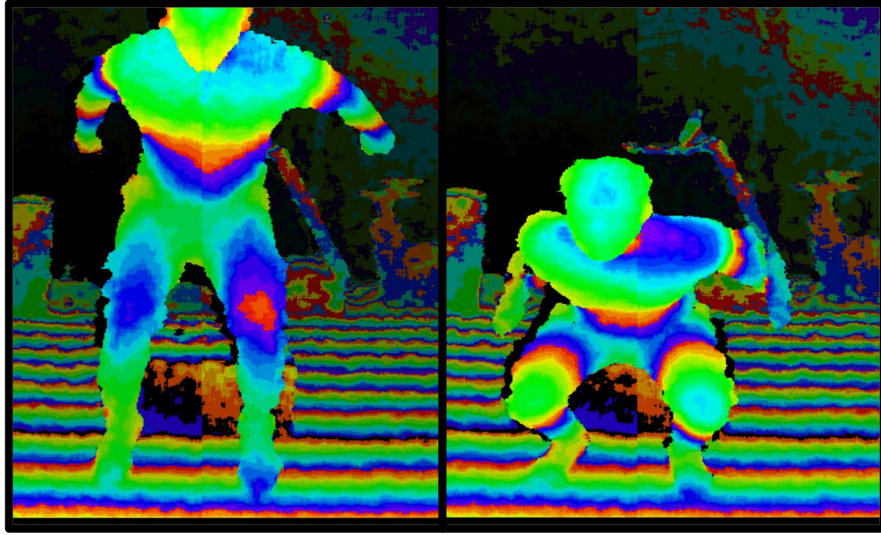


Figure 5.1: *DVJ depth maps at initial contact (left) and maximum position (right).
Note: Changes in color indicate changes in depth value.*

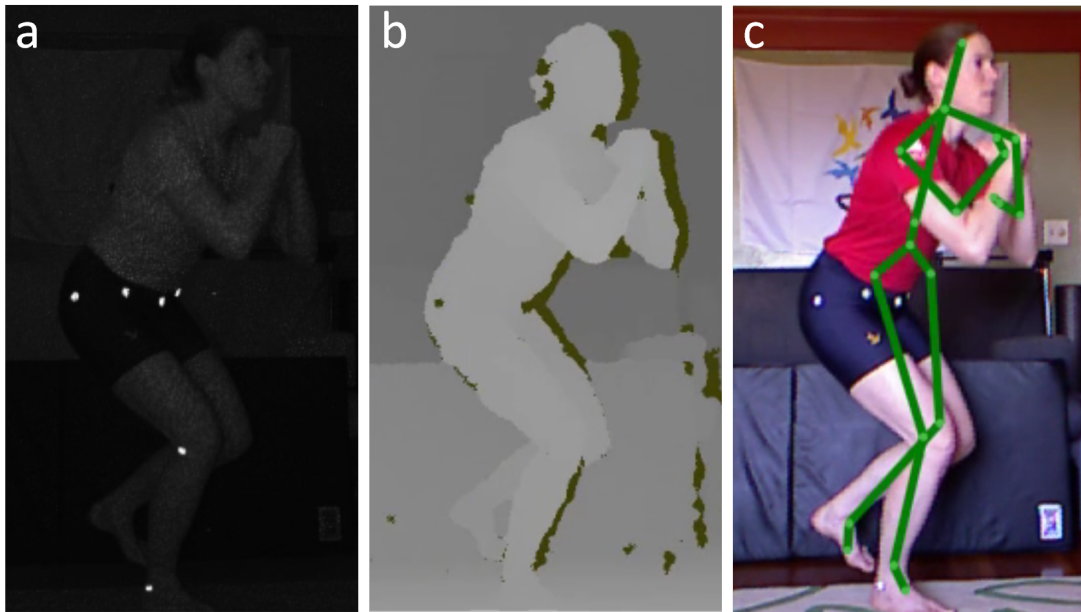


Figure 5.2: *Depth camera images: (a) 2D IR image; (b) 3D depth map image; (c) 3D estimated pose (from Microsoft SDK) overlaid on RGB image.*

tance. Using triangulation, the distance a speckle is offset or shifted from the reference indicates a change in depth measurement compared to the reference plane.

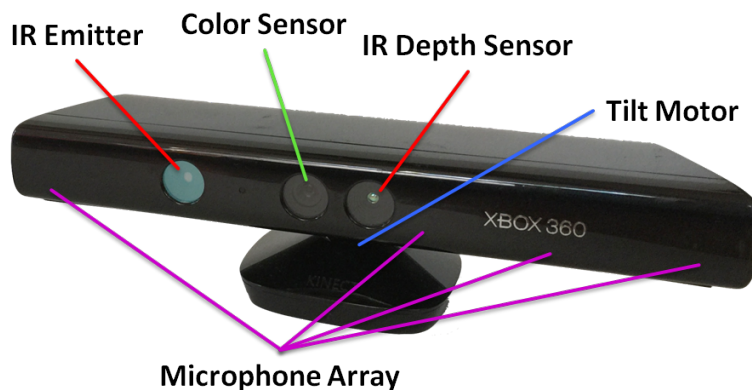


Figure 5.3: *Schematic of Microsoft Kinect depth camera, based on [79].*

The IR sensor can detect 1280×1024 pixels for each frame of data. However, due to bandwidth limitations the IR images are streamed at 640×480 pixels. This equates to 307,200 data points, with three (x, y, z) coordinates for spacial location, in each frame of data.

Lighting conditions, surface type and shape, occlusions, shadows, and distance can all impact the quality of the depth data, Figure 5.4. Strong lighting conditions (ambient light or over exposure due to reflections) can result in low contrast of the speckle pattern, relative to the background, resulting in outliers or gaps (erosions) of the depth (point cloud) data. Occlusions occur when the IR camera cannot detect an area of the scene (even though it may have been illuminated by the IR laser pattern). Shadows occur when an area is not illuminated by the IR laser but detected by the IR sensor. Both occlusions and shadows result in gaps in the point cloud data.

In the operating range of the sensor (0.5 - 5.0 m) the point density decreases with increasing distance from the sensor to the object and the random error of

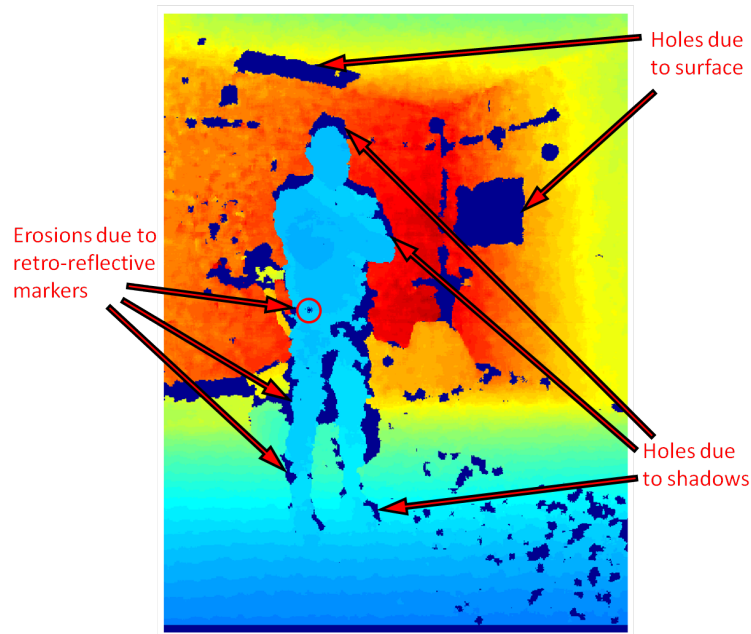


Figure 5.4: *Depth map image exemplifying erosion due to markers, shadows, and surfaces.*

depth measurement increases proportionally to the square distance from the sensor to the object. For depth resolution, at 1 m the point spacing is about 2 mm, at 3 m the point spacing is 2.5 cm, and at 5 m the point spacing is close to 7 cm. The random error in depth measurement is a few millimeters at 0.5 m from the sensor and reaches 4 cm at the maximum range of 5 m. It is important to understand the parameters around the quality of depth data when investigating potential uses for the Kinect camera.

In addition, there is an off center distortion in the IR image, with the largest distortion, appearing in the upper left hand corner. It was not investigated in this paper how consistent the distortion was between cameras and the necessity of individual calibration to compensate for this systematic error. The RGB camera has a more centered distortion and requires calibration to the depth data or colors could be incorrectly associated with surfaces.

The 3D estimated pose constructs a simple skeleton with estimated joint centers based on pattern recognition [107].

It is important to note that careful selection of clothing can help to reduce the potential of depth map erosion at the site of a retro-reflective marker, Figure 5.5. We also spent some time investigating treating the markers with a coating to reduce retro-reflectivity, Figure 5.6.

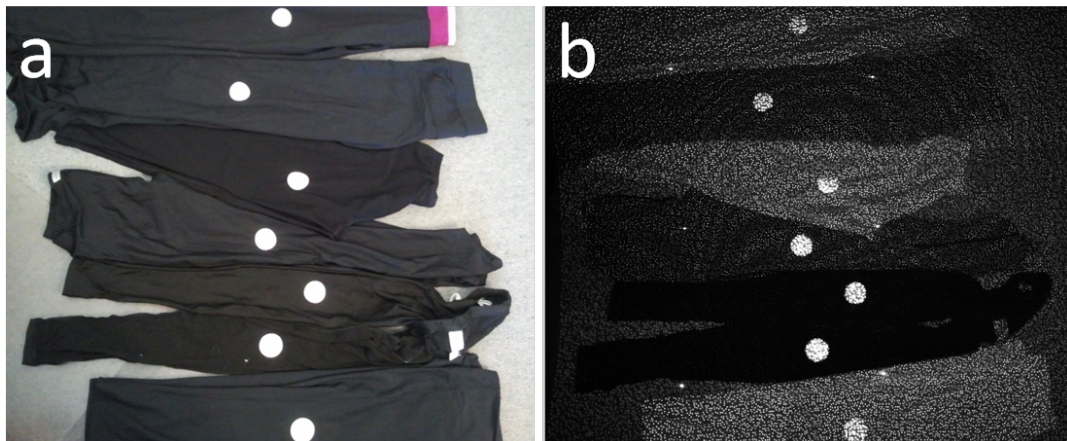


Figure 5.5: *Depth camera image comparison: (a) RGB image of different clothing; (b) 2D IR image of same scene illustrating contrast differences with different materials of the same dark color.*

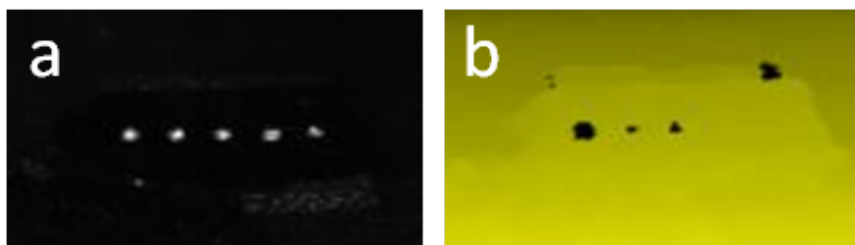


Figure 5.6: *Depth images of markers with layers of coating increasing from left to right, (a) 2D IR image; (b) 3D depth map image.*

5.2 System Development to Improve Accuracy

Our Low-Cost Movement Assessment System (LCMAS) extracts biomechanically relevant metrics from marker position data, and generates high-quality human kinematic profiles. Difficult to obtain outside a laboratory setting, these kinematic data are inherently valuable. They can be processed in order to extract application-specific metrics. These metrics are valuable for standardized quantitative functional outcomes desired for clinical comparative effectiveness trials, and for the generation of large databases of normative musculoskeletal function. Quantitative metrics also allow a participant's results to be tracked over time. These data have been previously shown to be valuable for knee injury risk prediction [81].

5.2.1 Initial Functionality

For each participant, specific anatomical reference points are located and retro-reflective markers are adhered to the surface of the skin above these points. The participant faces the depth camera and performs an assessment maneuver. The depth camera acquires raw data (2D infrared image, 3D depth map, and 3D estimated pose) and streams this data to a connected computer. We captured all of our depth data using the open source program OpenNI. We also captured time stamp information from the CPU.

All post-processing is completed in MATLAB (MathWorks, Natick, MA, USA). First, a select series of frames that encompass the maneuver is identified. In each frame, the 2D IR image data is processed by fine-tuning and applying filter parameters to enhance the contrast between markers and surroundings. The centroid of the 2D markers are located. The 2D marker locations are overlaid onto the 3D point cloud data and the 3D coordinates are extracted from the points in the surrounding neighborhood, Figure 5.7. This process is repeated for all selected

frames. In the original iteration of the system, markers were labeled in one frame and propagated through the other frames using a simple algorithm.

5.2.2 Implemented Improvements

Additions to initial functionality created our LCMAS system (LCMAS-Single, Figure 5.8) and include: establishing an independent laboratory coordinate system, reducing processing time and improving accuracy of marker position by cropping point cloud data to remove background objects and ground plane, increasing marker detection by added hole filling in the point cloud data where depth map had been eroded at marker location, stabilizing marker tracking with a user interface, and the creation of marker location processing which enabled the extraction of kinematic and kinetic metrics. A schematic of the initial processing and improvements are shown in Figure 5.9.

5.2.2.1 Independent Laboratory Coordinate System and Point Cloud Cropping

With the 307,200 data points per frame, any data processing can be significantly impeded by dealing with extraneous points. Performing a simple crop beyond the depth of interest removes many unnecessary points. However many points still remain in the ground plane and background objects and they can contribute to inaccuracies in marker detection if they are in the neighborhood of the 2D IR centroid overlay.

In order to identify and crop ground plane and background points, an independent laboratory reference coordinate system was established. The initial coordinate system, basis $\{\mathbf{C}_1, \mathbf{C}_2, \mathbf{C}_3\}$, assigned to the point cloud data is based on the camera orientation and is not necessarily aligned with the ground plane or background plane. Simply cropping data from a given dimension of point cloud

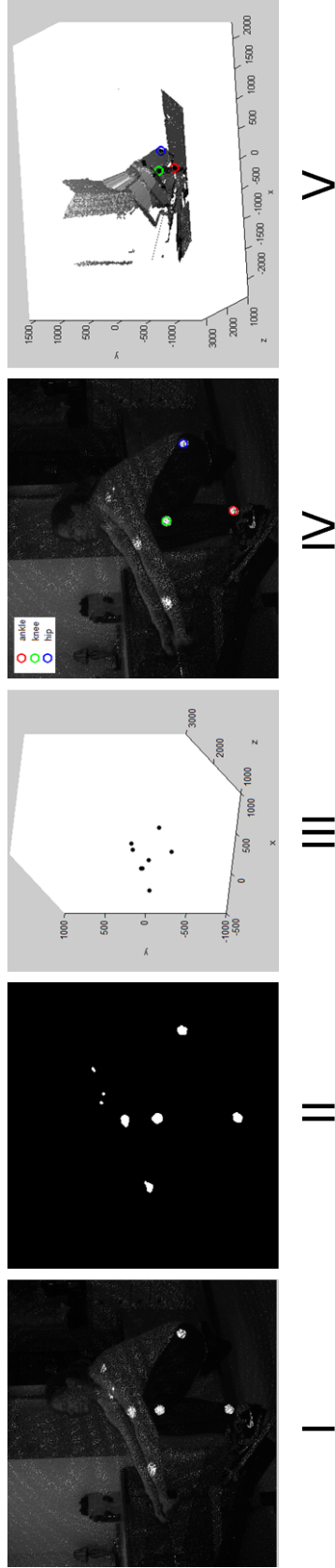


Figure 5.7: Marker location extraction: (I) 2D IR image; (II) 2D IR image with enhanced contrast; (III) centroid locations from 3D overlay; (IV) labels on 2D IR image; (V) labels on 3D points.

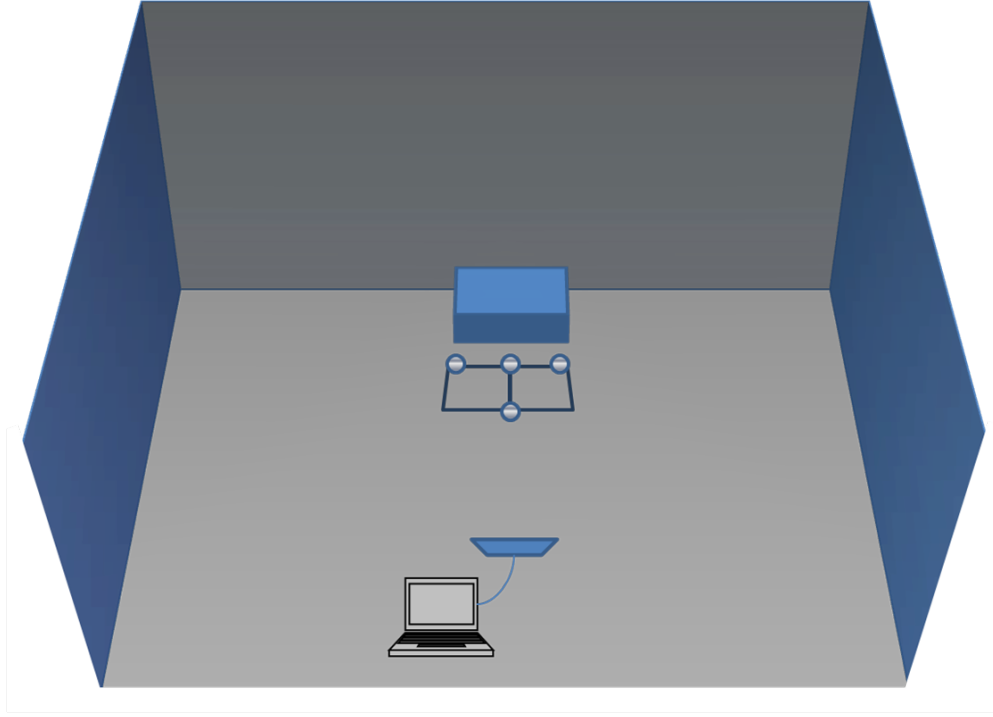


Figure 5.8: *Clinical Capture Environment: LCMAS-Single.*

data would yield inconsistent results and potentially remove desired data points or fail to remove extraneous points. To consistently identify the reference coordinate system, we chose to employ the 4 ground reference “T” markers at the edges of the force plates in Figure 5.10. Note that the reference markers were identified by performing a separate round of data processing, without cropping, for the capture volume. The markers across the top of the “T” are used to identify vector $\mathbf{k}'_1$, and the markers along the stem of the “T” identify vector $\mathbf{k}_2$. Vector $\mathbf{k}_3$ is the cross product of these two vectors. Next, to ensure orthogonality of the coordinate system we establish vector $\mathbf{k}_1$ as the cross product of $\mathbf{k}_2$ and $\mathbf{k}_3$.

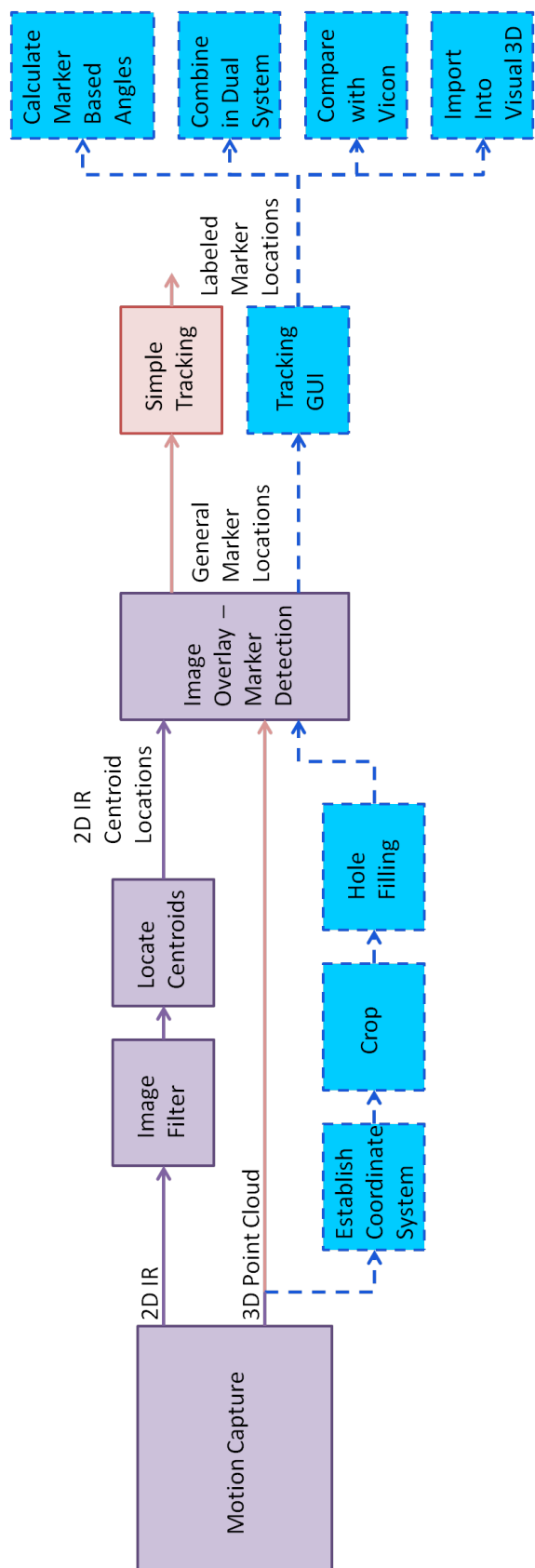


Figure 5.9: Low-Cost Motion Capture Process with original stages in solid lines and improvements in dashed lines. The original process followed the purple and red paths. The improved process follows the purple and blue paths.

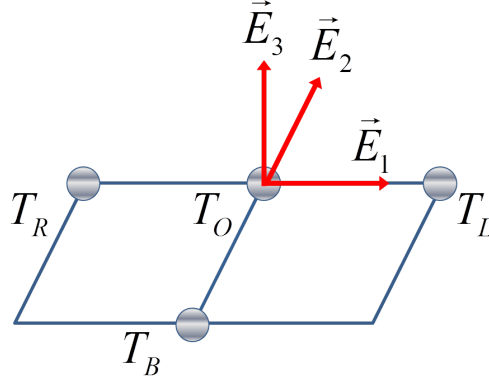


Figure 5.10: Force plate with “T” markers and laboratory basis vectors.

$$\begin{aligned}
\mathbf{k}'_1 &= \left[\overrightarrow{P_{T_R} P_{T_L}} \right]_C \\
\mathbf{k}_2 &= \left[\overrightarrow{P_{T_B} P_{T_O}} \right]_C \\
\mathbf{k}_3 &= \mathbf{k}'_1 \times \mathbf{k}_2 \\
\mathbf{k}_1 &= \mathbf{k}_2 \times \mathbf{k}_3
\end{aligned} \tag{5.1}$$

Finally, we set each of these vectors to unit length.

$$\hat{\mathbf{k}}_1 = \frac{\mathbf{k}_1}{\|\mathbf{k}_1\|} \quad \hat{\mathbf{k}}_2 = \frac{\mathbf{k}_2}{\|\mathbf{k}_2\|} \quad \hat{\mathbf{k}}_3 = \frac{\mathbf{k}_3}{\|\mathbf{k}_3\|} \tag{5.2}$$

Once we have an orthonormal coordinate system established, we can transform all of the point cloud data from the camera basis into the fixed laboratory basis $\{\mathbf{E}_1, \mathbf{E}_2, \mathbf{E}_3\}$.

$$\mathbf{E}_1 = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \quad \mathbf{E}_2 = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} \quad \mathbf{E}_3 = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \tag{5.3}$$

We create a rotation matrix, R , using directional cosines and set the origin at the marker at the intersection of the top and stem of the “T”, P_{T_O} .

$$l_{ij} = \frac{\mathbf{E}_i \cdot \mathbf{k}_j}{\|\mathbf{E}_i\| \|\mathbf{k}_j\|} = \hat{\mathbf{E}}_i \cdot \hat{\mathbf{k}}_j, \quad (i = 1, 2, 3), \quad (j = 1, 2, 3) \tag{5.4}$$

$$L = \begin{bmatrix} l_{11} & l_{12} & l_{13} \\ l_{21} & l_{22} & l_{23} \\ l_{31} & l_{32} & l_{33} \end{bmatrix} \quad (5.5)$$

$$R = \frac{L}{|L|} \quad (5.6)$$

Each valid point, P_i , in the camera coordinate system can be located by a vector, $[\mathbf{v}_i]_C$.

$$[\mathbf{v}_i]_C = \left[\overrightarrow{P_O P_i} \right]_C \quad (5.7)$$

where P_O is the origin of the camera coordinate system.

In order to locate P_i in the laboratory fixed basis, we proceed with the following transformation:

$$[\mathbf{v}_i]_E = R \left[[\mathbf{v}_i]_C - [\mathbf{v}_{T_O}]_C \right] \quad (5.8)$$

where

$$[\mathbf{v}_{T_O}]_C = \left[\overrightarrow{P_O P_{T_O}} \right]_C \quad (5.9)$$

and

$$[\mathbf{v}_i]_E = \left[\overrightarrow{P_{T_O} P_i} \right]_E. \quad (5.10)$$

All the exercises of interest take place on the force plates so any point cloud data beyond this area can be removed. In addition, the area below the “T” markers is the ground plane and can be removed. All of these point cloud locations are indexed and replaced with not-a-number (NaN) value in the unrotated (original) point cloud, Figure 5.13. By using the indexed locations we simplify processing, avoiding rotating all of the data points back to the original coordinate system and introducing error.

To proceed with marker detection, we must use the untransformed point cloud coordinates. However, following marker location extraction, if we wish to analyze the marker coordinates in the independent laboratory coordinate system, we can simply use the above equations to rotate and translate the data.

5.2.2.2 Hole Filling

Now that we have reduced the chance of introducing ground plane and background information in the marker detection process, we turn our attention to filling-in the erosions in the depth map data. The erosions have a depth value of zero and when replaced by NaN, create holes in the depth map, Figure 5.11. To populate these erosions with values, we employ an algorithm modeled from Hudson [53] (note that more sophisticated methods exist and we hope to utilize these in future work [19, 20, 110]). Each zero value is indexed, creating a mask, so only these values are modified by the hole filling technique. This preserves the data captures as well as reducing processing time. Next, we find the mean value of the sampling neighborhood (a 7x7 pixel square or kernel with the zero value in the center was chosen for this study) and replace the zero with this mean value (not including any zeros in the calculation). This process is applied to all zero points and iterated until no zero values remain. Note: a median value could have also been used or a different size neighborhood.

If the background is not cropped before this technique is employed, the populated values for the holes will be skewed by the background values, Figure 5.12. Note the color pattern of the filled holes in Figure 5.12b and the streaks of surface data between the subject and the background in Figure 5.12c. This is undesirable for our purposes, thus cropping occurred prior to hole filling.

For the data presented in this work, the hole filling method was applied to each dimension of point cloud data independently. This method better preserves the detected edge of the participant. For faster processing the image coordinate could be used and only the depth coordinates filled. Once we have filled the holes in the cropped point cloud data, Figure 5.13, we are ready to proceed with marker detection as described in initial functionality.

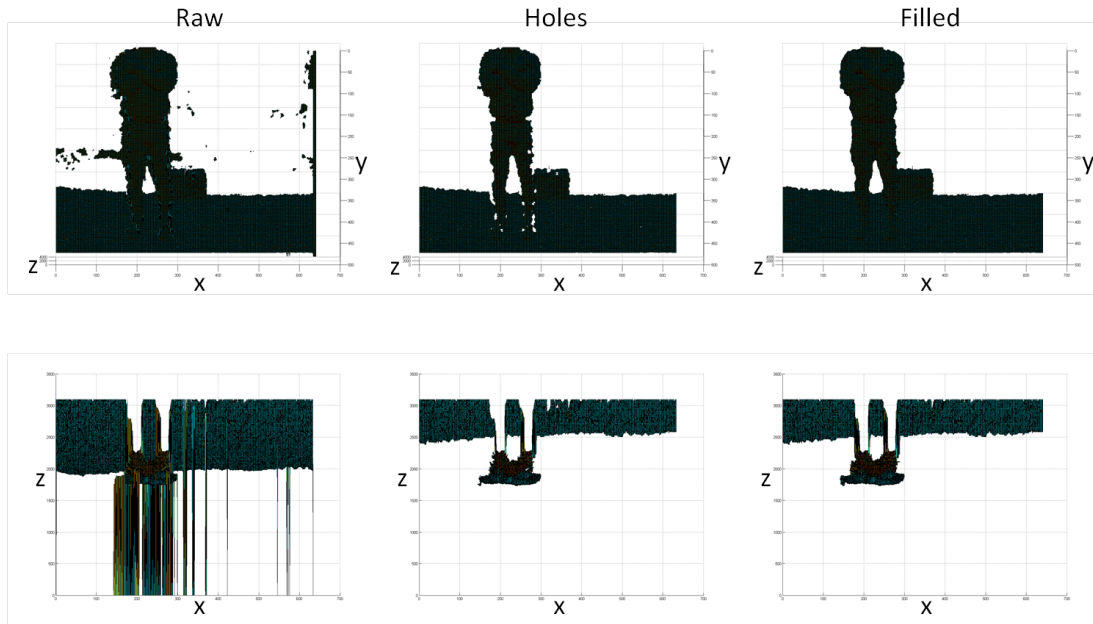


Figure 5.11: *Depth map data illustrating raw (left), holes (center), and filled (right) data.*

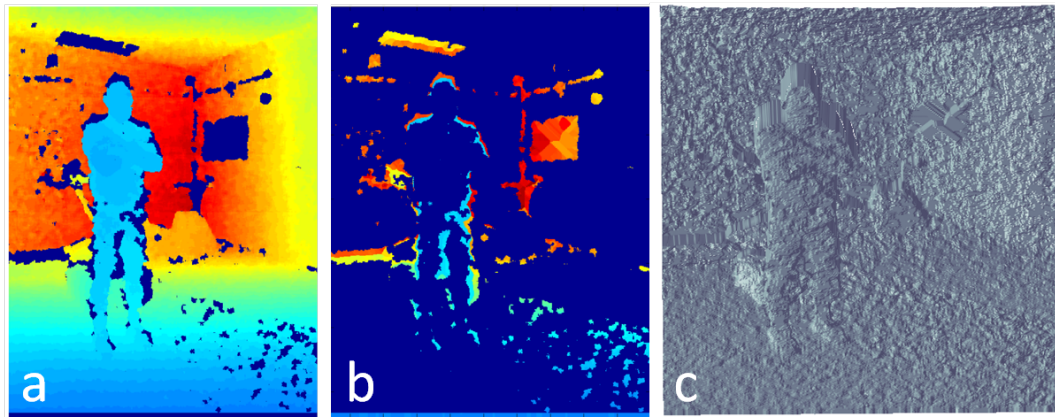


Figure 5.12: *Depth map processing: (a) raw depth map image; (b) depth map image of populated hole values; (c) filled 3D image.*

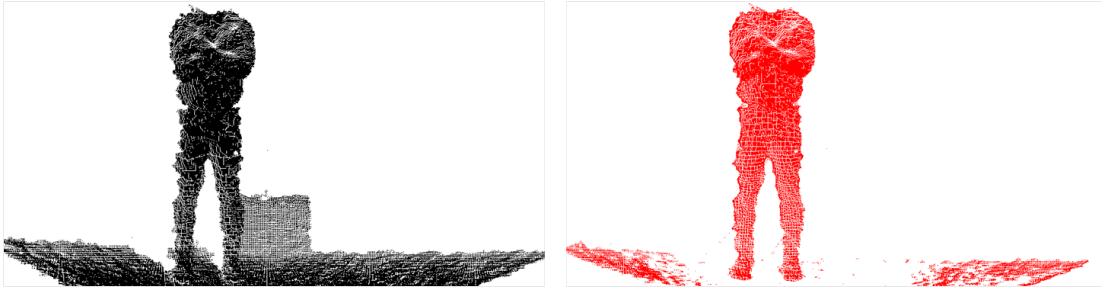


Figure 5.13: *Point cloud data: original with gross background cropping (left) and refined ground plane and background cropping with hole filling (right).*

5.2.2.3 Tracking Interface

We were fortunate to have rotation student, Jennifer Hu, aid our motion capture efforts. I guided Ms. Hu in the development of a GUI based tracking program, Figure 5.14. The program started with the initial functionality described earlier but allowed user interaction to access each frame independently. With this access, the user can check, assign, or reassign marker labels in each frame, greatly increasing confidence in labeling assignments. This access to labeled markers allows us to proceed with combining multiple depth cameras, calculating marker based angles, comparing to the industry gold standard system, and importing into robust modeling programs.

5.2.2.4 Dual Depth Cameras

We spent some time investigating simultaneous use of multiple Kinect cameras to increase the surface area of a participant visible within a testing volume. We noted some interference and increased erosion of the point cloud data. This effect is presumably due to the multiple cameras operating in the same range of wavelength (827 nm [79]) in the light spectrum. Observationally the interference seems to be diminished by vibrations but we did not run an experiment to note the impact vibration had on accuracy. We positioned the depth cameras at approximately 90

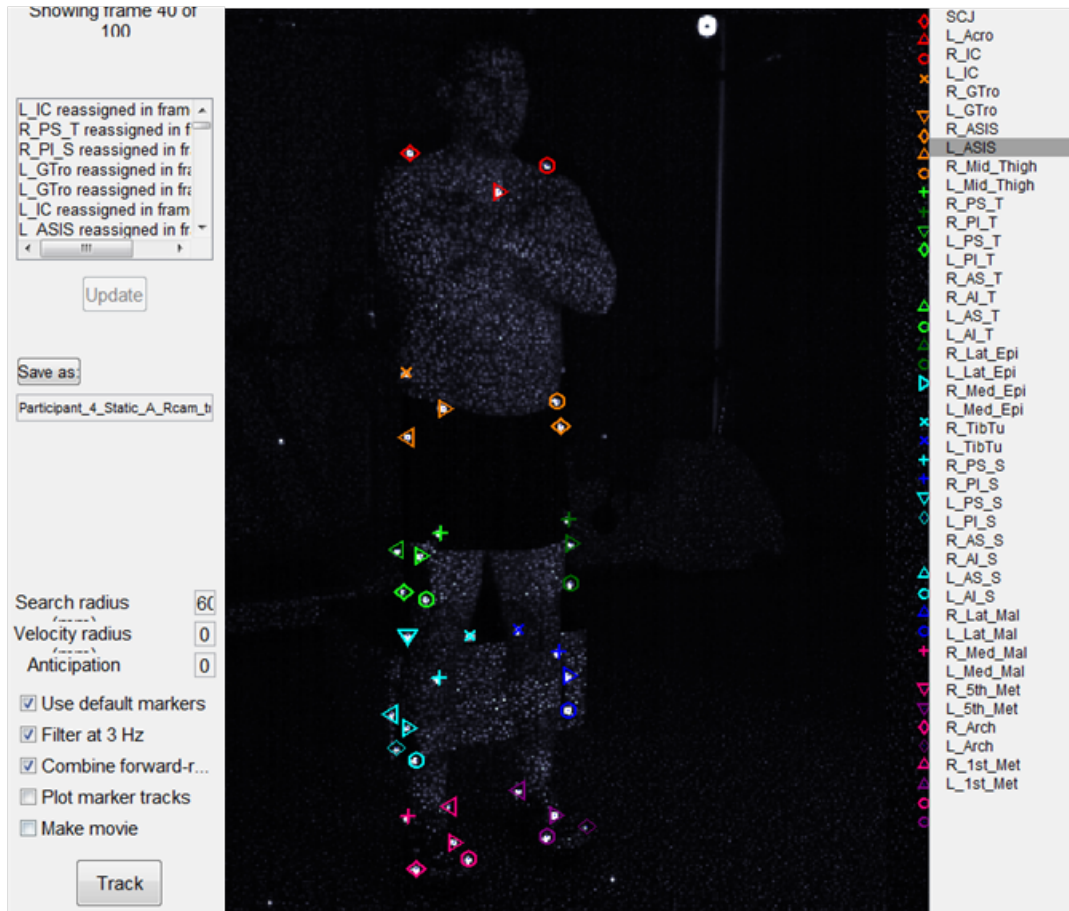


Figure 5.14: *Example frame of labeled markers in tracking GUI.*

degrees from one another and 45 degrees off the frontal plane to try and minimize interference while still gathering as much marker data as possible, Figure 5.15. Left and Right depth cameras were triggered by the same experimenter. More detail on how these signals are combined is provided in Chapter 7.

5.2.2.5 Calculation of Marker Based Angles

We use the 3D marker locations to calculate estimates of joint angles. Markers and vectors are illustrated in Figure 5.16. Note these are comparable to the visual interpretations a clinician would use to estimate joint angles. First, segment vectors are established using the marker locations. Then, the angle between the

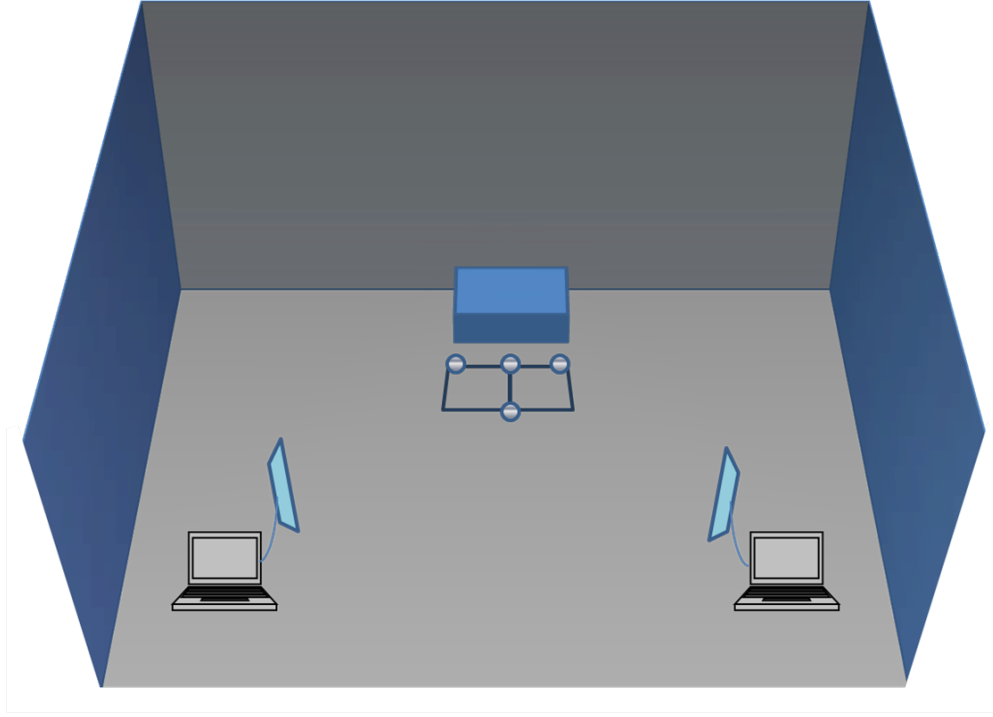


Figure 5.15: *Clinical Capture Environment: LCMAS-Dual.*

vectors is calculated. Adduction/abduction angles are adjusted by $\frac{\pi}{2}$. In our computer code we also included directional checks to distinguish between flexion and extension. A simplified version of the calculations are in the equations below. Similar calculations were also performed for the left lower extremity.

Hip

Vectors

$$\mathbf{P}_H = P_{R_{IC}} - P_{R_{GTro}} \quad \text{Pelvis} \quad (5.11)$$

$$\mathbf{H}_H = P_{L_{GTro}} - P_{R_{GTro}} \quad \text{Hip line} \quad (5.12)$$

$$\mathbf{T}_H = P_{R_{LatEpi}} - P_{R_{GTro}} \quad \text{Thigh} \quad (5.13)$$

Flexion/Extension Angle

$$\theta_{H_F/E} = \cos^{-1} \left(\frac{\mathbf{T}_H \cdot \mathbf{P}_H}{\|\mathbf{T}_H\| \|\mathbf{P}_H\|} \right) \quad (5.14)$$

Adduction/Abduction Angle

$$\theta_{H_{Ad/Ab}} = \cos^{-1} (\hat{\mathbf{x}} \cdot \hat{\mathbf{z}}) - \cos^{-1} \left(\frac{\mathbf{T}_H \cdot \mathbf{H}_H}{\|\mathbf{T}_H\| \|\mathbf{H}_H\|} \right) \quad (5.15)$$

Knee

Vectors

$$\mathbf{T}_K = P_{R_{GTro}} - P_{R_{LatEpi}} \quad \text{Thigh} \quad (5.16)$$

$$\mathbf{S}_K = P_{R_{LatMal}} - P_{R_{LatEpi}} \quad \text{Shank} \quad (5.17)$$

Flexion/Extension Angle

$$\theta_{K_F/E} = \cos^{-1} \left(\frac{\mathbf{S}_K \cdot \mathbf{T}_K}{\|\mathbf{S}_K\| \|\mathbf{T}_K\|} \right) \quad (5.18)$$

Adduction/Abduction Angle

$$\theta_{K_{Ad/Ab}} = \cos^{-1} (\hat{\mathbf{x}} \cdot \hat{\mathbf{z}}) - \cos^{-1} \left(\frac{\hat{\mathbf{x}} \cdot \mathbf{S}_K}{\|\mathbf{S}_K\|} \right) \quad (5.19)$$

Ankle

Vectors

$$\mathbf{S}_A = P_{R_{LatEpi}} - P_{R_{LatMal}} \quad \text{Shank} \quad (5.20)$$

$$\mathbf{F}_A = P_{R_{5thMet}} - P_{R_{LatMal}} \quad \text{Foot} \quad (5.21)$$

Dorsiflexion/Plantarflexion Angle

$$\theta_{A_{F/E}} = \cos^{-1} \left(\frac{\mathbf{F}_A \cdot \mathbf{S}_A}{\|\mathbf{F}_A\| \|\mathbf{S}_A\|} \right) \quad (5.22)$$

5.2.2.6 Additional Functionality

Beyond the initial functionality improvements, we have worked to import marker locations from LCMAS into Visual3D enabling synchronization with force plate data and the application of robust modeling of kinematic and kinetic parameters. More detail is provided in Chapters 7 and 8. With this capability we were also able to calculate a center of mass position in three dimensions and center of mass relative to base of support. The later metric calculation is detailed in Chapter 8.

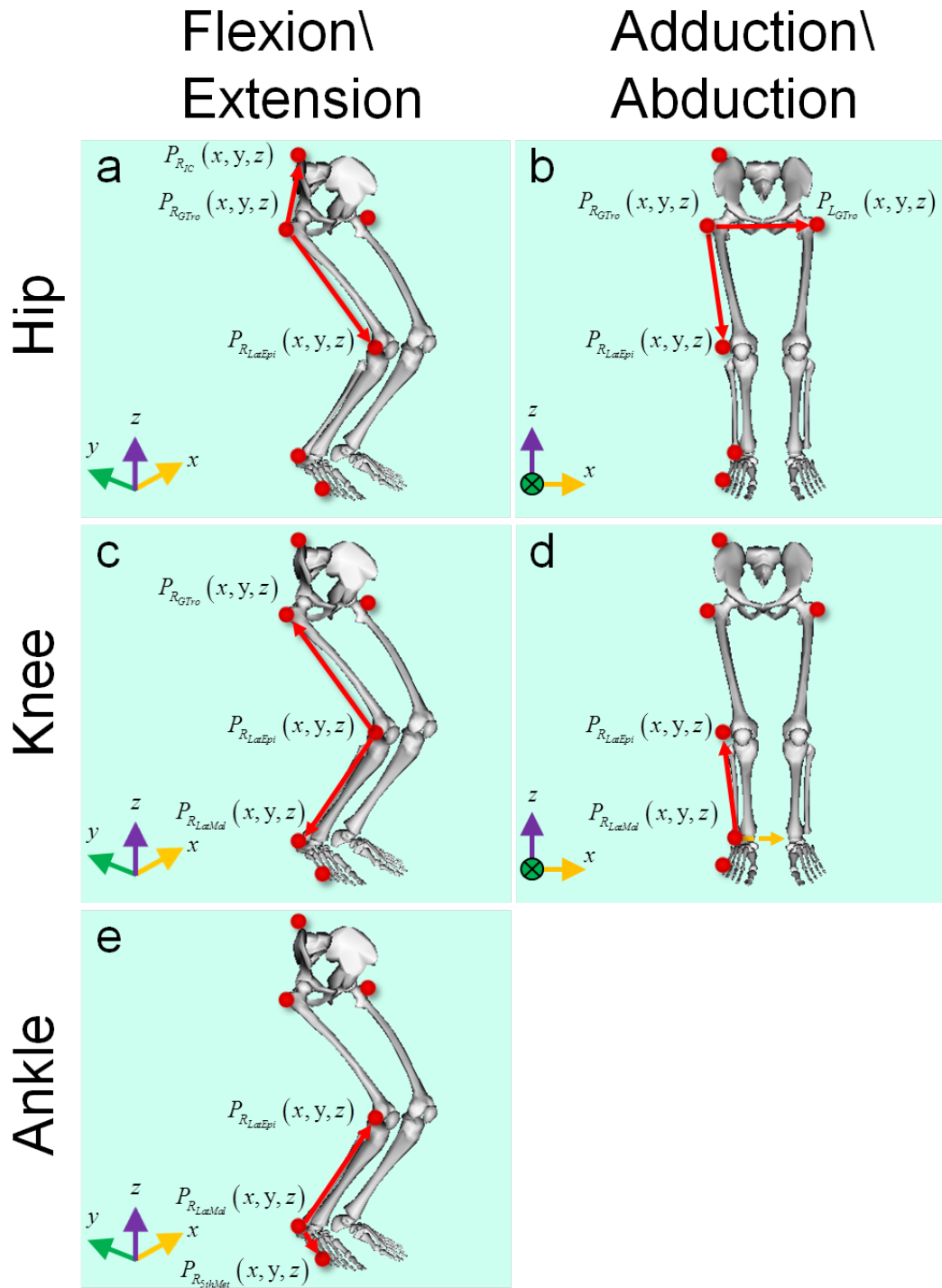


Figure 5.16: Marker based angle measurements for the hip, knee, and ankle. Images were composed using OpenSim [31].

CHAPTER 6

Low-Cost Movement Assessment System - Kinect2

6.1 System Function - Kinect2

The Kinect2 is the newer version of Microsoft's depth camera, Figure 6.1. It has similar functionality to the original Kinect, however, it utilizes time of flight technology for depth measurements. It also features a more robust skeleton, with 25 points compared to the 15 points in the earliest version. We did not modify the raw output data. We enhanced the skeleton generated by the Kinect2 from the point cloud data.



Figure 6.1: *Kinect2 depth sensing camera. Image obtained from the public domain.*

6.2 System Development to Improve Accuracy

6.2.1 Implemented Improvements

We refer to the motion capture system, utilizing the Kinect2 with our enhancements, as the Low-Cost Movement Assessment System-2 (LCMAS-2). All calculations are performed using a customized MATLAB script. We use the data from the generated skeleton and assign mass and center of mass (COM) position locations to each segment based on Dempster’s body segment parameters [101]. We then can calculate an overall COM for the model. We also spatially and temporally synchronized the LCMAS-2 data with the Vicon data, enabling use to use the force plate data. Using the LCMAS-2 data we implemented joint angle calculations based on the skeleton joint center positions. In addition, we assigned segment coordinate systems and ensured orthogonality. Next we assigned inertial properties based on Chandler [25] via Chaffin [24]. We were then able to use inverse dynamics to take force plate data and calculate joint reaction forces and net joint moments.

6.2.1.1 Center of Mass Assignments

Calculations in this section are based on equations found in Robertson et al. [101]. Here we make the assumption that the COM of each segment lies between joint centers on the long axis ($\mathbf{Z}$ for the shank and thigh, and $\mathbf{Y}$ for the foot).

To assign mass, m_s , to each segment of the skeleton we utilize the following equation:

$$m_s = p_s M \quad (6.1)$$

where p_s is the segment percentage of total mass, M , and is obtained from Dempster’s body segment parameters, Table 6.1. The use of these parameters is common in biomechanics research but it should be noted that it preferable to use more in-

dividualized representative parameters for the specific participant or population of interest, when possible.

Table 6.1: *Dempster's Body Segment Parameters* [101].

Segment	Endpoints (proximal to distal)	Segment Mass/ Total Mass p_s	Center of Mass/ Segment Length (from proximal end) $B_{proximal}$
Foot	Ankle to ball of foot	0.0145	0.500
Shank	Knee to ankle center	0.0465	0.433
Thigh	Hip to knee center	0.1000	0.433
Pelvis	L4-L5 to trochanter	0.1420	0.105
Thorax and abdomen	C7-T1 to L4-L5	0.3550	0.630
Head	C7-T1 to ear canal	0.0810	1.000
Hand	Wrist center to knuckle of 3 rd finger	0.0060	0.506
Forearm	Elbow to wrist center	0.0160	0.430
Upper arm	Glenohumeral joint to elbow center	0.0280	0.436

The location of each segment's COM, r_s , is calculated with the following equation:

$$r_s = r_{s,proximal} + B_{s,proximal}(r_{s,distal} - r_{s,proximal}) \quad (6.2)$$

where $r_{s,proximal}$ is the position of the segment's proximal end, $r_{s,distal}$ is the position of the segment's distal end, and $B_{s,proximal}$ is the ratio of the location of the COM from the segment's proximal end to the segment's length. Values for $B_{s,proximal}$ are listed in Table 6.1.

The total model COM position, r_{total} , is located using the segment COM positions, weighted by segment mass, Equation 6.3.

$$r_{total} = \sum_{s=1}^S p_s r_s \quad (6.3)$$

A visualization of the Kinect2 skeleton and the LCMAS-2 skeleton with segment and total COM positions is shown in Figure 6.2.

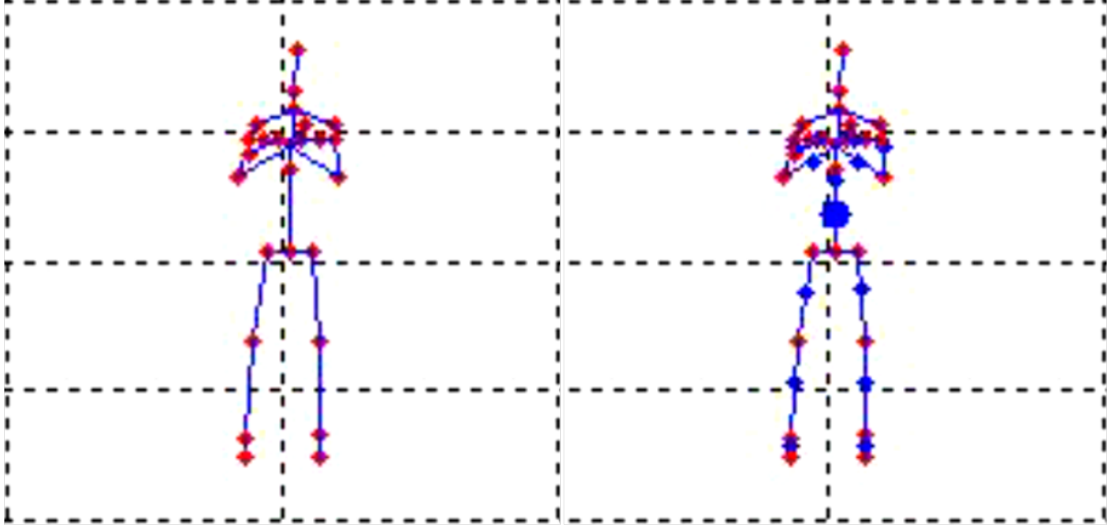


Figure 6.2: *Example of Kinect2 skeleton (left) and LCMAS-2 skeleton (right). Body segments are shown as blue lines, joints positions are shown as small red dots, segment center of mass (COM) positions are shown as small blue dots, and total model COM position is shown as large blue dot.*

6.2.1.2 Synchronization with Gold Standard Data

To accommodate the partial Visual3D model of the Vicon data (missing arms and head), a partial model COM was also calculated for LCMAS-2 and used in the synchronization calculations.

Data from the LCMAS-2 is captured at approximately 30 frames per second. However, the capture rate is nonuniform within a data file. In order to address this inconsistency, we also capture CPU timestamps. Now we can properly space the data. We interpolate the data to match the time step of the Vicon system.

Next, to temporally synchronize the signals, we focus on vertical component of COM for both the Vicon and LCMAS-2 models for 3 repetitions of the selected

maneuver. The signals are temporarily filled and smoothed according to an analysis of residuals. We then identify the minimum low position of COM for the three repetitions in each system, Figure 6.3 (top left). Next we shift the LCMAS-2 data on the time scale to match the Vicon data based on the average offset of the three repetitions, Figure 6.3 (bottom left).

Now to spatially synchronize the data, we identify select 3D points in both systems over the first quarter and last quarter of the three repetitions. In the Vicon data these points are bilateral acromion, greater trochanter, lateral epicondyle, tibial tuberosity, lateral malleolus, and COM. In the LCMAS-2 data the corresponding points are bilateral shoulder, hip, knee, knee, ankle, and COM. Each knee is used twice in the LCMAS-2 data to balance the corresponding lateral epicondyle and tibial tuberosity from the Vicon data. For the registration, in both systems the COM is weighted at 50 percent and the other 10 points share the remaining 50 percent weighting evenly. Then we register these weighted components of the LCMAS-2 to Vicon using a modified version of the MATLAB function for calculating singular value decomposition, “svd”. Then we use the output rotation and translation data to transform the LCMAS-2 data. The three components of COM from both systems are shown in Figure 6.3 (top right unrotated and bottom right rotated). Now the LCMAS-2 signals are matched to the Vicon and force plate signals, Figure 6.4, allowing for use of the force plate data in metric calculations for the LCMAS-2 model. With these newly obtained metrics we can proceed to system comparisons.

In the future we plan to independently associate the LCMAS-2 to the force plate signals to create a completely independent system that does not use the Vicon data for registration.

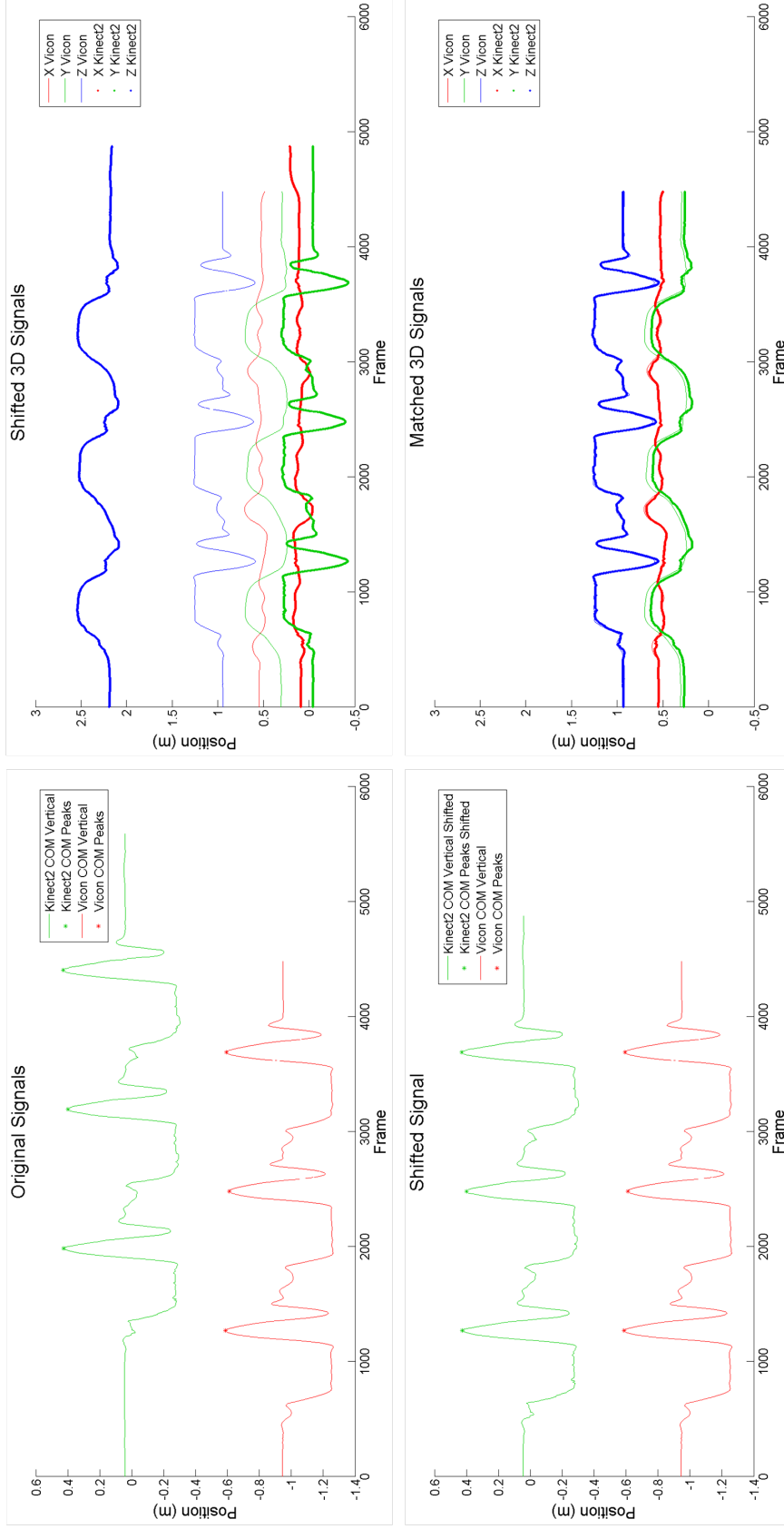


Figure 6.3: Example of LCMAS-2 and Vicon COM data: original vertical components (top left), temporally synchronized vertical components (bottom left), temporally synchronized 3 components (top right), and temporally and spatially synchronized 3 components (bottom right).

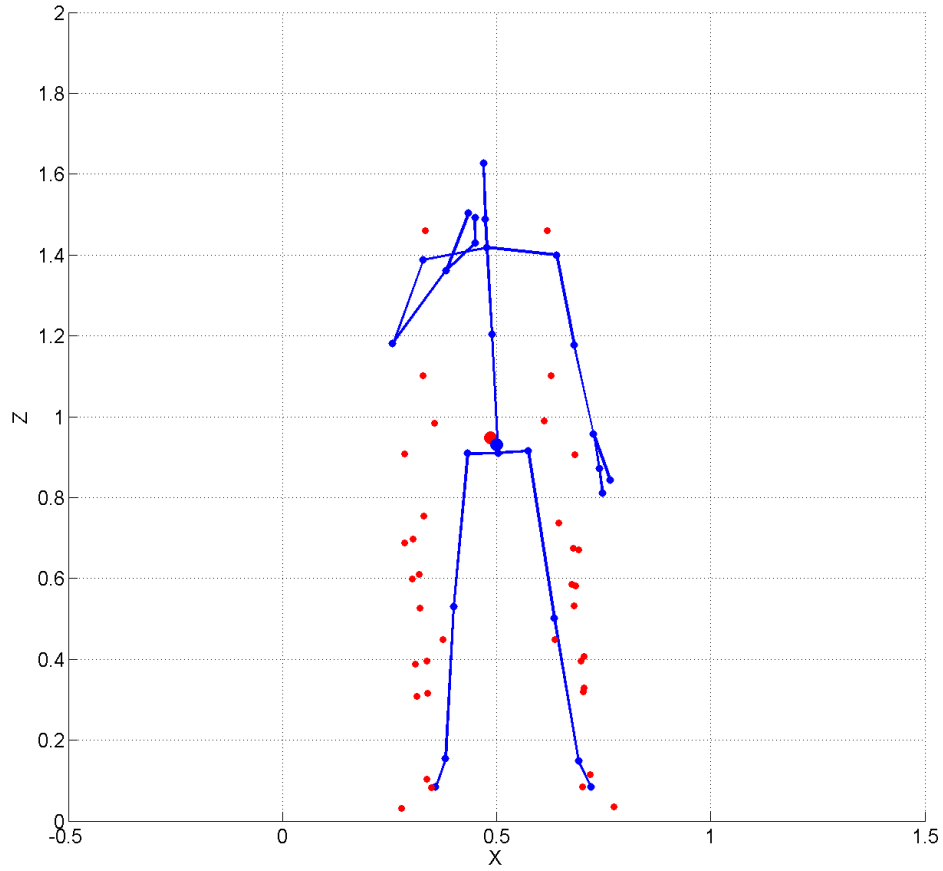


Figure 6.4: *Matched LCMAS-2 skeleton to Vicor markers. Note small red dots are Vicor markers, large red dot is Vicor COM; small blue dots are LCMAS-2 joints joined by blue lines representing skeleton segments, and large blue dot is LCMAS-2 COM.*

6.2.1.3 Joint Angle Calculations

Here we use the same angle definitions we used when calculating the marker based angles in Chapter 5.2.2.5, replacing the marker position with corresponding skeleton joint center location from LCMAS-2. The only exception is the pelvis vector.

For marker based angles, a vector was constructed between the greater trochanter and iliac crest markers. With joint center locations, a vector is constructed between the hip center and mid-torso skeleton points. This vector is translated to both hip joint centers and then the hip flexion angle calculations proceed as they did previously in marker based angles.

6.2.1.4 Segment Coordinate System Definitions

The segment coordinate system definitions correspond to the general direction and definitions outlined in the gold standard Visual3D model in Chapter 2.2.1 and Figure 2.3. Since we are simply connecting joint centers to create segments, in order to create a 3D coordinate system for each segment we need to define each segment's frontal plane based on its relative orientation to other segments. Each segment's coordinate system definitions are detailed below.

Pelvis

The first component of the pelvis coordinate system, $\mathbf{X}_{Pelvis}$, is defined as the unit vector constructed from subtracting the left hip position from the right hip position and dividing by the norm of the same calculation. Next, we define a mid-hip position as the average of the two hip positions from the skeleton. A vector, $\mathbf{Y}'_{Pelvis}$, in the segment's transverse plane is identified from the subtraction of the skeleton hip joint center from our newly defined mid-hip position. Based on the relative position of these points, positive in in the anterior direction. The superior-inferior axis, $\mathbf{Z}_{Pelvis}$, is defined as the unit vector that is perpendicular to the segment's transverse plane and obtained from the cross product of $\mathbf{X}_{Pelvis}$ and $\mathbf{Y}'_{Pelvis}$ divided by its norm. Finally, to ensure an orthogonal coordinate system, the second component, $\mathbf{Y}_{Pelvis}$, is defined as the cross product of $\mathbf{Z}_{Pelvis}$ and $\mathbf{X}_{Pelvis}$.

Thigh

For the thigh we start by defining the third component, $\mathbf{Z}_{Thigh}$, as the unit vector along the line connecting the knee and hip positions from the skeleton, with positive in the superior direction. The medial-lateral axis, $\mathbf{X}_{Thigh}$, is defined as the cross product of $\mathbf{Z}_{Shank}$ and $\mathbf{Z}_{Thigh}$ divided by its norm ($\mathbf{Z}_{Shank}$ defined below). Again to complete the orthogonal coordinate system the remaining component, $\mathbf{Y}_{Thigh}$, is obtained from the cross product of the other two components, $\mathbf{Z}_{Thigh}$ and $\mathbf{X}_{Thigh}$.

Shank

The establishment of the shank coordinate system closely resembles that of the thigh. First we define $\mathbf{Z}_{Shank}$ as the unit vector in the superior direction along the line connecting ankle and knee joint positions from the skeleton. Next we define $\mathbf{X}_{Shank}$ as the unit vector of the cross product of $\mathbf{Z}_{Shank}$ and $\mathbf{Z}_{Thigh}$ divided by its norm. It is important to note that now $\mathbf{X}_{Shank}$ is equivalent to $\mathbf{X}_{Thigh}$. Finally we complete the orthogonal coordinate system with $\mathbf{Y}_{Shank}$ by taking the cross product of $\mathbf{Z}_{Shank}$ and $\mathbf{X}_{Shank}$.

Foot

For the foot, we would like the coordinate system to be in a similar orientation as the other segments in the anatomical position. This desire means that we define the second component, $\mathbf{Y}_{Foot}$, as the unit vector along the line connecting toe and ankle positions from the skeleton, with positive in the anterior direction. The medial-lateral axis, $\mathbf{X}_{Foot}$, is the cross product of $\mathbf{Y}_{Foot}$ and $\mathbf{Z}_{Shank}$ divided by its norm. Finally, the definition of $\mathbf{Z}_{Foot}$ ensures orthogonality of the coordinate system as the cross product of $\mathbf{X}_{Foot}$ and $\mathbf{Y}_{Foot}$.

Virtual Foot

The definition of the coordinate system for the virtual foot follows a similar procedure to that of the foot. The second component of the coordinate system, $\mathbf{Y}_{VirtualFoot}$, is the unit vector in the anterior direction along the line connecting the toe position ground projection and ankle position ground projection (no vertical component) of the skeleton. The third component, $\mathbf{Z}_{VirtualFoot}$, is a unit vector in the vertical direction. And finally the first component, $\mathbf{X}_{VirtualFoot}$, is the cross product of $\mathbf{Y}_{VirtualFoot}$ and $\mathbf{Z}_{VirtualFoot}$.

Floating Axes for Joint Coordinate Systems

When we define the joint coordinate systems for each joint, we use the first component of the proximal segment's coordinate system, $\mathbf{X}_{proximal}$, and the third component of the distal segment's coordinate system, $\mathbf{Z}_{distal}$. To complete the coordinate system we must define the floating axis, $\mathbf{Y}_{float}$, as the mutually perpendicular unit vector. The floating axis for the hip, $\mathbf{Y}_{Hip}$, is the cross product of $\mathbf{Z}_{Thigh}$ and $\mathbf{X}_{Pelvis}$ divided by its norm. Similarly, the floating axis for the knee, $\mathbf{Y}_{Knee}$, is the cross product of $\mathbf{Z}_{Shank}$ and $\mathbf{X}_{Thigh}$ divided by its norm. Here it is also important to note that since $\mathbf{X}_{Shank}$ is equivalent to $\mathbf{X}_{Thigh}$ then $\mathbf{Y}_{Knee}$ is equivalent to $\mathbf{Y}_{Shank}$, so that now the joint coordinate system is equivalent to the distal coordinate system. Next we define the floating axis for the ankle, $\mathbf{Y}_{Ankle}$, as the cross product of $\mathbf{Z}_{Foot}$ and $\mathbf{X}_{Shank}$ divided by its norm. Finally, the floating axis for the virtual ankle, $\mathbf{Y}_{VirtualAnkle}$, is the cross product of $\mathbf{Z}_{VirtualFoot}$ and $\mathbf{X}_{Shank}$ divided by its norm.

We do not use standard joint angle definitions with these coordinate systems. For example, in the knee the calculation is the same for flexion but we would

negate adduction/abduction and internal/external rotation by the way we defined the coordinate systems. These unit vectors are assigned so we have a coordinate system to use with our force and moment calculations.

6.2.1.5 Velocity and Acceleration

Calculations in this section are based on equations found in Robertson et al. [101]. We use the finite difference method to calculate each segment's linear velocity, $\mathbf{v}_s$, and linear acceleration, $\mathbf{a}_s$, in the global coordinate system, where $r_{s,t}$ is the position of the center of mass of each segment at each time, t .

$$\mathbf{v}_{s,t} = \frac{r_{s,t+1} - r_{s,t-1}}{2\Delta t} \quad (6.4)$$

$$\mathbf{a}_{s,t} = \frac{r_{s,t+1} - 2r_{s,t} + r_{s,t-1}}{\Delta t^2} \quad (6.5)$$

To calculate angular velocity, $\boldsymbol{\omega}_s$, and angular acceleration, $\boldsymbol{\alpha}_s$, of each segment, we first calculate the rotation matrix of the segment relative to the Global Coordinate System, R , at each point in time, t . We then use the following equations to calculate the finite differences of the rotation matrices to obtain angular velocity.

$$R_{\Delta} = R_{t+1}R_{t-1} \quad (6.6)$$

$$|\boldsymbol{\omega}_{s,t}| = \frac{\delta}{2\Delta t} \quad (6.7)$$

Here δ is the rotation about the helical axis defined by unit vector, $\hat{\nu}$.

$$\delta = \cos^{-1} \left(\frac{R_{\Delta 11} + R_{\Delta 22} + R_{\Delta 33} - 1}{2} \right) \quad (6.8)$$

$$\hat{\boldsymbol{\nu}} = \frac{\begin{bmatrix} R_{\Delta 23} - R_{\Delta 32} \\ R_{\Delta 31} - R_{\Delta 13} \\ R_{\Delta 12} - R_{\Delta 21} \end{bmatrix}}{2\sin\delta} \quad (6.9)$$

$$\hat{\mathbf{u}} = R'_{t-1}\hat{\boldsymbol{\nu}} \quad (6.10)$$

Here $\hat{\mathbf{u}}$ is $\hat{\boldsymbol{\nu}}$ transformed into the Global Coordinate System.

Finally, we assemble our segment's angular velocity, $\boldsymbol{\omega}_s$, in the Global Coordinate System

$$\boldsymbol{\omega}_{s,t} = |\boldsymbol{\omega}_{s,t}| \hat{\mathbf{u}} \quad (6.11)$$

We can now use finite difference to obtain angular acceleration, $\boldsymbol{\alpha}_s$, from angular velocity, $\boldsymbol{\omega}_s$.

$$\boldsymbol{\alpha}_{s,t} = \frac{\boldsymbol{\omega}_{s,t+1} - \boldsymbol{\omega}_{s,t-1}}{2\Delta t} \quad (6.12)$$

6.2.1.6 Inertial Properties

Next we must establish the inertial properties of each segment. With the LCMAS-2 skeleton we lack the joint width information Visual3D uses to construct segment volumes and thus inertial properties. Instead we turn to the literature to obtain standardized values. For our calculations we use inertial properties from Chandler [25] via Chaffin [24], Table 6.2.

Table 6.2 lists components of C which is the ratio of radius of gyration, K , to segment length L .

$$C = \frac{K}{L} \quad (6.13)$$

The segment lengths are calculated from the average segment lengths in series of static frames at the beginning of each participant's data capture session. The components of C construct a diagonal matrix which can be used to calculate the

Table 6.2: *Inertial Properties from Chandler [25] via Chaffin [24]. C is the ratio of radius of gyration (K) to segment length (L). Motion axes to allow the motion: x = sagittal plane motion; y = frontal plane motion; z = horizontal plane motion.*

Segment	Link	Cx	Cy	Cz
Foot	Foot length	0.26	0.25	0.12
Shank	Fibular height	0.28	0.28	0.08
Thigh	Trochanterion height – fibular height	0.28	0.28	0.12
Torso	Torso length (Suprasternale height – trochanterion height)	0.43	0.35	0.21
Head	Head length	0.32	0.31	0.34
Hand	Hand breadth	0.50	0.46	0.27
Upper arm	Acromion - radiale	0.26	0.25	0.10

diagonal matrix for the mass moment of inertial of each segment about its center of gravity, I'_s .

$$I'_s = m_s C^2 L^2 \quad (6.14)$$

Again, m_s is the segment mass.

Now we proceed to computation of each segment's inertial contributions to net joint moment. For ease in calculation, we convert ω_s and α_s to the segment's coordinate system.

$$\omega'_s = R_s \omega_s \quad (6.15)$$

$$\alpha'_s = R_s \alpha_s \quad (6.16)$$

Now, we calculate each segment's inertial contributions to net joint moment

$\boldsymbol{\tau}_s^I$ in the each segment's coordinate system.

$$\boldsymbol{\tau}_s^I = \frac{d}{dt} (I'_s \boldsymbol{\omega}'_s) = I'_s \boldsymbol{\alpha}'_s + \boldsymbol{\omega}'_s \times (I'_s \boldsymbol{\omega}'_s) \quad (6.17)$$

Finally, we convert $\boldsymbol{\tau}_s^I$ into the Global Coordinate System.

$$\boldsymbol{\tau}_s^I = R'_s \boldsymbol{\tau}_s'^I \quad (6.18)$$

Now we have all the components necessary to proceed to our inverse dynamics calculations.

6.2.1.7 Inverse Dynamics

Calculations in this section are based on equations found in [101]. We make the assumptions that joint forces are equal and opposite about the joint and that joint moments are equal and opposite about the joint.

The joint reaction force, $\mathbf{F}_j$, is generalized in the following equation.

$$\mathbf{F}_j = \left(\sum_{s=1}^S m_s (\mathbf{a}_s - \mathbf{g}) \right) - \mathbf{F}_{grf} \quad (6.19)$$

Here the summation is performed over all segments distal to the joint, S , gravity is $\mathbf{g}$, and the ground reaction force, $\mathbf{F}_{grf}$, is obtained from the force plate data.

The net joint moment, $\boldsymbol{\tau}_j$, is generalized in the following equation.

$$\boldsymbol{\tau}_j = \left(\sum_{s=1}^S \boldsymbol{\tau}_s^I + \mathbf{r}_{j.s} \times m_s (\mathbf{a}_s - \mathbf{g}) \right) - \boldsymbol{\tau}_{grf} - (\mathbf{r}_{j.grf} \times \mathbf{F}_{grf}) \quad (6.20)$$

Here the summation is performed over all segments distal to the joint, S , the vector from the joint to a distal segments COM is $\mathbf{r}_{j.s}$, the vector from the joint to ground reaction force is $\mathbf{r}_{j.grf}$, and the free moment, $\boldsymbol{\tau}_{grf}$, is obtained from the force plate data.

Visualizations of these variables are presented in Figure 6.5.

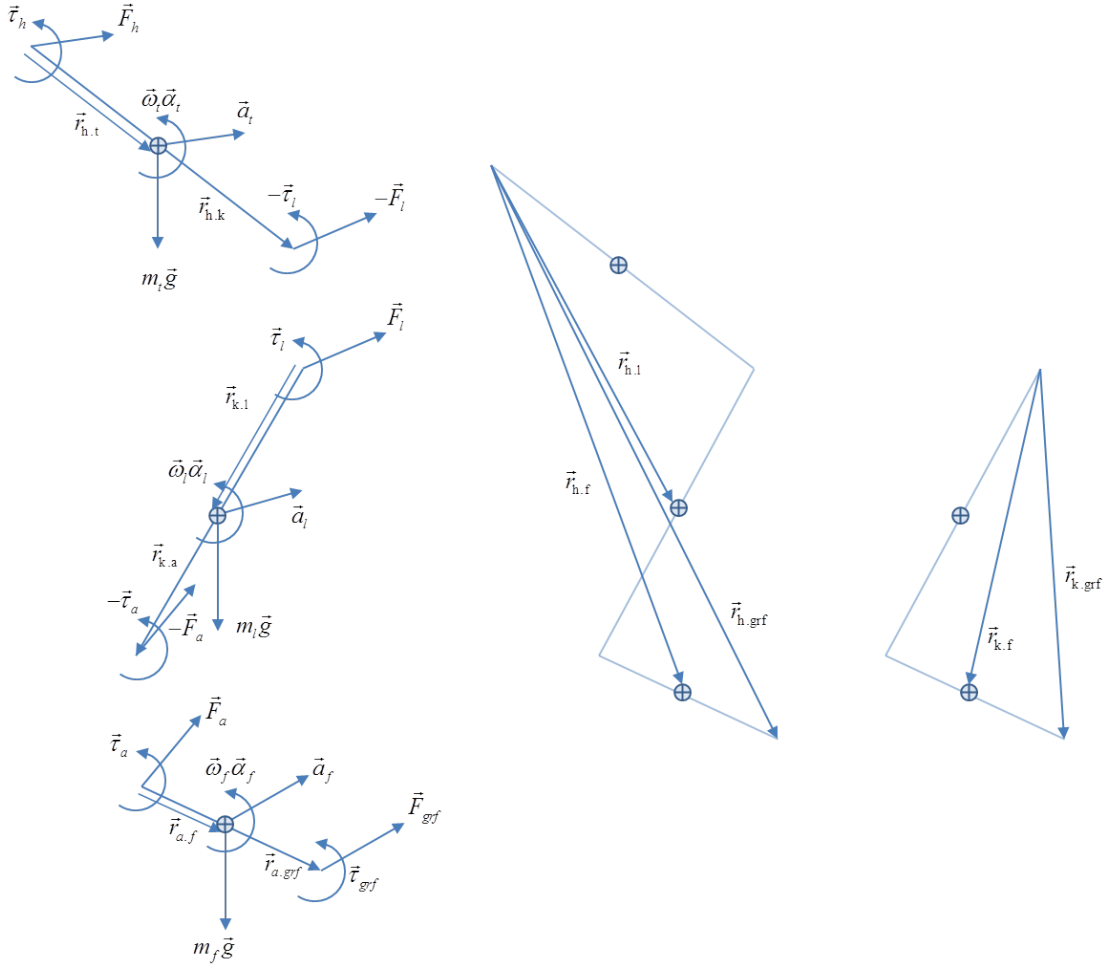


Figure 6.5: *Free body diagrams of the thigh, shank, and foot (left), vectors from proximal end of thigh to distal segments COM and ground reaction force (center), and vectors from proximal end of shank to distal segment COM and ground reaction force (right). Based on [101, Figure 7.3, p. 154].*

These equations enable the calculations of joint reaction force and net joint moment with the synchronized force plate data from Visual3D. The joint reaction force and net joint moment are calculated in the Global Coordinate System and then can simply be dotted into the corresponding joint coordinate system, proximal coordinate system, and distal coordinate system, for comparison to Visual3D values.

Part III

System Comparisons

CHAPTER 7

Marker Position Comparison Between Low-Cost Depth Camera Systems and Vicon

7.1 Overview

We hypothesize that with the processing improvements from Chapter 5, an inexpensive depth camera, such as the Microsoft Kinect, can be used to obtain, 1) single camera and 2) simultaneous left and right side dual camera 3D marker measurements of comparable magnitude to soft tissue artifact, compared to the high-cost gold standard Vicon motion capture system (Oxford Metrics, UK). In addition, the processing improvements will increase the number of markers validly detected and the surfaces, ground or participant, on which the markers are placed will impact the level of detection. An example of dual depth maps and participant marker configuration are shown in Figure 7.1.

7.2 Methods

The study was approved by University of California, San Francisco, Committee on Human Research (IRB 12-10253). Adult volunteers, 3 male and 3 female, provided signed informed consent. The Vicon (Oxford Metrics, UK), Single Depth Camera System, and Dual Depth Camera System were set-up with a testing volume that mimicked a 10'x10' clinical examination room with four reference markers placed in a "T" configuration on the floor. The Single Depth Camera System was centered

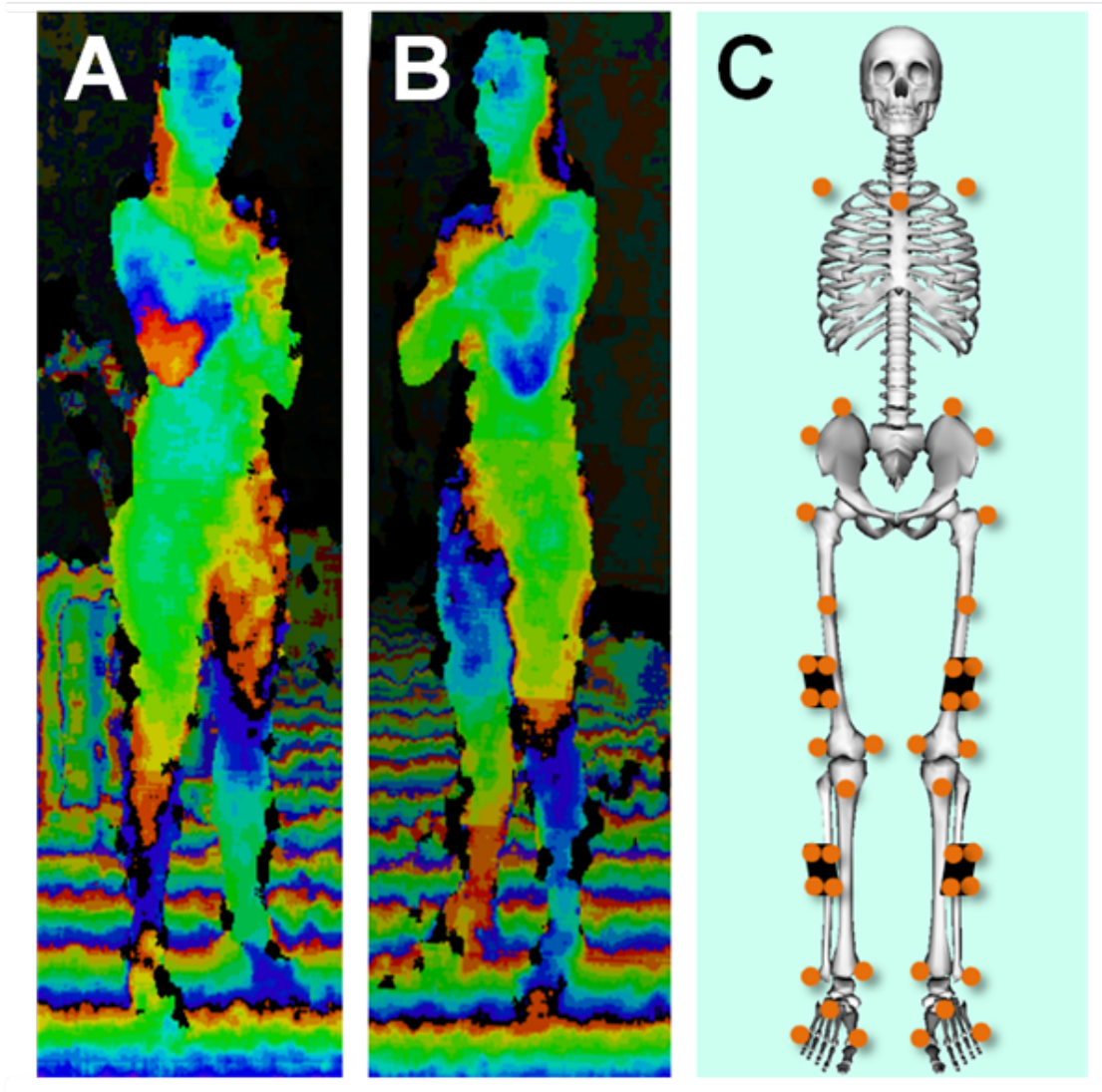


Figure 7.1: (A) *Depth map right side*; (B) *Depth map left side*; (C) *Complete marker set*. Image composed using *OpenSim* [31].

in the frontal plane, while the Dual Depth Cameras were oriented in the corners of the testing volume, facing the subject, offset from the frontal plane, Figure 7.2. Each depth camera was within a 2-3 m range of the participant testing location and connected to a computer running a custom MATLAB (MathWorks Natick, MA, USA) script and Open NI Viewer to capture depth information.

Forty-eight retro-reflective markers were placed on each participant, by the

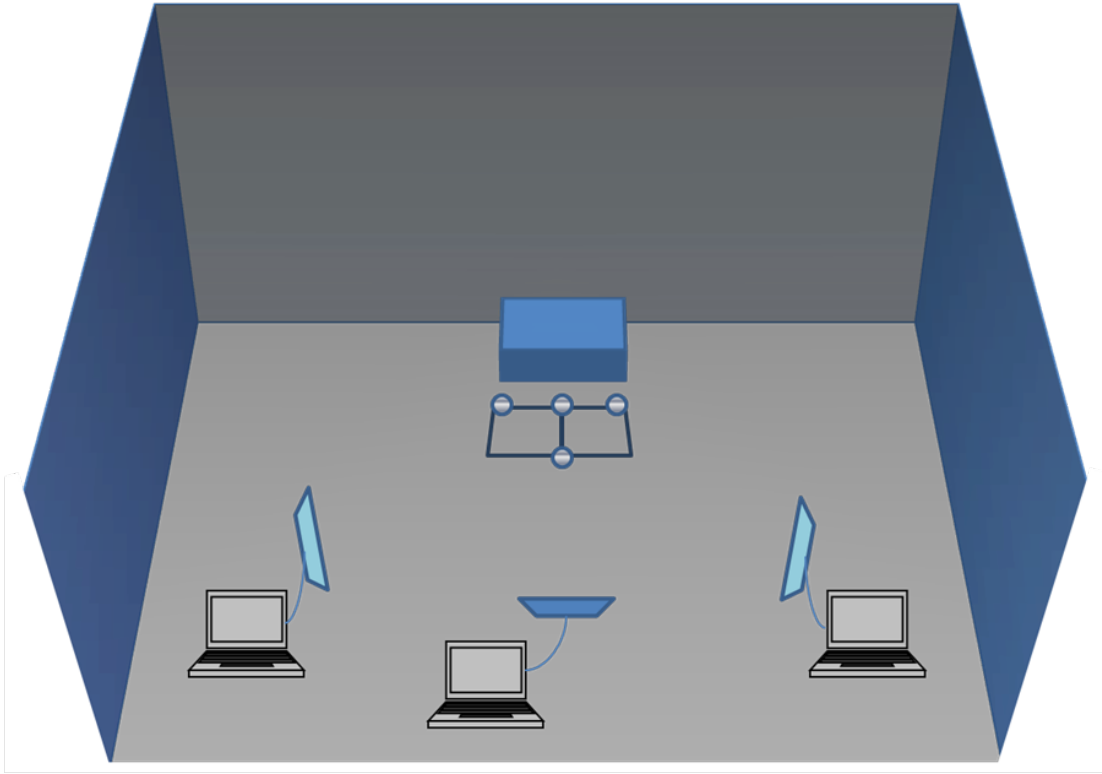


Figure 7.2: *Clinical Capture Environment comprised of both the Single Depth Camera System (center) and the Dual Depth Camera System (left and right).*

same experimenter, in a configuration for detection by the Vicon system and the low-cost depth camera based systems. For each participant (“P”), 43 markers were assessed, Figure 7.1C and Table 2.1.

Static trials were captured, consisting of the testing volume with reference markers and the marked participants. The static trials were recorded simultaneously with the infrared 10-camera Vicon system and with either 1) the Single Depth Camera System or 2) the Dual Depth Camera System. This process, including remarkering of the participant, was repeated multiple times in a testing session. Participants attended two testing sessions one week apart.

7.2.1 Data Processing

Vicon System

Procedures are detailed in Chapter 2 with labeled marker locations exported to ASCII files for import to MATLAB for comparison calculations.

Single Depth Camera System

In this setup we gathered data in the frontal plane, Figure 7.2. Other orientations are certainly possible and need to be optimized for each task. We recorded simultaneously with Vicon. A custom MATLAB script was used to process the data with the old method and new method detailed in Chapter 5. In the Vicon system, position coordinates for each marker were averaged over the 250 frames of Vicon data, captured at 250Hz. In the Single Depth Camera System, position coordinates for each marker were averaged over the first 80 frames collected (sampling rate of 30 frames/second). Three upper torso markers and 4 ground T markers were registered (using code including the MATLAB function for calculating singular value decomposition, “svd”) from the two systems and matched labels were compared. The difference between the Single Depth Camera System datasets and the Vicon data were calculated in x, y, z , directions and absolute difference, R .

Dual Depth Camera System

We positioned the depth cameras sideways (to increase field of view in the vertical direction) at approximately 90 degrees from one another and 45 degrees off the frontal plane to try and minimize interference while still gathering as much marker data as possible, Figure 7.2. Left and Right depth cameras were triggered by the same experimenter. A custom MATLAB script was used to process the data with the old method and new method detailed in Chapter 5. In the Vicon

system, position coordinates for each marker were averaged over the 250 frames of Vicon data, captured at 250Hz. In the Dual Depth Camera System, position coordinates for each marker were averaged over the first 80 frames collected (sampling rate of 30 frames/second). The left camera coordinates were registered to the right camera coordinates based on the 4 ground reference “T” and the 3 upper torso markers. The average position between the right and left data was calculated. All three datasets, i) Right Depth Camera, ii) Left Depth Camera, and iii) Average Depth Camera, were rotated and translated to a coordinate system aligned with the average position of the ground reference “T” markers. Labeled Vicon data was imported into MATLAB, averaged, and registered to the average position of the 4 ground reference “T” and the 3 upper torso markers. The difference between the 3 Dual Depth Camera System datasets (i-iii) and the Vicon data were calculated in x, y, z , directions and absolute difference, R .

General

Each marker of each trial in each of the one Single Depth Camera System and three Dual Depth Camera System data sets was examined. Markers with an absolute difference of 4 cm or less met our valid threshold. This value corresponds to the random error in depth measurement at the 5 m maximum range of the sensor [62]. Mean difference and standard deviation (SD) compared to the Vicon system were reported for markers with >70% of valid trials.

A Combined Depth Camera data set was also compiled from the Dual Depth Camera data sets. For each individual “T” and “P” marker, priority was given to Average Depth Camera data. If that data did not present for a marker, the Combined Depth Camera data set was augmented with either the Left Depth Camera or Right Depth Camera data, if available.

Unpaired t-tests were performed to evaluate if differences exist between “T” and “P” marker differences in all valid data sets. These tests were also performed

to evaluate “T” and “P” marker differences between i) Right Depth Camera, ii) Left Depth Camera, and iii) Average Depth Camera (with a Holm-Sidak correction to set the family level of significance at $\alpha_T = 0.05$ ¹) as well as between iv) Combined Depth Camera and v) Single Depth Camera data sets ($\alpha = 0.05$).

This data processing procedure was performed before and after the implementation of system improvements of point cloud cropping, point cloud hole filling, and tracking detailed in Chapter 5. Unpaired t-tests were performed between the old and new processing for “T” and “P” markers in all valid and data sets. For all statistical evaluations, the overall level of significance was set at $\alpha = 0.05$. Finally, the percentage change in number of markers detected of each type in each data set, from old processing to new processing, was calculated.

7.3 Results

For the Dual Depth Camera System: the ground reference “T” had 23 trials calculated for 4 markers in each of the 3 i) Right Depth Camera, ii) Left Depth Camera, and iii) Average Depth Camera datasets; and the static participant had 13 trials calculated for 43 markers in each of the 3 datasets. For all three datasets, markers meeting our valid threshold criteria were identified. Mean differences and SD are reported (old processing: Table 7.1; new processing: Table 7.3).

For the Single Depth Camera System: the ground reference “T” had 12 trials calculated for 4 markers; and the static participant had 8 trials calculated for 43 markers. Markers meeting our valid threshold criteria were identified. For each valid marker, the mean difference and SD was reported (old processing: Table 7.2; new processing: Table 7.4).

¹For the Holm-Sidak correction, p -values of the multiple comparisons are determined and ordered from smallest to largest. Then, each p -value is compared to the corresponding p_{crit} obtained from $p_{crit_j} = 1 - (1 - \alpha_T)^{1/(k-j+1)}$. Where k is the total number of comparisons and j is the comparison number. For our purposes $k = 3$ and $\alpha_T = 0.05$ thus, $p_{crit_1} = 0.0170$, $p_{crit_2} = 0.0253$, and $p_{crit_3} = 0.0500$.[\[41\]](#)

Table 7.1: *Old processing datasets of the mean difference and standard deviation, between markers detected with Vicon and Depth Camera (i) Right; (ii) Left; (iii) Average. Note: “T” denotes reference; “P” denotes Participant.*

Depth Camera		Right		Left		Average	
	# Marker Name	Valid Trials (%)	Difference (cm)	Valid Trials (%)	Difference (cm)	Valid Trials (%)	Difference (cm)
T	1T 'AR'	100.0	1.26 (0.50)	100.0	1.72 (0.55)	100.0	0.90 (0.29)
	2T 'CTop'	100.0	1.53 (0.68)	100.0	1.08 (0.31)	100.0	0.87 (0.41)
	3T 'AL'	87.0	2.49 (0.57)	100.0	1.18 (0.64)	100.0	1.58 (0.44)
	4T 'CBot'	100.0	1.67 (0.40)	100.0	1.20 (0.37)	100.0	1.10 (0.28)
P	1 'R_Acro'	92.3	2.19 (0.39)	92.3	1.32 (0.60)	92.3	1.63 (0.26)
	2 'SCJ'	100.0	2.80 (0.63)	100.0	2.53 (0.90)	100.0	2.18 (0.52)
	3 'L_Acro'	100.0	1.71 (0.68)	100.0	1.49 (0.79)	100.0	1.37 (0.42)
	4 'R_IC'						
	5 'L_IC'			84.6	1.36 (0.65)		
	6 'R_GTro'						
	7 'L_GTro'			76.9	0.99 (0.51)		
	8 'R_ASIS'						
	9 'L_ASIS'			84.6	2.53 (0.92)	76.9	2.32 (0.59)
	10 'R_Mid_Thigh'						
	11 'L_Mid_Thigh'			76.9	2.77 (0.52)	76.9	1.91 (0.61)
	12 'R_PS_T'						
	13 'R_PL_T'						
	14 'L_PS_T'						
	15 'L_PL_T'			76.9	1.98 (0.80)		
	16 'R_AS_T'						
	17 'R_AI_T'						
	18 'L_AS_T'			84.6	2.21 (0.95)	92.3	1.93 (0.62)
	19 'L_AI_T'			92.3	2.73 (0.68)	84.6	1.73 (0.79)
	20 'R_Lat_Epi'						
	21 'L_Lat_Epi'			100.0	1.26 (0.88)		
	22 'R_Med_Epi'	100.0	1.89 (0.98)			100.0	1.61 (0.93)
	23 'L_Med_Epi'						
	24 'R_TibTu'						
	25 'L_TibTu'						
	26 'R_PS_S'						
	27 'R_PL_S'						
	28 'L_PS_S'						
	29 'L_PL_S'						
	30 'R_AS_S'						
	31 'R_AI_S'						
	32 'L_AS_S'	84.6	1.12 (0.82)	76.9	2.83 (1.16)	100.0	2.13 (0.95)
	33 'L_AI_S'			76.9	2.40 (0.90)		
	34 'R_Lat_Mal'						
	35 'L_Lat_Mal'			100.0	1.25 (0.71)		
	36 'R_Med_Mal'			100.0	1.97 (0.88)	84.6	1.95 (1.05)
	37 'L_Med_Mal'						
	38 'R_5th_Met'						
	39 'L_5th_Met'	92.3	2.40 (0.79)	100.0	1.65 (0.79)	100.0	1.17 (0.51)
	40 'R_Arch'	92.3	2.55 (0.70)	100.0	2.28 (0.82)	100.0	1.17 (0.51)
	41 'L_Arch'						
	42 'R_1st_Met'						
	43 'L_1st_Met'						

Table 7.2: *Old processing datasets of mean difference and standard deviation, between markers detected with Vicon and (i) Dual Combined Depth Camera; (ii) Single Depth Camera. Note: “T” denotes reference; “P” denotes Participant.*

Depth Camera		Dual – Combined			Single		
T	# Marker Name	Valid Trials (%)	Difference (cm)	Dataset	Valid Trials (%)	Difference (cm)	Dataset
T	1T 'AR'	100.0	0.90 (0.29)	Average	100.0	0.73 (0.29)	Center
	2T 'CTop'	100.0	0.87 (0.41)	Average	100.0	0.75 (0.46)	Center
	3T 'AL'	100.0	1.58 (0.44)	Average	100.0	0.52 (0.38)	Center
	4T 'CBot'	100.0	1.10 (0.28)	Average	100.0	0.55 (0.28)	Center
P	1 'R_Acro'	92.3	1.63 (0.26)	Average	100.0	1.21 (0.32)	Center
	2 'SCJ'	100.0	2.18 (0.52)	Average	100.0	2.10 (0.52)	Center
	3 'L_Acro'	100.0	1.37 (0.42)	Average	100.0	1.39 (0.58)	Center
	4 'R_IC'				75.0	2.48 (1.39)	Center
	5 'L_IC'	84.6	1.36 (0.65)	Left			
	6 'R_GTro'						
	7 'L_GTro'	76.9	0.99 (0.51)	Left			
	8 'R_ASIS'				87.5	1.59 (0.48)	Center
	9 'L_ASIS'	76.9	2.32 (0.59)	Average			
	10 'R_Mid_Thigh'				87.5	1.96 (0.78)	Center
	11 'L_Mid_Thigh'	76.9	1.91 (0.61)	Average			
	12 'R_PS_T'						
	13 'R_PL_T'						
	14 'L_PS_T'						
	15 'L_PL_T'	76.9	1.98 (0.80)	Left			
	16 'R_AS_T'				100.0	1.63 (0.80)	Center
	17 'R_AI_T'				87.5	1.81 (0.93)	Center
	18 'L_AS_T'	92.3	1.93 (0.62)	Average			
	19 'L_AI_T'	84.6	1.73 (0.79)	Average			
	20 'R_Lat_Epi'						
	21 'L_Lat_Epi'	100.0	1.26 (0.88)	Left			
	22 'R_Med_Epi'	100.0	1.61 (0.93)	Average			
	23 'L_Med_Epi'				71.4	2.33 (1.30)	Center
	24 'R_TibTu'						
	25 'L_TibTu'						
	26 'R_PS_S'						
	27 'R_PL_S'						
	28 'L_PS_S'						
	29 'L_PL_S'						
	30 'R_AS_S'				87.5	1.85 (1.45)	Center
	31 'R_AI_S'						
	32 'L_AS_S'	100.0	2.13 (0.95)	Average			
	33 'L_AI_S'	76.9	2.40 (0.90)	Left			
	34 'R_Lat_Mal'						
	35 'L_Lat_Mal'	100.0	1.25 (0.71)	Left			
	36 'R_Med_Mal'	84.6	1.95 (1.05)	Average			
	37 'L_Med_Mal'				85.7	1.76 (0.81)	Center
	38 'R_5th_Met'				87.5	1.08 (0.89)	Center
	39 'L_5th_Met'	100.0	1.17 (0.51)	Average			
	40 'R_Arch'	100.0	1.17 (0.51)	Average			
	41 'L_Arch'						
	42 'R_1st_Met'						
	43 'L_1st_Met'				100.0	1.34 (1.07)	Center

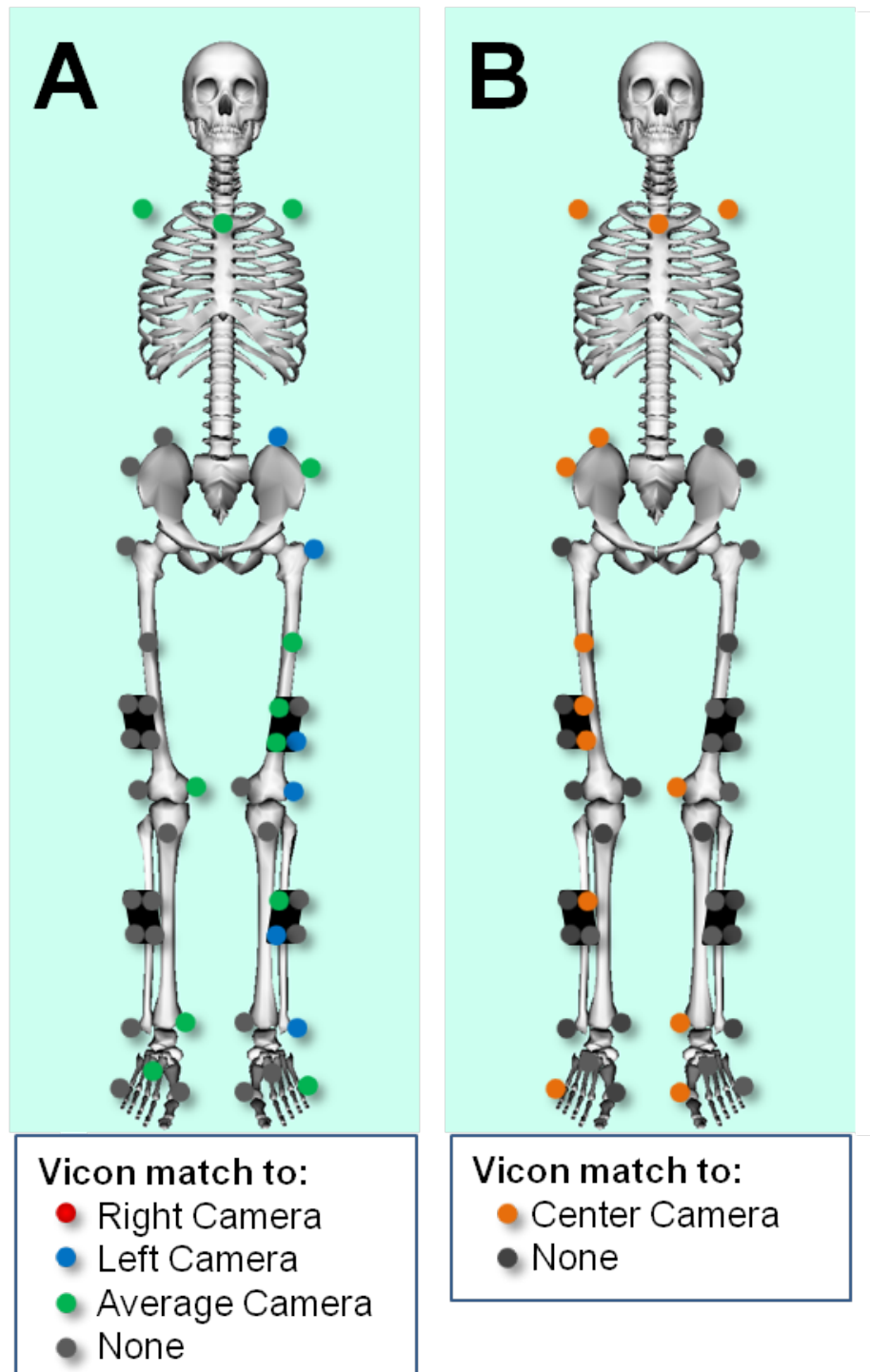


Figure 7.3: *Old processing marker sets for (A) Combined Dual Depth Camera; (B) Single Depth Camera. Image composed using OpenSim [31].*

Table 7.3: *New processing datasets of the mean difference and standard deviation, between markers detected with Vicon and Depth Camera (i) Right; (ii) Left; (iii) Average. Note: “T” denotes reference; “P” denotes Participant.*

Depth Camera		Right		Left		Average	
T	# Marker Name	Valid Trials (%)	Difference (cm)	Valid Trials (%)	Difference (cm)	Valid Trials (%)	Difference (cm)
T	1T 'AR'	100.0	1.35 (0.71)	100.0	1.59 (0.62)	100.0	0.85 (0.39)
	2T 'CTop'	100.0	1.55 (0.80)	100.0	0.96 (0.40)	100.0	0.84 (0.43)
	3T 'AL'	87.0	2.25 (0.65)	100.0	1.00 (0.72)	100.0	1.34 (0.41)
	4T 'CBot'	100.0	1.35 (0.47)	100.0	1.06 (0.29)	100.0	0.78 (0.14)
P	1 'R_Acro'	92.3	2.11 (0.41)	92.3	1.32 (0.62)	92.3	1.58 (0.28)
	2 'SCJ'	100.0	2.69 (0.61)	100.0	2.45 (0.77)	100.0	2.06 (0.50)
	3 'L_Acro'	100.0	1.58 (0.62)	100.0	1.31 (0.72)	100.0	1.19 (0.40)
	4 'R_IC'						
	5 'L_IC'			84.6	1.41 (0.68)		
	6 'R_GTro'						
	7 'L_GTro'			76.9	1.07 (0.52)		
	8 'R_ASIS'						
	9 'L_ASIS'			84.6	2.60 (0.84)	92.3	2.60 (0.74)
	10 'R_Mid_Thigh'			84.6	3.08 (0.56)		
	11 'L_Mid_Thigh'	100.0	2.07 (1.17)	76.9	2.90 (0.51)	100.0	2.36 (0.87)
	12 'R_PS_T'						
	13 'R_PL_T'						
	14 'L_PS_T'						
	15 'L_PL_T'			84.6	2.19 (1.06)		
	16 'R_AS_T'						
	17 'R_AI_T'						
	18 'L_AS_T'			92.3	2.32 (0.92)	100.0	2.00 (0.77)
	19 'L_AI_T'			92.3	2.81 (0.70)	100.0	1.95 (0.73)
	20 'R_Lat_Epi'						
	21 'L_Lat_Epi'			100.0	1.08 (0.57)		
	22 'R_Med_Epi'	84.6	1.98 (0.77)			100.0	1.51 (0.80)
	23 'L_Med_Epi'						
	24 'R_TibTu'						
	25 'L_TibTu'						
	26 'R_PS_S'						
	27 'R_PL_S'						
	28 'L_PS_S'			76.9	2.17 (0.91)		
	29 'L_PL_S'						
	30 'R_AS_S'						
	31 'R_AI_S'						
	32 'L_AS_S'	84.6	0.99 (0.87)	100.0	2.77 (1.15)	100.0	1.76 (0.87)
	33 'L_AI_S'	76.9	1.07 (0.37)	92.3	2.10 (1.04)	100.0	1.50 (0.72)
	34 'R_Lat_Mal'						
	35 'L_Lat_Mal'			100.0	1.03 (0.59)		
	36 'R_Med_Mal'			100.0	1.52 (1.02)	92.3	1.94 (0.85)
	37 'L_Med_Mal'						
	38 'R_5th_Met'						
	39 'L_5th_Met'			100.0	1.39 (0.38)	100.0	2.15 (0.58)
	40 'R_Arch'	84.6	2.68 (0.56)	92.3	2.27 (1.18)	100.0	1.85 (0.73)
	41 'L_Arch'	100.0	2.45 (0.93)	84.6	2.07 (1.14)	100.0	1.96 (0.94)
	42 'R_1st_Met'			100.0	1.94 (0.54)	100.0	1.32 (0.61)
	43 'L_1st_Met'			84.6	2.55 (1.05)	100.0	2.77 (0.63)

Table 7.4: *New processing datasets of mean difference and standard deviation, between markers detected with Vicon and (i) Dual Combined Depth Camera; (ii) Single Depth Camera. Note: “T” denotes reference; “P” denotes Participant.*

Depth Camera		Dual – Combined			Single		
	# Marker Name	Valid Trials	Difference	Dataset	Valid Trials	Difference	Dataset
		(%)	(cm)		(%)	(cm)	
T	1T 'AR'	100.0	0.85 (0.39)	Average	100.0	0.64 (0.30)	Center
	2T 'CTop'	100.0	0.84 (0.43)	Average	100.0	0.74 (0.46)	Center
	3T 'AL'	100.0	1.34 (0.41)	Average	100.0	0.51 (0.40)	Center
	4T 'CBot'	100.0	0.78 (0.14)	Average	100.0	0.46 (0.30)	Center
P	1 'R_Acro'	92.3	1.58 (0.28)	Average	87.5	1.23 (0.34)	Center
	2 'SCJ'	100.0	2.06 (0.50)	Average	100.0	2.02 (0.50)	Center
	3 'L_Acro'	100.0	1.19 (0.40)	Average	100.0	1.38 (0.52)	Center
	4 'R_IC'				87.5	2.54 (1.40)	Center
	5 'L_IC'	84.6	1.41 (0.68)	Left	75.0	2.89 (0.81)	Center
	6 'R_GTro'						
	7 'L_GTro'	76.9	1.07 (0.52)	Left	100.0	2.27 (0.59)	Center
	8 'R_ASIS'				100.0	1.91 (0.90)	Center
	9 'L_ASIS'	92.3	2.60 (0.74)	Average			
	10 'R_Mid_Thigh'	84.6	3.08 (0.56)	Left	87.5	1.86 (0.76)	Center
	11 'L_Mid_Thigh'	100.0	2.36 (0.87)	Average			
	12 'R_PS_T'						
	13 'R_PL_T'						
	14 'L_PS_T'						
	15 'L_PL_T'	84.6	2.19 (1.06)	Left			
	16 'R_AS_T'				100.0	1.54 (0.85)	Center
	17 'R_AI_T'				100.0	1.89 (0.92)	Center
	18 'L_AS_T'	100.0	2.00 (0.77)	Average	75.0	2.50 (0.26)	Center
	19 'L_AI_T'	100.0	1.95 (0.73)	Average	75.0	2.53 (0.79)	Center
	20 'R_Lat_Epi'						
	21 'L_Lat_Epi'	100.0	1.08 (0.57)	Left	87.5	2.38 (0.81)	Center
	22 'R_Med_Epi'	100.0	1.51 (0.80)	Average	71.4	2.90 (0.76)	Center
	23 'L_Med_Epi'				85.7	2.60 (1.32)	Center
	24 'R_TibTu'						
	25 'L_TibTu'						
	26 'R_PS_S'						
	27 'R_PL_S'						
	28 'L_PS_S'	76.9	2.17 (0.91)	Left			
	29 'L_PL_S'						
	30 'R_AS_S'				87.5	1.50 (1.00)	Center
	31 'R_AI_S'				87.5	2.32 (0.74)	Center
	32 'L_AS_S'	100.0	1.76 (1.76)	Average	75.0	2.27 (0.48)	Center
	33 'L_AI_S'	100.0	1.50 (0.72)	Average	87.5	2.89 (0.67)	Center
	34 'R_Lat_Mal'						
	35 'L_Lat_Mal'	100.0	1.03 (0.59)	Left			
	36 'R_Med_Mal'	92.3	1.94 (0.85)	Average	71.4	2.01 (1.01)	Center
	37 'L_Med_Mal'				85.7	2.05 (0.92)	Center
	38 'R_5th_Met'				87.5	1.48 (0.90)	Center
	39 'L_5th_Met'	100.0	2.15 (0.58)	Average	100.0	2.44 (0.45)	Center
	40 'R_Arch'	100.0	1.85 (0.73)	Average	71.4	2.49 (0.60)	Center
	41 'L_Arch'	100.0	1.96 (0.94)	Average	100.0	1.35 (0.85)	Center
	42 'R_1st_Met'	100.0	1.32 (0.61)	Average	87.5	1.82 (1.04)	Center
	43 'L_1st_Met'	100.0	2.77 (0.63)	Average	100.0	1.68 (0.95)	Center

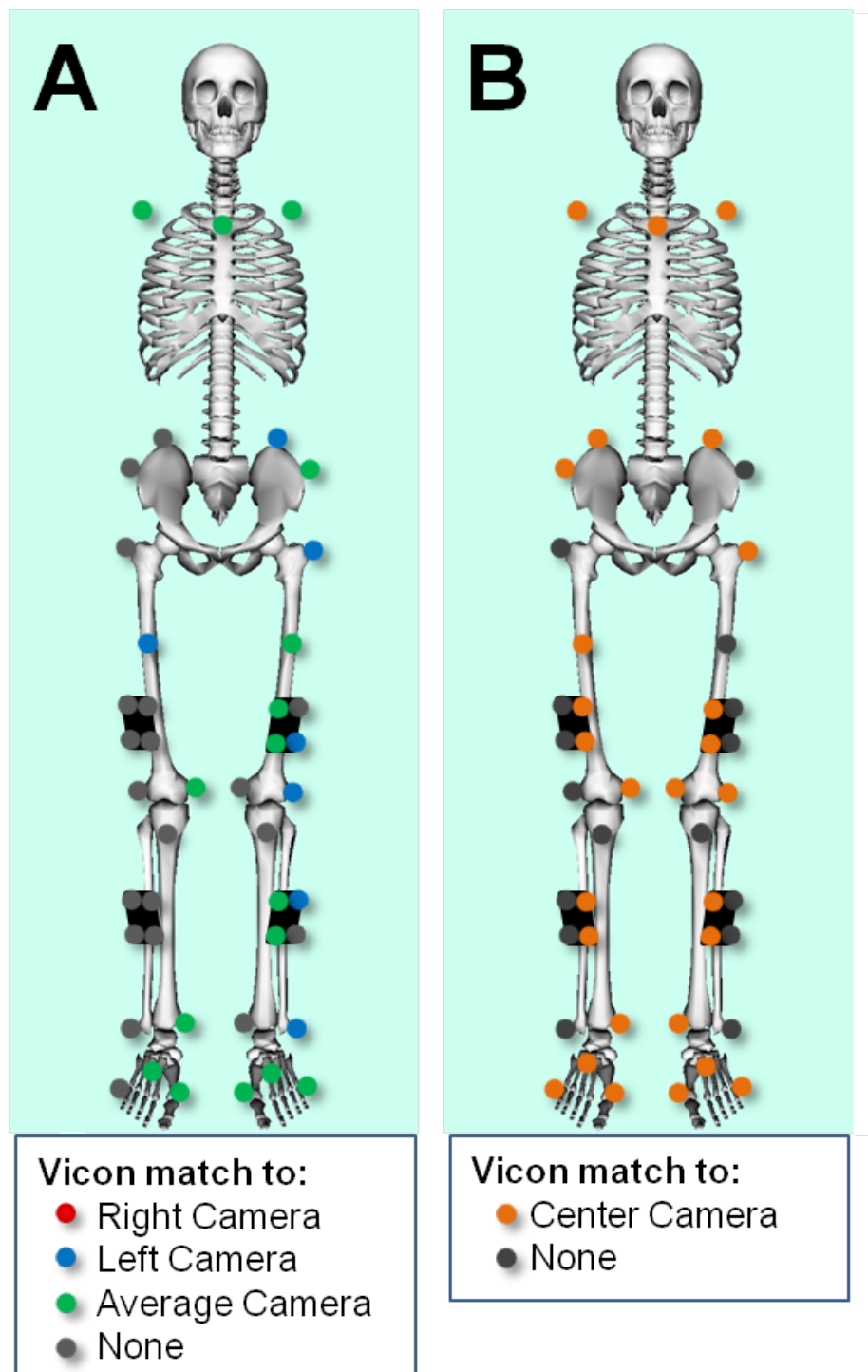


Figure 7.4: *New processing marker sets for (A) Combined Dual Depth Camera; (B) Single Depth Camera. Image composed using OpenSim [31].*

The valid individual markers values from the Dual Combined Depth Camera System are compiled in Tables 7.2 and 7.4 for ease of comparison to the valid Single Camera data. An illustration of identified markers from the old system are presented in Figure 7.3 and from the new system in Figure 7.4.

Only a few markers in either the Left or Right Depth Camera data sets had a lower mean differences to Vicon and a significant difference (with a Holm-Sidak correction to set the family level of significance at $\alpha_T = 0.05$) to the Average Depth Camera data set and were not used in the Combined Depth Camera data set. For old processing this marker was Marker 32 (Left anterior-superior shank) in the Right Depth Camera data set ($p = 0.0114$). For new processing this marker was Marker 39 (Left 5th Metatarsal) in the Left Depth Camera data set ($p = 0.0006$).

Mean and standard deviation between each data set and each marker type compared to Vicon are detailed below and presented in Table 7.5. The statistical p -values between marker types for each data set are also detailed in Table 7.5. In addition, p -values from the unpaired t-test comparing “T” and “P” marker differences between old and new processing are presented in Table 7.5. There was a statistically significant difference ($p < 0.05$) for the Average Depth Camera and Combined Depth Camera datasets for the “T” markers. There was also a statistically significant difference ($p < 0.05$) for the Combined Depth Camera and Single Depth Camera datasets for the “P” markers. Percentage change in number of markers detected of each type in each data set, from old processing to new processing, is also listed in Table 7.5.

For comparisons between the a) Left, Right, and Average Depth Camera data sets and b) Combined Depth Camera data set and Single Depth Camera data sets for old and new processing, “T” and “P” marker types, p -values are reported in Table, 7.5. There was a significant difference (a) $p < 0.016$) for “T” marker types for all comparisons. For old processing “P” marker types were significantly different between Average Depth Camera and Right Depth Camera ($p = 0.0008$)

and Left Depth Camera ($p = 0.0243$) data sets. For new processing “P” marker types were significantly different ($p = 0.0060$) between Combined Depth Camera and Single Depth Camera data sets.

Unique marker counts for each type of marker (“T” and “P”) for old and new processing are also presented in Table 7.5.

Old Processing - Dual

The Right Depth Camera Data provided a valid matches to Vicon for 4 “T” markers and 7 “P” markers, the Left Depth Camera Data provided valid matches to Vicon for 4 “T” markers and 17 “P” markers, and the Average Depth Camera Data provided valid matches for 4 “T” markers 12 “P” markers. When compiled into the Combined Depth Camera data set, there were 4 valid “T” markers and 18 valid “P” markers. We also calculated the mean and SD of the difference in position of all valid markers markers between the Vicon system and those observed with i) Right Depth Camera, ii) Left Depth Camera, iii) Average Depth Camera , and iv) Combined Depth Camera datasets, Table 7.5. There was a statistically significant difference ($p < 0.01$) between the “T” data and “P” data in each of the four data valid sets.

Old Processing - Single

The Single Depth Camera Data provided a valid match to Vicon for 4 “T” markers and 13 “P” markers. We also calculated the mean and SD of the difference in position of all valid markers between the Vicon system and those observed with the Single Depth Camera system, Table 7.5. There was a statistically significant difference ($p < 0.0001$) between the “T” data and “P” data for the old processing Single Depth Camera data set.

New Processing - Dual

The Right Depth Camera Data provided valid matches to Vicon for 4 “T” markers and 9 “P” markers, the Left Depth Camera Data provided valid matches to Vicon for 4 “T” markers and 22 “P” markers, and the Average Depth Camera Data provided valid matches for 4 “T” markers and 16 valid “P” markers. When compiled into the Combined Depth Camera data set, there were 4 valid “T” markers and 23 valid “P” markers. We also calculated the mean and SD of the difference in position of all valid markers between the Vicon system and those observed with i) Right Depth Camera, ii) Left Depth Camera, iii) Average Depth Camera, and iv) Combined Depth Camera datasets, Table 7.5. There was a statistically significant difference ($p < 0.01$) between the “T” data and “P” data in each of the four data valid sets.

New Processing - Single

The Single Depth Camera Data provided a valid match to Vicon for 4 “T” markers and 27 “P” markers. We also calculated the mean and SD of the difference in position of all valid markers between the Vicon system and those observed with the Single Depth Camera system, Table 7.5. There was a statistically significant difference ($p < 0.0001$) between the “T” data and “P” data for the new processing Single Depth Camera data set.

7.4 Discussion

We were able to determine a Combined Dual Depth Camera marker set by prioritizing the Average Depth Camera data and supplementing it with either the Left or the Right Depth Camera data. This hierarchy seems justified with only one marker in each of the old processing and the new processing procedures showing improved detection by either the Left or Right Depth Camera over the Average

Table 7.5: Mean difference, with standard deviation in parentheses, between valid marker data sets detected with Vicon and (i) Right Depth Camera; (ii) Left Depth Camera; (iii) Average Depth Camera; (iv) Combined Dual Depth Camera and (v) Single Depth Camera. Note: “T” denotes ground reference “T”; “P” denotes Participant; n is the number of markers in each evaluation; p-value is the result of the unpaired t-test statistical analysis.

Old Processing

Depth Camera	Right	Left	Average	Combined	Single
	Valid Difference (cm) n	Valid Difference (cm) n	Valid Difference (cm) n	Valid Difference (cm) n	Valid Difference (cm) n
T	1.71(0.70) 89	1.29(0.54) 92	1.11(0.46) 92	1.11(0.46) 92	0.64(0.36) 48
P	2.11(0.88) 86	1.96(0.97) 198	1.74(0.76) 144	1.67(0.80) 211	1.70(0.93) 86
p-value	0.0010	<0.0001	<0.0001	<0.0001	<0.0001
	Right to Left p-value	Right to Average p-value	Right to Combined p-value	Left to Average p-value	Single to Combined p-value
	0.2778	<0.0001	<0.0001	0.0159	<0.0001
		0.0008		0.0243	0.7802

New Processing

Depth Camera	Right	Left	Average	Combined	Single
	Valid Difference (cm) n	Valid Difference (cm) n	Valid Difference (cm) n	Valid Difference (cm) n	Valid Difference (cm) n
T	1.60(0.75) 89	1.15(0.59) 92	0.95(0.42) 92	0.95(0.42) 92	0.59(0.38) 48
P	1.99(0.93) 107	2.00(1.02) 260	1.90(0.81) 205	1.84(0.87) 284	2.07(0.90) 185
p-value	0.0017	<0.0001	<0.0001	<0.0001	<0.0001
	Right to Left p-value	Right to Average p-value	Right to Combined p-value	Left to Average p-value	Single to Combined p-value
	0.9303	<0.0001	0.3770	0.0088	<0.0001
				0.2519	0.0060

Old Compared with New Processing

Depth Camera	Right	Left	Average	Combined	Single
	Valid Change p-value n(%)	Valid Change p-value n(%)	Valid Change p-value n(%)	Valid Change p-value n(%)	Valid Change p-value n(%)
T	0.3132 0.0	0.0949 0.0	0.0147 0.0	0.0147 0.0	0.5097 0.0
P	0.3627 24.4	0.6713 31.3	0.0633 42.4	0.0266 34.6	0.0020 115.1
	Right Unique Markers Old New	Left Unique Markers Old New	Average Unique Markers Old New	Combined Unique Markers Old New	Single Unique Markers Old New
	4 4	4 4	4 4	4 4	4 4
	7 9	17 22	12 16	18 23	13 27

Depth Camera. In particular, when you consider we hope to use this technology to capture dynamic trials, in which the participant moves and thus the marker position changes, it does not seem prudent to assign a single marker to solely Left or Right Depth Camera detection when Average Depth Camera detection is available.

We did not expect all markers to be in view. The Right Depth Camera for both old and new processing detected a fewer number of unique “P” markers than the Left Depth Camera. This limited the total number of Average Depth Camera unique “P” marker detections. Khoshelham and Elberink [62] discussed an off center distortion of the IR image. Perhaps this distortion is the root cause of the discrepancy between Left and Right data sets. We also rotated both depth camera in the same direction. Perhaps maintaining the Left camera position and rotating the Right camera by 180 degrees will improve detection. In addition, the participant position in the testing volume, relative to the cameras, may have been a factor in the difference observed. Future work will include calibration to compensate for systematic IR distortion and investigation into camera orientation.

When looking at comparisons between the Left, Right, and Average Depth Camera data sets in both the old and new processing for “T” markers we saw significant differences. The differences between Left and Right could be expected based on the discrepancies discussed earlier with the Left and Right Depth Camera detection. The difference between Average Depth Camera and both the Left and Right Depth Camera could also be expected since in the data handling the Vicon data was registered to Average data set points, including the 4 “T” markers. For the “P” markers we only saw a significant difference between the two individual cameras of the dual system and Average Depth Camera data sets for old processing. This may be attributed to the benefit of more information and data registration process.

In looking at the comparison between the Combined Depth Camera data set

and the Single Depth Camera data sets for old and new processing, “T” marker types were significantly different. We suspect the Single Depth Camera data set had a smaller mean difference to the Vicon data because of the simple frontal plane orientation relative to the ground reference “T”. For the new processing “P” marker detection was also significantly different. We suspect the increased difference between the Single Depth Camera Data and Vicon may be attributed to the inclusion of a larger array of markers. In the Single Depth Camera data set we detected 27 unique valid markers compared to the 23 in the Combined Depth Camera data set. In both old and new processing the Combined Dual Depth Camera detected fewer unique markers when compared to the Single Depth Camera system. Again, we suspect that future work looking at IR distortion and camera orientation may address this discrepancy and improve detection with the Dual Depth Camera systems.

The significant difference between the “T” and “P” data (Table 7.5) for all data sets with old and new processing suggests several potential system differences that should be investigated further. The “T” markers were on a flat stationary surface while the “P” markers were on a participant at different orientations relative to the cameras. The different backgrounds could influence the marker detection. Markers on the edge of surfaces could result in depth measurement error. Placement of the participant in the field of view, camera orientation, and the tracking algorithm could all affect marker detection. Even with all these potential sources of variation, both the “T” and “P” data from the Low-Cost Systems had a difference compared to the Vicon system on the order of error due to soft tissue artifact between 3D fluoroscopy and stereophotogrammetry, which found up to 3.1 cm SD for the thigh and 2.1 cm SD for the shank [112]. However, care should be taken when interpreting prior studies where markers were only evaluated on flat surfaces when determining joint angles [104].

In comparing the old processing to new processing we saw a significant dif-

ference between the “T” markers detection in the Average Depth Camera data set and thus the Combined Depth Camera, since it was comprised on all Average data. All 4 markers were detected in both old and new processing, so the reduced mean difference between Average (and Combined) depth Camera data relative to Vicon is attributed to processing improvements.

In comparing the old processing to new processing we saw a significant difference between the “P” markers detection in the Combined Depth Camera and Single Depth Camera data sets. There was a 34.6% increase in overall number of markers validly detected, with an increase from 18 to 23 unique markers validly detected, for the Combined Depth Camera data set. There was a 115.1% increase in overall number of markers validly detected, with an increase from 13 to 27 unique markers validly detected, for the Single Depth Camera data set. So, we see a slight increase in the mean of the difference between low-cost and Vicon systems, this can be attributed to more unique markers meeting the valid criteria and being included into the comparison calculations, and a large increase in overall number of markers detected.

It should be noted that across all 5 Depth Camera data sets there was an increase in overall number of markers validly detected, with an increase in unique markers validly detected. This suggests that for all Depth Camera systems the new processing represents an improved method. Also, pending additional process improvements for the Dual Depth Camera System, the Single Depth Camera System can detect more unique valid markers making it a more desirable system. In addition, the Single Depth Camera system has the advantage of reduced data processing with half of the data files to process and markers to label when compared to the dual system.

An inexpensive depth camera, such as the Microsoft Kinect, can be used to obtain 3D marker position measurements that are comparable to the high-cost reference standard Vicon motion capture system. The processing improvements

employed improved the number of markers validly detected by the systems and the surface on which the markers are detected significantly impacted marker detection. Future work will include investigating sources of data discrepancy to continue the increase number of markers validly detected, and optimize the testing protocol and data handling to obtain a clinically relevant movement assessment system.

7.5 Significance

Low-cost motion capture systems will potentially bridge the gap to making accurate movement-screening assessment tools accessible to a larger population.

CHAPTER 8

Study Design: Test-Retest Reliability

8.1 Introduction

In Chapter 1 we discussed at length the necessity of a low-cost screening tool for quantitative clinical assessments. Other researchers have looked at low-cost depth cameras and either 1) used the built-in estimated pose (skeleton) to assess slow grand maneuvers [14] or limited kinematics [93, 113] which are insufficiently accurate to enable detailed biomechanical analyses, or 2) evaluated markers on flat surfaces [104] which we showed in Chapter 7 may yield different results than markers positioned on a study participant. To our knowledge no other research team has looked at these low-cost depth cameras as a viable tools for highly-quantitative clinical screening maneuvers.

With the improvements we have made, LCMAS-Single and LCMAS-2 are good candidates for continued evaluation. In order to assess the potential of either LCMAS as a clinical screening tool we need to examine how consistently they make measurements and how these measurements compare to the industry gold standard Vicon system. Then, to evaluate the viability as a screening tool, compare these measurements to the minimal clinically important differences (*MCID*) from the scientific literature Chapter 1.5).

According to Crossley [28], “The minimal clinically important difference quantifies the minimal difference that patients or practitioners consider clinically important and thus will indicate a relevant change in the patient’s symptoms.[2, 55]”

We will take our *MCIDs* to be the difference between mean values in the literature data and compare these to our smallest detectable difference (*SDD*) for each metric. Ultimately we hope to identify if any of the *SDDs* for kinematic and kinetic metrics detected with either LCMAS are small enough to reliably detect values necessary to screen for ACL injury risk and rehabilitation, determined by the *MCID* threshold levels set in by the scientific literature (Chapter 1.5), Figure 8.1.

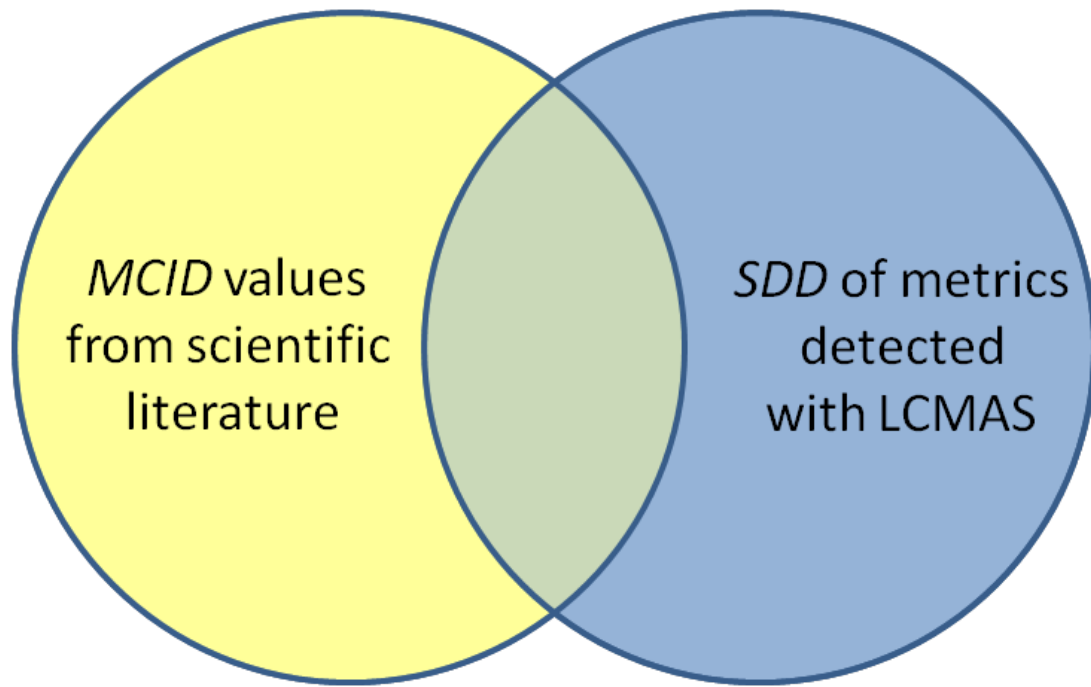


Figure 8.1: *Venn diagram of MCID values of metrics from the scientific literature and SDD of metrics evaluated by LCMAS.*

We hypothesize that one or more of our Low-Cost Movement Assessment Systems will have repeatable measures and *SDD* smaller than the *MCID* values from the scientific literature for some of the metrics (e.g. joint angles, forces, moments, center of mass position relative to base of support position) between at-risk and normal populations, enabling use of the system as a screening tool for ACL injury risk and rehabilitation.

8.2 Methods

In order to identify the test-retest reliability, we will examine intra-system repeatability between repetitions (within a day) and between days, as well as inter-system reliability, for each LCMAS and Vicon.

The study was approved by University of California, San Francisco, Committee on Human Research (IRB 12-10253). Volunteers, 3 male and 3 female, provided signed informed consent. At the time of testing, participants were free of lower extremity injury. One participant reported no history of lower extremity injuries. While three participants reported history of lower extremity injury on one side and two participants reported history of lower extremity injuries on both sides.

The Vicon (Oxford Metrics, UK), LCMAS-Single, and LCMAS-2 were set-up with a testing volume that mimicked a 10'x10' clinical examination room with four reference markers placed in a “T” configuration on the floor. The LCMAS-2 was centered in the frontal plane and the LCMAS-Single was positioned directly above, Figure 8.2. Data was simultaneously captured with the gold standard Vicon system and at both the LCMAS-Single and LCMAS-2. Each low-cost depth camera was within a 2-3 m range of the participant testing location and connected to a computer running a custom software to capture depth information. For the LCMAS-Single the software consisted of a custom MATLAB (MathWorks Natick, MA, USA) script and Open NI Viewer. For the LCMAS-2 the software was built using the Microsoft Kinect for Windows SDK.

Forty-eight retro-reflective markers were placed on each participant, by the same experimenter, in a configuration for detection by the Vicon system and the LCMAS-Single system, Table 2.1.

Static trials were captured, consisting of the testing volume with reference markers and the marked participants. Next, we removed the calibration markers for the collection of dynamic trials. We collected several sets of movement

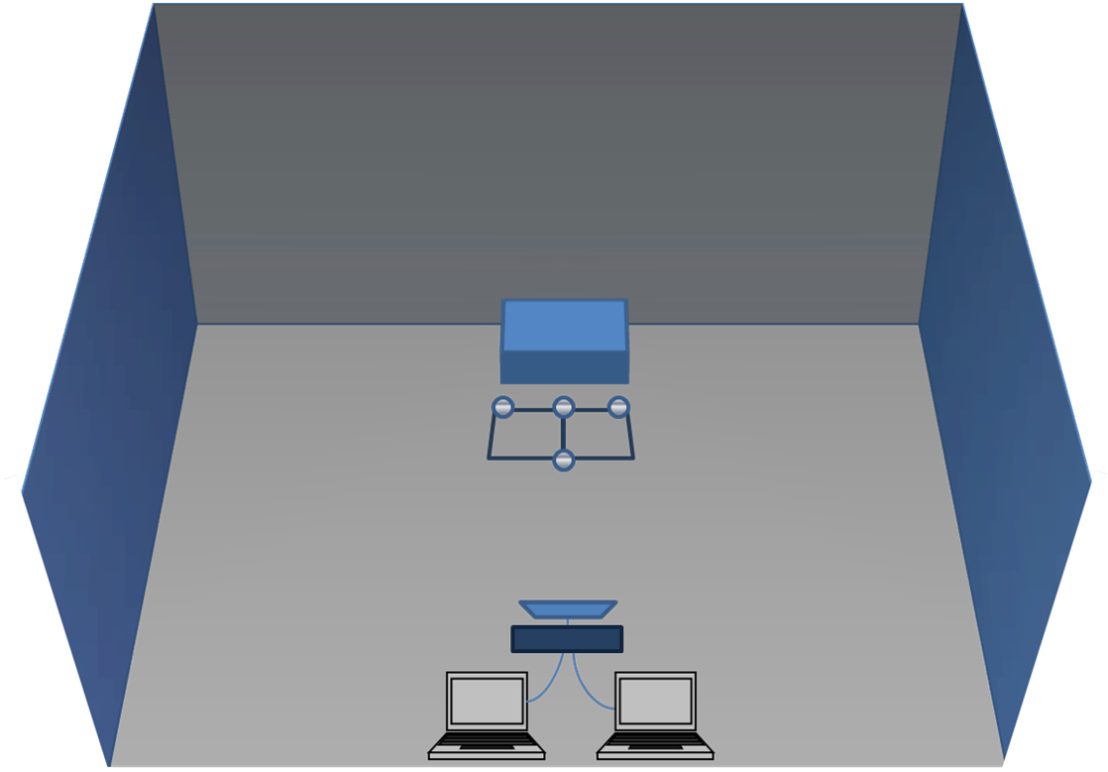


Figure 8.2: *Clinical Capture Environment comprised of both the LCMAS-Single (top) and LCMAS-2 (bottom).*

screening data for the study participants performing 3 repetitions per set of drop vertical jump (DVJ), single leg squats (SLSR, SLSL) and double leg squat (DLS). Adequate practice was allowed to decrease learning effects. This data consists of two days of data capture separated by one week, with multiple sets of repetitions captured per session. A schematic depicting the data sets used in this evaluation is shown in Figure 8.3.

Data handling for each system is detailed below. The metrics detected by each system are shown in Figure 8.4, with forces and moments reported in the proximal, distal, and joint coordinate system (JCS), totaling 73 metrics for Vicon and LCMAS-Single and 64 metrics (in black) for LCMAS-2.

		Motion Capture System			
Session	Set	LCMAS _{single}		LCMAS2	Vicon
Day 1	D	6DOF IK	X	Kinect Static Vicon Static	X
Day 2	F	6DOF IK	X	Kinect Static Vicon Static	X

Figure 8.3: *Study design.*

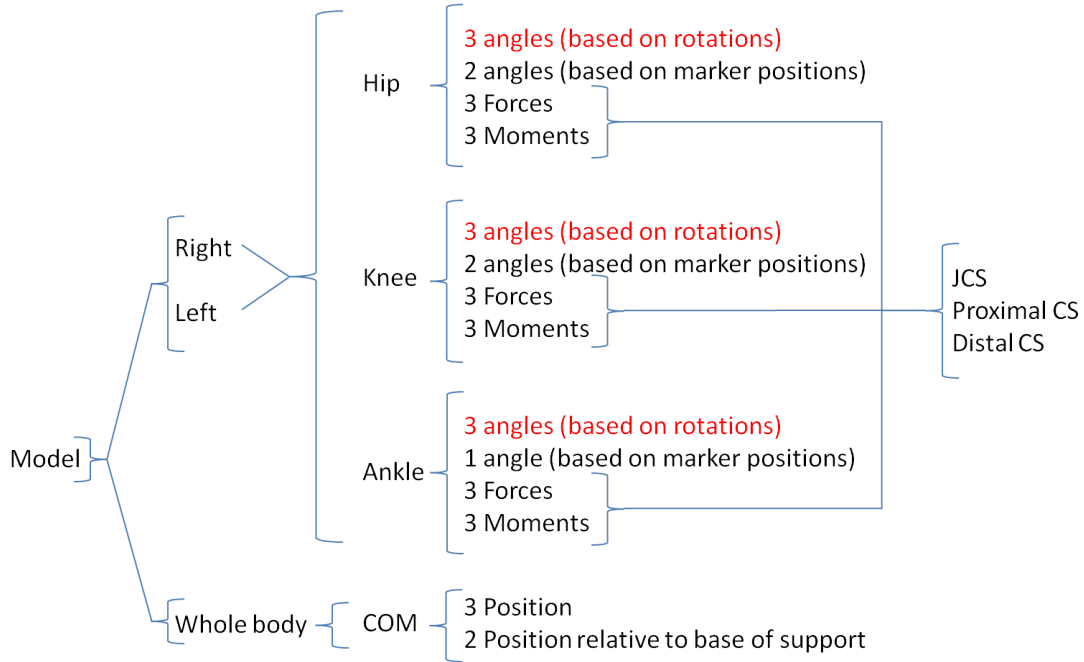


Figure 8.4: *Metrics evaluated in each system for comparison. Note: Metrics in black are the metrics attempted to be detected in LCMAS-2, metrics in red (segment rotation based joint angles) were not attempted.*

8.2.1 Data Processing

Vicon

Specifics on the gold standard motion capture system and kinematic and kinetic data processing are detailed in Chapter 2. Complete, multi-repetition, unfiltered kinematic and kinetic motion capture data files were exported from Vi-

sual3D and imported into MATLAB for post-processing. To facilitate comparison to both LCMAS-Single and LCMAS-2, unfiltered components of each metric of Vicon data was partitioned into the repetitions identified by force plate signals that were tagged events in Visual3D. Then the first and last data point of each repetition for each component of each metric was identified. Next the data was filtered according to analysis of residuals detailed in Chapter 2 at 12 Hz. Then a shape preserving polynomial filled any gaps in data between the identified points at the beginning and the end of the repetitions.

In MATLAB we also calculated an additional metric, center of mass (COM) relative to base of support (BOS), often used to evaluate balance. COM position is calculated in Visual3D and included in the previously mentioned exported data. BOS position is calculated by determining the magnitude of the force vector detected by each force plate ($||\mathbf{F}_R||$ and $||\mathbf{F}_L||$) and using that magnitude to weight the center of pressure (COP) location from each force plate (COP_R and COP_L). The weighting determines the location between the two COPs.

$$||\mathbf{F}_T|| = ||\mathbf{F}_R|| + ||\mathbf{F}_L|| \quad (8.1)$$

$$BOS = \frac{\mathbf{F}_R}{||\mathbf{F}_T||} COP_R + \frac{\mathbf{F}_L}{||\mathbf{F}_T||} COP_L \quad (8.2)$$

Then our metric of interest COM relative to BOS is a simple subtraction.

$$COM_{relBOS} = COM - BOS \quad (8.3)$$

Since the COP occurs on the ground plane making the vertical component constant, we are only concerned with two components (medial/lateral and anterior/posterior) of this COM relative to BOS metric.

To establish validation cut-points for the LCMAS data, the Vicon data was analyzed. In the Vicon data, for each component of each metric over all subjects

a) the maximum and minimum values were determined and b) the peak absolute value of slope was determined for a 1% change in stance.

We also analyzed the Vicon data to establish peak metric ranges for the LCMAS data. The percentage of stance when each minimum and maximum peak metrics occurred was noted for each participant in the Vicon data. The extreme values of the range of occurrence was used to establish the ranges for the LCMAS data.

For each evaluated signal percentage of stance curves and five different peak metrics, i) minimum value, ii) maximum value, iii) range of motion (ROM) of values, iv) value at initial contact (or first valid data point), and v) value at maximum knee flexion (MKF), were used in system comparisons outlined in the next section.

Dynamic data was processed for DLS, SLS, and DVJ maneuvers.

LCMAS - Single

Data was processed with system improvements detailed in Chapter 5. The data processing was intensive at this early stage in system development, thus only DVJ data was analyzed for this study. DVJ was chosen from the three different maneuvers as it was deemed the most demanding on the participants and data capture, due to the higher loading and speed of movement of the activity.

Initially, visual inspection of the raw depth map data frames was used to identify the start (feet first contact force plates) and end (feet take-off from force plates) of repetition. Then the depth camera data was processed from three frames before initial contact to three frames after take-off to ensure capture of the entire maneuver.

To proceed with a thorough analysis the LCMAS-Single data needed to be spatially and temporally synchronized to the Vicon data. In order to spatially

synchronize the LCMAS-Single data to Vicon, LCMAS-Single marker position data was rotated and translated into the Vicon lab coordinate system based on the ground reference markers and the three upper torso markers from the static reference posture capture, as previously discussed in Chapter 7.

To temporally synchronize the data, we first used the CPU time stamp information to properly space the data. The LCMAS-Single has an inconsistent frame sampling rate, thus we cannot assume even time steps between frames. Then each repetition was roughly temporally aligned based on 5th metatarsal marker velocity and force plate signal. Next, LCMAS-Single marker position data was imported into Visual3D, Figure 8.5, based on this rough temporal alignment. Then we performed a manual temporal fine tuning, centering the repetition over the beginning and the end of the time series to align with initiation and termination of force plate signals. This fine tuning involved an iterative process where the time adjustment necessary was noted and applied to the LCMAS-Single data in MATLAB and then the LCMAS-Single data was re-imported into Visual3D for confirmation of proper alignment.

Once marker data was spatially and temporally synchronized to Vicon data, four different processing procedures were separately applied to the LCMAS-Single data in Visual3D. The first procedure used a 6DOF model and the Vicon static data for the reference posture, the second procedure used an inverse kinematic (IK) model, in which all joints had 3DOF of rotation and the pelvis had 6DOF, and the Vicon static data for the reference posture. The next two processing procedures differed from the first two in that they utilized the Kinect static data for reference posture while using the same 6DOF and IK models for kinematic and kinetic calculations. The Vicon and 4 LCMAS-Single processing procedures used the same force plate data which consisted of force vectors, free moments, and center of pressure. Once kinematic and kinetic calculations were completed in Visual3D, all metrics were exported to MATLAB for post-processing. In MATLAB we also

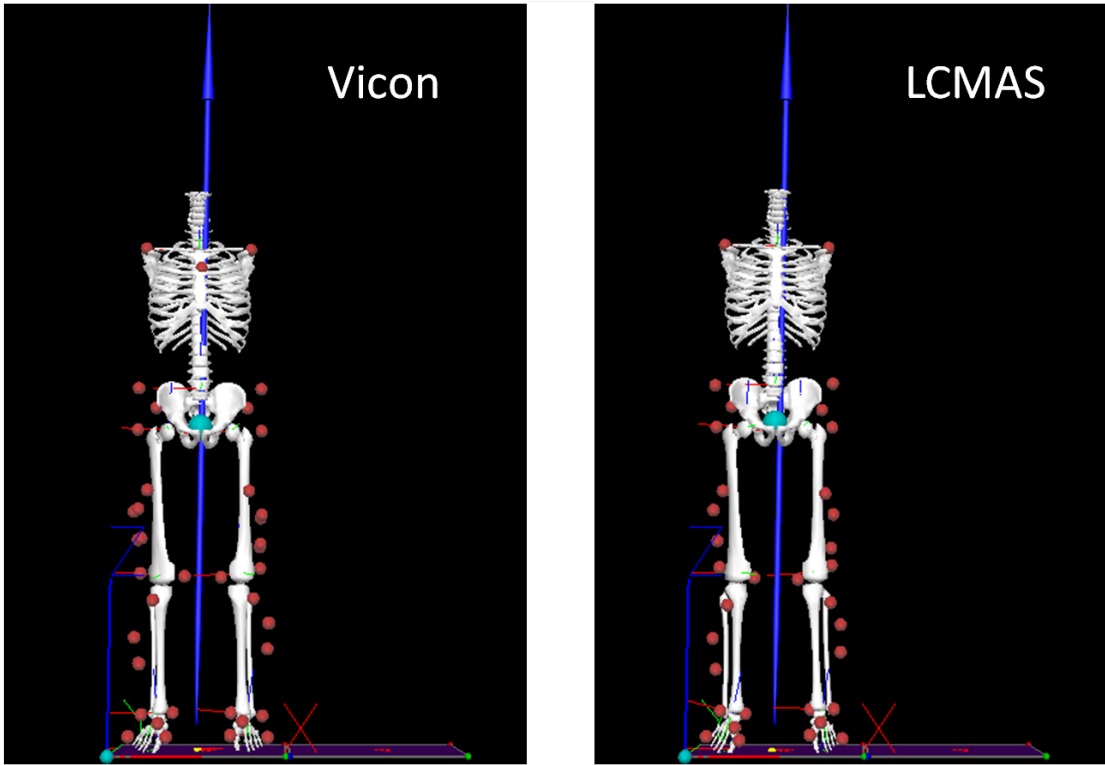


Figure 8.5: *Example of marker, model, and force vector visualization in Visual3D for Vicon (left) and LCMAS-Single.*

calculated an the additional metric, center of mass (COM) relative to base of support (BOS) described in the prior *Vicon* section.

The Vicon event tags for the beginning and end of repetition were used to partition the data into repetitions. Next, the data was filtered according to analysis of residuals detailed in Chapter 2 at 2.5 Hz. Then a polynomial was fit to the data: 3rd order for angle and position components; 7th order for force and moment components.

Next, each component of each metric of LCMAS-Single data was evaluated for validity. We set our validity criteria at a minimum of 50% of raw data points gathered in a repetition. If the data meets this first criteria, then the processed signal is compared to the corresponding Vicon signal cut-points. For this com-

parison first we evaluate the minimum and maximum signals. If at least one of these values are more than 50% above or below the range established by the Vicon data, it is deemed invalid, Figure 8.6. Then we evaluate the absolute value of metric slope between 1% of stance intervals. If the data is more than twice as steep as the slope established by the Vicon data at any increment, the repetition is considered invalid. If the LCMAS-Single signal meets all of these criteria, it is considered valid and progressed on to system comparisons.

Finally to extract peak metrics for i) minimum value, ii) maximum value, iii) range of motion (ROM) of values, iv) value at initial contact (or first valid data point), and v) value at maximum knee flexion (MKF), we looked to the ranges of percent stance set by the Vicon data. We doubled the range of minimum and maximum percent of stance seen in the Vicon data, limited by the extremes of 0% and 100% stance, Figure 8.6.

The five peak metrics and percentage of stance curves were used in system comparisons outlined in the next section.

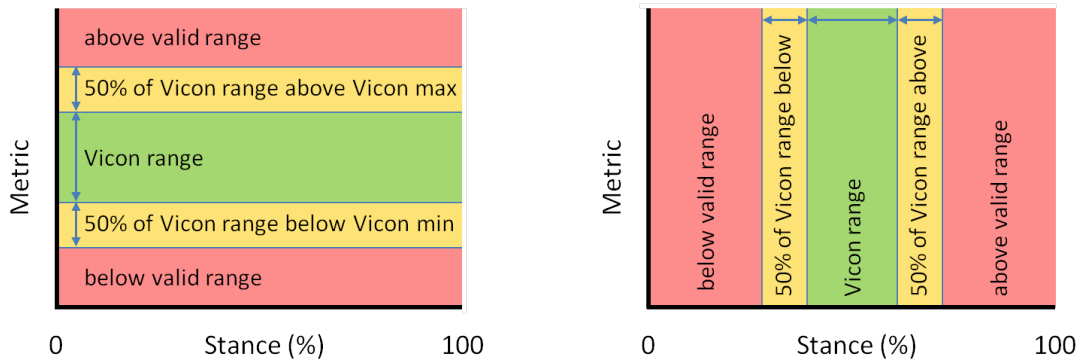


Figure 8.6: *Data ranges. Image on left illustrates setting the upper and lower thresholds in the validation criteria, while the image on the right represents the window of percent stance in which peak values were obtained.*

LCMAS - 2

The alignment with the Visual3D COM and force plate signal is detailed in Chapter 6. In MATLAB we also calculated an the additional metric, center of mass (COM) relative to base of support (BOS) described in the prior *Vicon* section. The repetition partitioning, filtering, signal validation, and extraction of peak metrics was the same as detailed in the prior *LCMAS - Single* section.

The five peak metrics and percentage of stance curves were used in system comparisons outlined in the next section.

Dynamic data was processed for DLS, SLS, and DVJ maneuvers.

8.2.2 Data Analysis

For each system we would like to assess the within-day and between-day repeatability for the full repetition time profiles as well as the peak value of each metric. These intra-system reliability measures are also known as test-retest reliability and help us evaluate the “consistency of a test or measure” [121]. Additionally, we would like to compare the reliability of each LCMAS to the industry gold standard Vicon system. Inter-system evaluations help us quantify the agreement between two methods of clinical measurement [11]. We would also like to determine: 1) if the marker based angles are good surrogate measures for the corresponding rotation based angle measurements; and 2) which coordinate system (proximal, distal, or joint) is the best to report force and moment data.

8.2.2.1 Statistical Analysis

Statistical analysis stemming from root mean squared (*RMS*) difference, analysis of variance (*ANOVA*), intraclass correlation coefficient (*ICC*) [108], standard error of measurement (*SEM*) [67], smallest detectable difference (*SDD*) [80] (also known as the smallest real difference (*SRD*) [67], repeatability coefficient (*RC*)

[16], minimum difference (MD) [121], or minimal detectable change (MDC)), and Bland-Altman plots [11, 10] are detailed below. According to Crossley [28], “The minimal clinically important difference quantifies the minimal difference that patients or practitioners consider clinically important and thus will indicate a relevant change in the patient’s symptoms.[2, 55]” We will take our minimal clinically important differences ($MCID$) to be the difference between mean values in the literature data and compare these to our SDD for each metric.

All RMS calculations were performed at 1% increments from 0% to 100% of the Stance Phase.

$$RMS = \sqrt{\frac{1}{N} \sum_{i=1}^N (X_i - \hat{X}_i)^2} \quad (8.4)$$

Where N is the number of data points, X_i is the data of the i th sample, $\hat{X}_i$ is the reference data of the i th sample.

Intra-System Repeatability - Between Repetitions

For each system, to assess within-session reliability of peak metrics we performed a one-way $ANOVA$ for the first two valid repetitions for each day of testing. The $ANOVA$ table corresponds to that used by Rankin and Stokes [98] for a one-way random effects model. Mean square (MS) values were then used as the source of variance in an $ICC_{(1,1)}$ calculation [98]. Where BMS is the between-subjects mean square with $DF_B = n - 1$ degrees of freedom and WMS is the within-subjects mean square with $DF_W = n(k - 1)$ degrees of freedom. Here n is number of subjects and k is number of repetitions.

$$ICC_{(1,1)} = \frac{BMS - WMS}{BMS + (k - 1)WMS} \quad (8.5)$$

The standard error of measurement (SEM) is:

$$SEM = \sqrt{WMS} \quad (8.6)$$

Smallest detectable difference (SDD) is:

$$SDD = 1.96 \times \sqrt{2} \times SEM \quad (8.7)$$

For Bland-Altman plots, the average value between repetitions for each subject is plotted on the horizontal axis and the difference between the same values, d , is plotted on the vertical axis. The mean difference ($\bar{d}$) is calculated and is an estimate of the bias between the measurements. The standard error (SE) of $\bar{d}$ is:

$$SE_{\bar{d}} = \frac{s_d}{\sqrt{n}} \quad (8.8)$$

where s_d is the standard deviation of d and n is the number of measurement comparisons.

To establish how certain we are in the value of $\bar{d}$ we calculated 95% confidence intervals (95% CI) for $\bar{d}$ [67]:

$$95\%CI_{\bar{d}} = \bar{d} \pm t \times SE_{\bar{d}} \quad (8.9)$$

where t is from the probability distribution based on $n - 1$ degrees of freedom.

In addition, to identify the range in which we would expect 95% of the differences to lie, we calculated 95% limits of agreement (95% LA):

$$95\%LA = \bar{d} \pm 1.96 \times s_d \quad (8.10)$$

To determine how certain we are in the 95% LA , we calculated the SE of the upper and lower 95% LA and 95% CI for each 95% LA [11].

$$SE_{LA} = 1.71 \times SE_{\bar{d}} \quad (8.11)$$

$$95\%CI_{95\%LA_{upper}} = 95\%LA_{upper} \pm t \times SE_{LA} \quad (8.12)$$

$$95\%CI_{95\%LA_{lower}} = 95\%LA_{lower} \pm t \times SE_{LA} \quad (8.13)$$

Next, we calculated 95% SDD which is similar to the 95% LA [67]:

$$95\%SDD = \bar{d} \pm SDD \quad (8.14)$$

We also calculated *RMS* values between the first two valid repetitions of each set, over the stance phase, for the two days of testing for each participant.

Intra-System Repeatability - Between Days

For each system, to assess between-session reliability of the mean value of peak metrics we performed a one-way *ANOVA*. The *ANOVA* table corresponds to that used by Rankin and Stokes [98] for a one-way random effects model. These new *MS* values were then used as the source of variance in the $ICC_{(1,k)}$ equation [98]. The calculations for *SEM* and *SDD* also use the equations above with *MS* and *DF* values from the new *ANOVA*. However, here *n* is number of subjects and *k* is number of days.

$$ICC_{(1,k)} = \frac{BMS - WMS}{BMS} \quad (8.15)$$

For Bland-Altman plots, the average value between days for each subject is plotted on the horizontal axis and the difference between the same values, *d*, is plotted on the vertical axis. The mean difference ($\bar{d}$) is calculated and is an estimate of the bias between the measurements. The other calculations described with the Bland-Altman analysis above were also calculated for the between-sessions investigation.

We also calculated *RMS* values between the mean metric profiles, over the stance phase, for the two days of testing for each subject.

Inter-System Reliability

To compare the reliability of the mean value of peak metric detection of each system to the industry gold standard, Vicon system, we performed a two-way, mixed-model, systems-fixed *ANOVA* for each day of testing. The *ANOVA* Table corresponds to that used by Rankin and Stokes [98] for a two-way, mixed-model, raters-fixed (Note: here we take the systems to be the raters). *MS* values were

then used as the source of variance in an $ICC_{(3,k)}$ calculation [98]. Where BMS is the between-subjects mean square with $DF_B = n - 1$ degrees of freedom, SMS is the between-systems (raters) mean square with $DF_S = k - 1$ degrees of freedom, and EMS is the error with $DF_E = (n - 1)(k - 1)$. Here n is number of subjects and k is number of systems (raters).

$$ICC_{(3,k)} = \frac{BMS - EMS}{BMS} \quad (8.16)$$

The standard error of measurement (SEM) now becomes:

$$SEM = \sqrt{EMS} \quad (8.17)$$

The calculation for SDD also use the equations above with the new SEM value.

The Bland-Altman calculations described above are also performed, this time comparing the mean from each testing session from each subject between two systems. We also calculated RMS values between individual repetitions and mean metric profiles, over the stance phase, for the two systems of testing for each subject.

8.2.2.2 System Evaluation

In order to proceed, we must first identify how to approach the massive amount of data we have just produced. Arguably, depending on the desired use of each low-cost system, it may be prudent to approach the data from a different direction. For example, once normative databases have been established and prospective studies performed for a variety of maneuvers and risk assessments, we may be much more interested in the intra-system repeatability for a wide range of metrics measured in the low-cost systems and less concerned with the correlation to the gold standard system. This potential future utility motivated us to perform the data analysis on the full spectrum of metrics. However, at this stage of development of the low-cost systems we will focus on the metrics identified in prior studies, detailed in Chapter 1.5.

Table 8.1: *Summary of primary and secondary variables examined in double leg maneuvers. Note: Initial contact (IC); range of motion (ROM); maximum knee flexion (MKF); center of mass (COM); base of support (BOS).*

Joint	Type	Primary Parameter	
Hip	Kinematic	Peak	Flexion
		ROM	Flexion
		IC	Ab/Adduction
	Kinetic	Peak	Flexion Moment
Ankle	Kinematic	ROM	Dorsiflexion
Knee	Kinematic	Peak	Flexion
		ROM	Flexion
		IC	Ab/Adduction
		Peak	Abduction
		Peak	Adduction
		Peak	Internal Rotation
	Kinetic	Peak	Abduction Moment

Joint	Type	Secondary Parameter	
Other	Position	ROM	COM relative to BOS
Hip	Kinematic	MKF	Flexion
		ROM	Adduction
		MKF	Adduction
		ROM	External Rotation
		MKF	External Rotation
Ankle	Kinematic	ROM	Pronation
Knee	Kinematic	ROM	Adduction
		MKF	Adduction
		MKF	External Rotation

Table 8.2: *Summary of primary and secondary variables examined in single leg maneuvers. Note: Initial contact (IC); range of motion (ROM); maximum knee flexion (MKF); center of mass (COM); base of support (BOS).*

Joint	Type	Primary Parameter	
Other	Position	ROM	COM relative to BOS
Hip	Kinematic	ROM	Flexion
		MKF	Flexion
		ROM	Adduction
		MKF	Adduction
		ROM	External Rotation
		MKF	External Rotation
Ankle	Kinematic	ROM	Dorsiflexion
		ROM	Pronation
Knee	Kinematic	Peak	Flexion
		ROM	Adduction
		MKF	Adduction
		MKF	External Rotation

Joint	Type	Secondary Parameter	
Hip	Kinematic	Peak	Flexion
		IC	Ab/Adduction
	Kinetic	Peak	Flexion Moment
Knee	Kinematic	ROM	Flexion
		IC	Ab/Adduction
		Peak	Abduction
		Peak	Adduction
		Peak	Internal Rotation
		Peak	Abduction Moment
	Kinetic	Peak	Abduction Moment

We took the metrics identified in Chapter 1.5 and for the double leg exercises (DVJ and DLS) we examine the double leg metrics as primary variables and the single leg metrics as secondary variables, compiled in Table 8.1. For single leg exercises (SLS) the metrics were prioritized in the opposite order, with the single leg metrics as primary variables and the double leg metrics as secondary variables, compiled in Table 8.2. When evaluating the COM position we chose the peak metric of ROM because this value was more likely to be repeatable than the laboratory based position between repetitions and days.

For these metrics, we start by checking the inter-system *ICC*. Since we are using the Vicon system as our gold standard, it is critical to have correlation between the low-cost systems and Vicon. An *ICC* of less than 0.40 is considered poor, an *ICC* of 0.40 to 0.75 is adequate, and an *ICC* above 0.75 is excellent. If the inter-system correlation is adequate or better (highly preferred) for detecting a particular metric, we proceed. Next, we compare the inter-system *SDD* to the literature *MCID* value. If the *SDD* is smaller than the *MCID*, we proceed to the intra-system comparisons.

For the low-cost intra-system comparisons we first look between repetitions. The assumption here is that a participant would be more consistent on the same day of testing with the same marker placement than one week later. We check for an adequate *ICC* and *SDD* using the same criteria described above. For the between days evaluation, the same checks are performed. Next, we round out our analysis by investigating the Bland-Altman and *RMS* values for inter- and intra-system comparisons.

The statistical analysis is summarized in Figure 8.7 with an overlay of boxes and numbers signifying order of consideration for system evaluations.

Finally, we also examine the intra-system evaluations for the Vicon system. These values are important for us to consider because they represent the consistency of the industry gold standard, especially relative to our low-cost systems.

Inter-System		Intra-System		
Day 1	Day 2	Day 1	Day 2	Between Days
Mean of repetitions		Between 1 st two valid repetitions		Mean of repetitions
ANOVA		ANOVA		ANOVA
ICC ¹		ICC ³		ICC ⁴
SDD ²		SDD		SDD
Bland-Altman		Bland-Altman		Bland-Altman ⁵
RMS (rep & mean)		RMS		RMS

Peak metrics

Compare MCID ^{2,3,4}

i) Min

ii) Max

iii) ROM

iv) IC

v) Max knee flexion

Metrics over stance phase

{

{

{

Figure 8.7: *Summary of statistical analysis used in system evaluations. Numbered boxes indicate order of consideration.*

In addition, they indicate the amount of error introduced by inconsistencies in our subjects performing the maneuvers and the marker placement by the experimenter.

Results and Discussion for the LCMAS-Single are presented in Chapter 9, while the corresponding information for the LCMAS-2 is presented in Chapter 10.

CHAPTER 9

Low-Cost Movement Assessment System-Single Compared to Vicon

Using the methods detailed in Chapter 8, we have processed and analyzed the LCMAS-Single and Vicon data for the drop vertical jump (DVJ). In this chapter we present the Results and Discussion for the inter-system reliability and the intra-system repeatability study for these systems.

9.1 Results

We first present a sample of the plots generated in our study. Our intent is to provide the reader with a comprehensive view of the scope of comparisons as well as a feel for the numerical values. The three types of plots are 1) center of mass (COM) relative to base of support (BOS), 2) root mean square (RMS), and 3) Bland-Altman. Details of each type of plot are explained below. Then, we present tables of numerical data for variables that passed the screening criteria for both the low-cost system compared to Vicon and for angle measurement comparisons between markers, from either the the low-cost or Vicon system, and rotations calculated in the Vicon system.

9.1.1 Center of Mass Relative to Base of Support

A sample COM relative to BOS plot is shown in Figure 9.1. This plot represents an overhead view where increasing X is towards the participant's left side, and

increasing Y is towards the participant's posterior direction. The lines, one for each system, represent the path (X, Y) of the COM relative to the BOS through the repetition. The stars represent initial contact. The origin is located at the BOS and marked with a circle on the plot. Note that while COM and BOS are both calculated in the laboratory coordinate system, this plot is not of the laboratory space as the BOS is not fixed in the laboratory system and may shift throughout the duration of the repetition. Interpretation of this plot is detailed in the Discussion section.

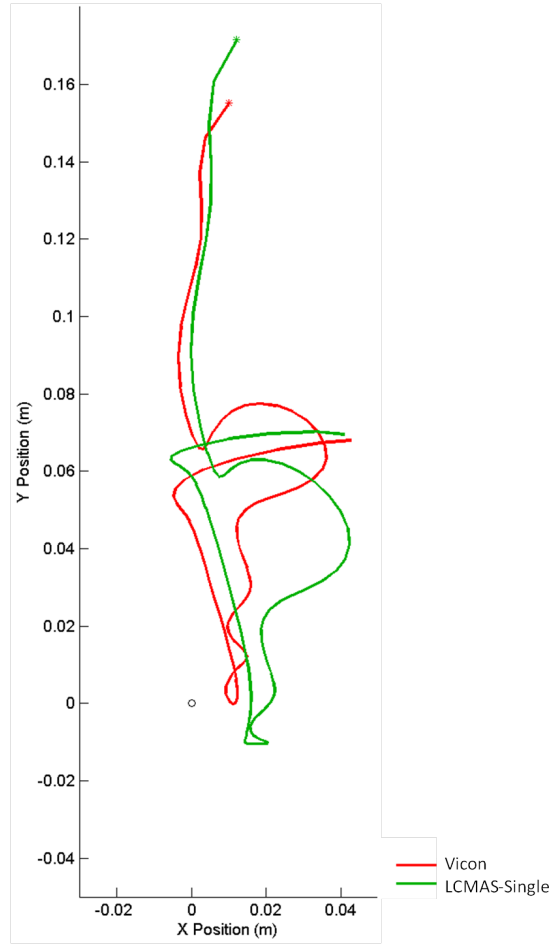


Figure 9.1: *Sample plot: center of mass relative to base of support. Note: Stars represent initial contact, circle represents base of support, decreasing Y is towards the participant's anterior direction.*

9.1.2 Root Mean Square Comparisons

The RMS plots show metric component profiles over the stance phase (x axis) of each repetition. The left column of plots contains angle data, while the center column displays force data, and the right column presents moment data. The exception to the described presentation of data is in the ankle plots, which instead of displaying a blank plot for the second component of marker angle data, we provide components of the COM position plots. Our evaluation yields four different types of RMS plots. Sample data output is shown in Figures 9.2 to 9.9.

9.1.2.1 Inter-System Comparisons

For the inter-system comparison, single repetition RMS comparisons for the right hip, knee, and ankle are shown in Figure 9.2, Figure 9.3, and Figure 9.4, respectively. The top row consists of data in the joint coordinate system (JCS), the middle row is composed of the first component of marker angle data and force and moment data in the proximal coordinate system (PCS), while the bottom row is comprised of the second component of marker angle data and force and moment data in the distal coordinate system (DCS). Again, in the case of the ankle data, components of COM position are presented in the bottom left plot. Vicon data is plotted using thin lines while data from our low-cost system is plotted in thick lines. The RMS value between corresponding lines of the Vicon and LCMAS are color coded and presented to the right of each plot window.

For the inter-system comparison, mean RMS comparisons for the right knee in the JCS are shown in Figure 9.5. The first, second, and third components of each metric are displayed in the respective row, with the columns corresponding to the prior description. The individual repetitions are plotted in colored lines, while the mean of those repetitions is plotted with a black line. Vicon data is plotted using thin lines while data from our low-cost system is plotted in thick lines. The RMS

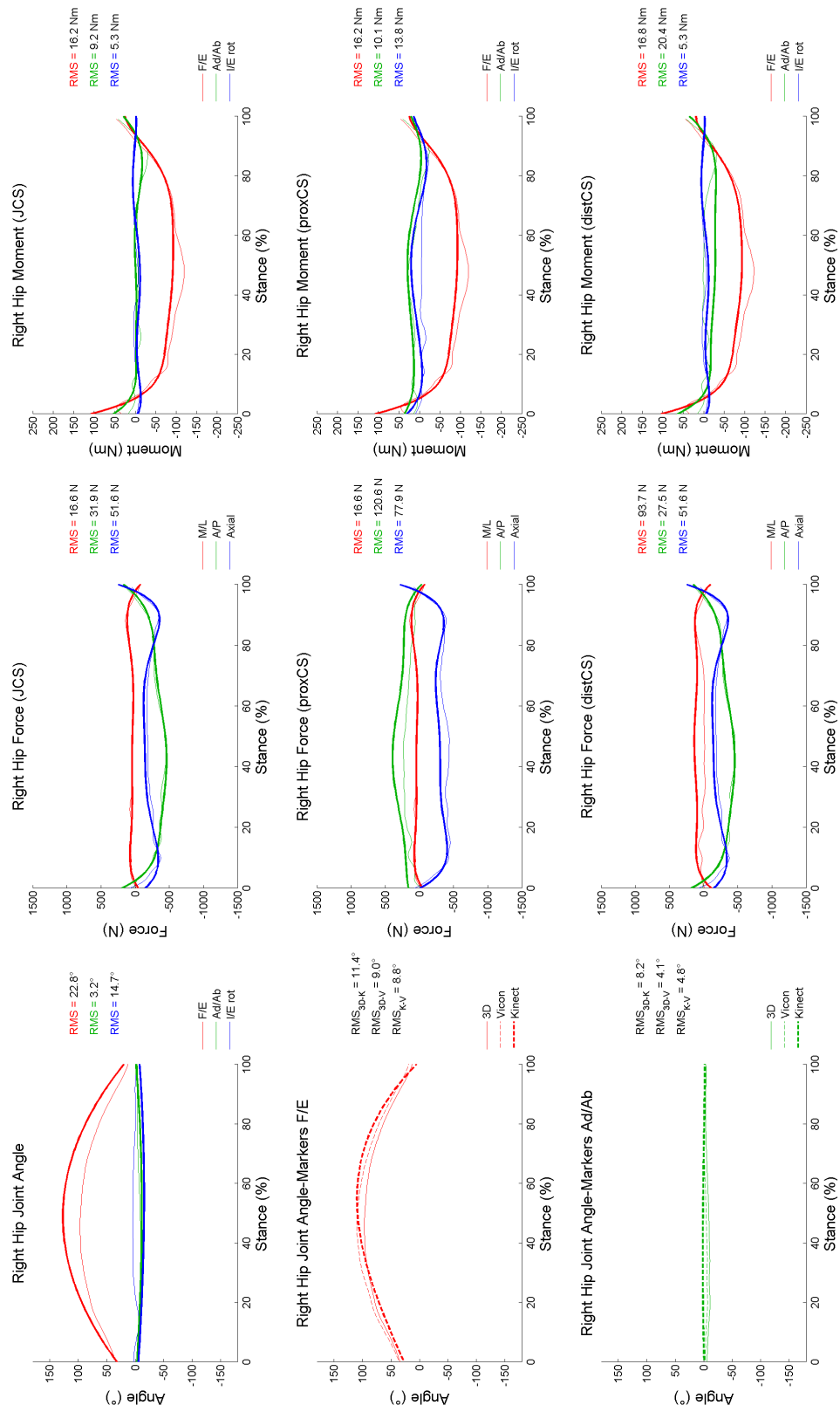


Figure 9.2: Sample Right Hip comparison data between individual repetitions from the LCMAS-Single (Vicon Static, IK) and Vicon System. Note: Thin lines Vicon, thick lines LCMAS-Single.

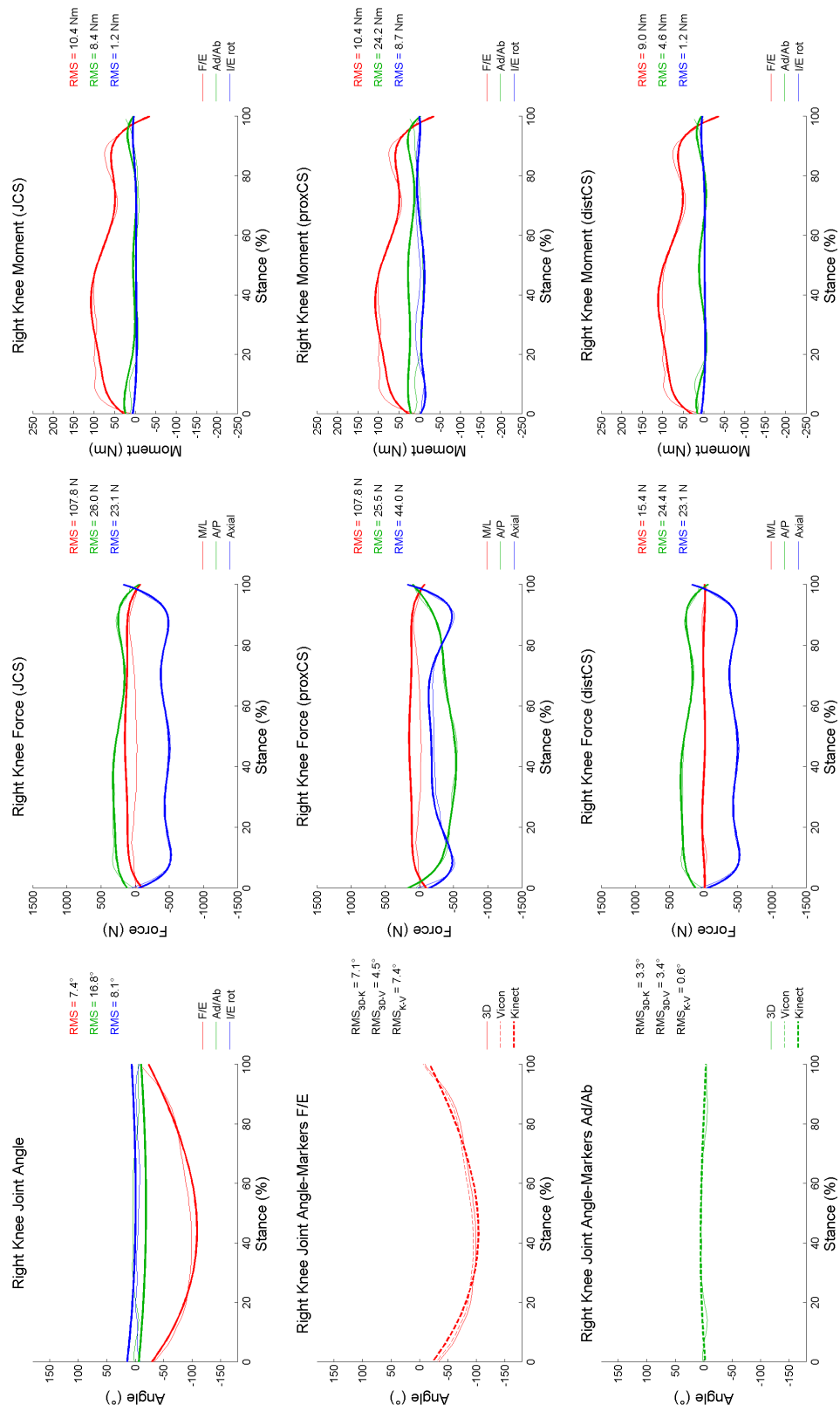


Figure 9.3: Sample Right Knee comparison data between individual repetitions from the LCMAS-Single (Vicon Static, IK) and Vicon System. Note: Thin lines Vicon, thick lines LCMAS-Single.

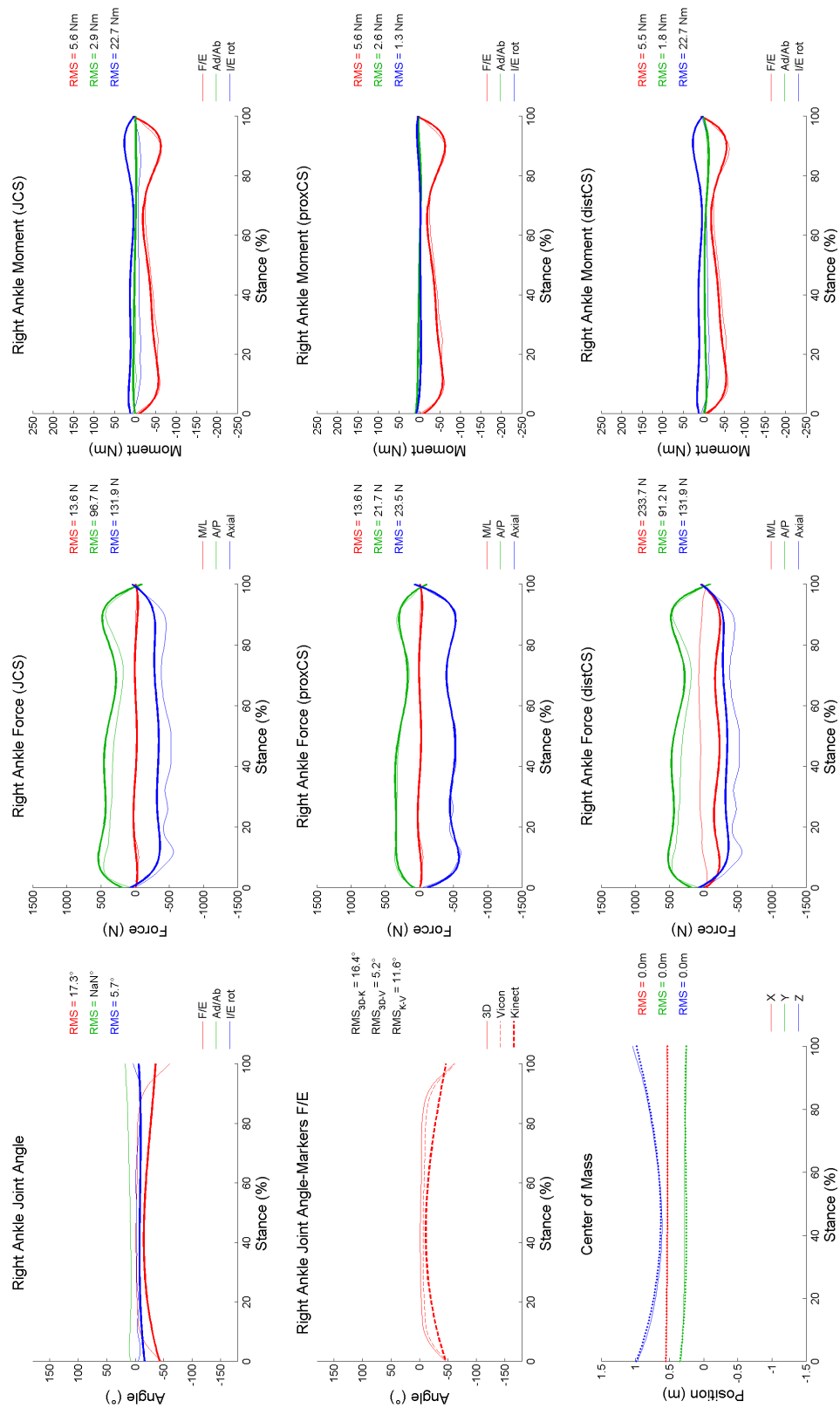


Figure 9.4: Sample Right Ankle comparison data between individual repetitions from the LCMAS-Single (Vicon Static, IK) and Vicon System. Note: Thin lines Vicon, thick lines LCMAS-Single.

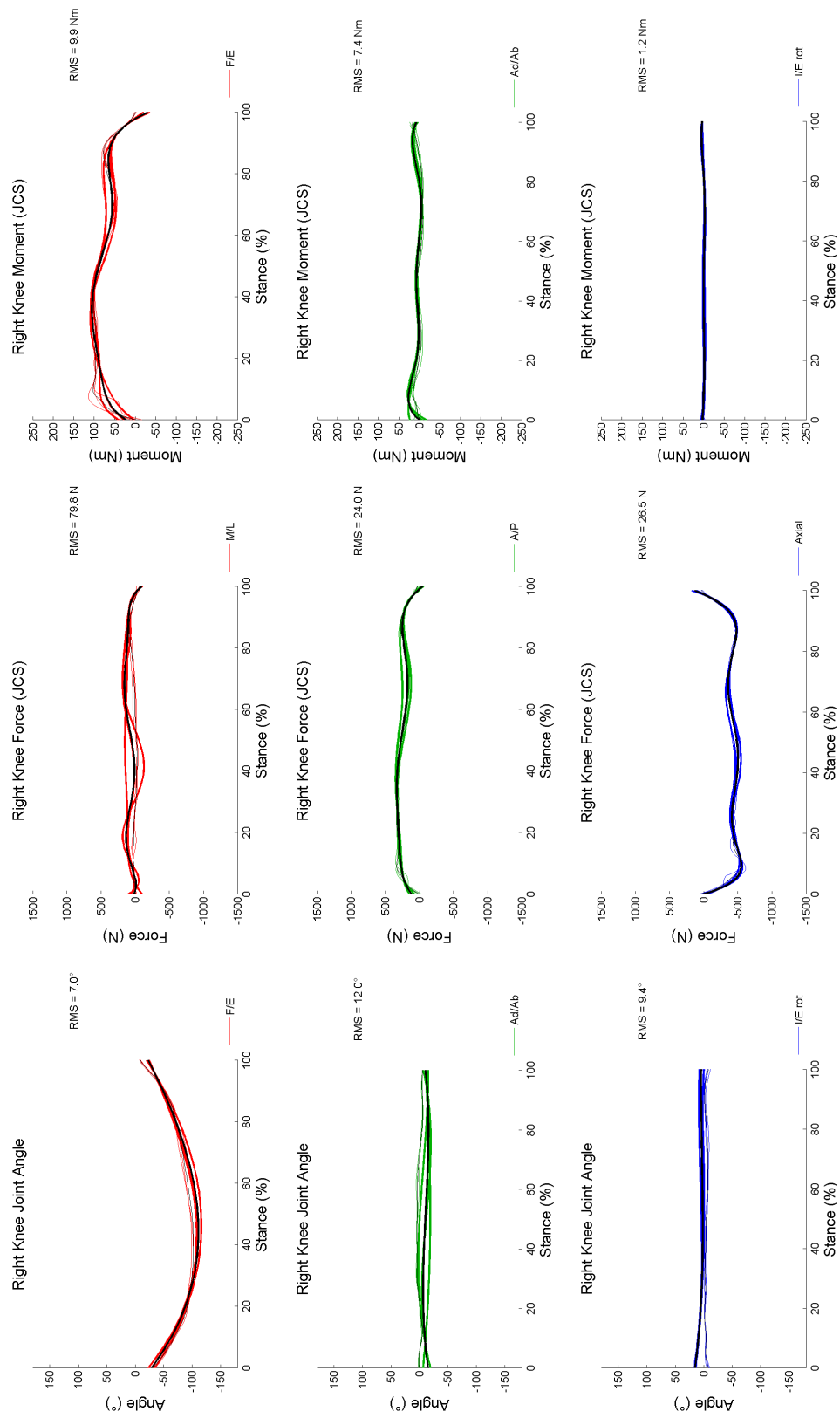


Figure 9.5: Sample Right Knee comparison data between mean of a set of repetitions from the LCMAS-Single (Vicon Static, IK) and Vicon System. Note: Thin lines Vicon, thick lines LCMAS-Single, colored lines repetitions, black lines set means.

value between corresponding mean lines of the Vicon and LCMAS is presented to the right of each plot window.

9.1.2.2 Intra-System Comparisons

Now we proceed to the intra-system comparisons. First we look at the between repetitions RMS comparisons for the right knee in the JCS in Figures 9.6 and 9.7 for the LCMAS and Vicon system, respectively. The first, second, and third components of each metric are displayed in the respective row, with the columns corresponding to the prior description. The second repetition is plotted using thin lines while data from the first repetition is plotted in thick lines. The RMS value between corresponding lines is presented to the right of each plot window.

Next we examine the intra-system between day RMS comparisons for the right knee in the JCS in Figures 9.8 and 9.9 for the LCMAS and Vicon system, respectively. The first, second, and third components of each metric are displayed in the respective row, with the columns corresponding to the prior description. The individual repetitions are plotted in colored lines, while the mean of those repetitions is plotted with a black line. Trial F is plotted using thin lines while data from Trial D is plotted in thick lines. The RMS value between corresponding mean lines is presented to the right of each plot window.

It should be noted that while primarily RMS data for the right knee in the JCS was presented here, similar evaluations were performed for the right knee in the PCS and DCS as well as the hip and ankle in all three coordinate systems. In addition, data was evaluated for the left side, for all three joints, in all three coordinate systems, as well as COM position. All of this data was evaluated in the four versions (i) Vicon static - 6DOF; ii) Vicon static - IK; iii) Kinect static - 6DOF; and iv) Kinect static - IK) of the LCMAS-Single and the Vicon datasets.

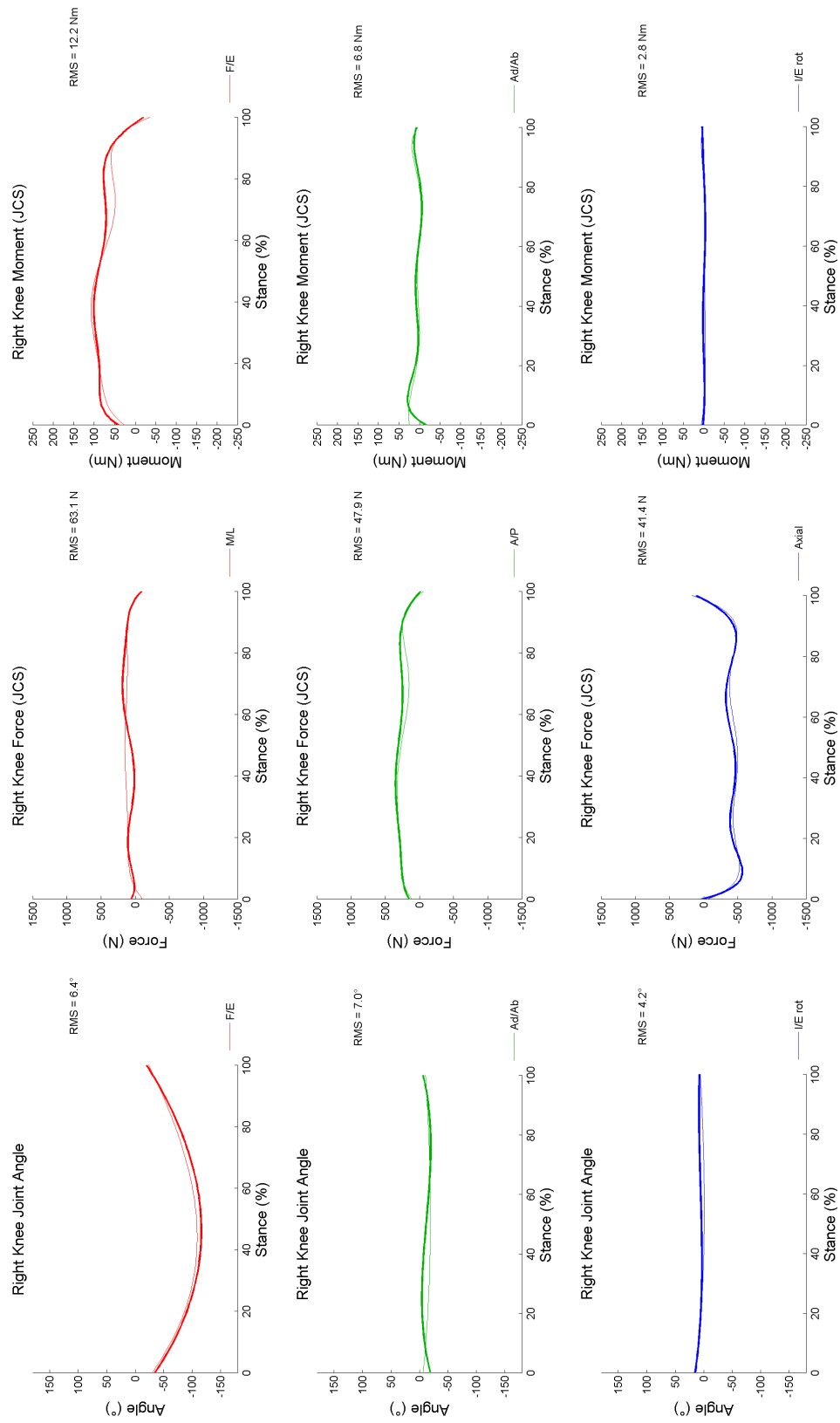


Figure 9.6: Sample Right Knee comparison data between individual repetitions of the same set from the LCMAS-Single (Vicon Static, IK). Note: Thin lines 2nd rep, thick lines 1st rep.

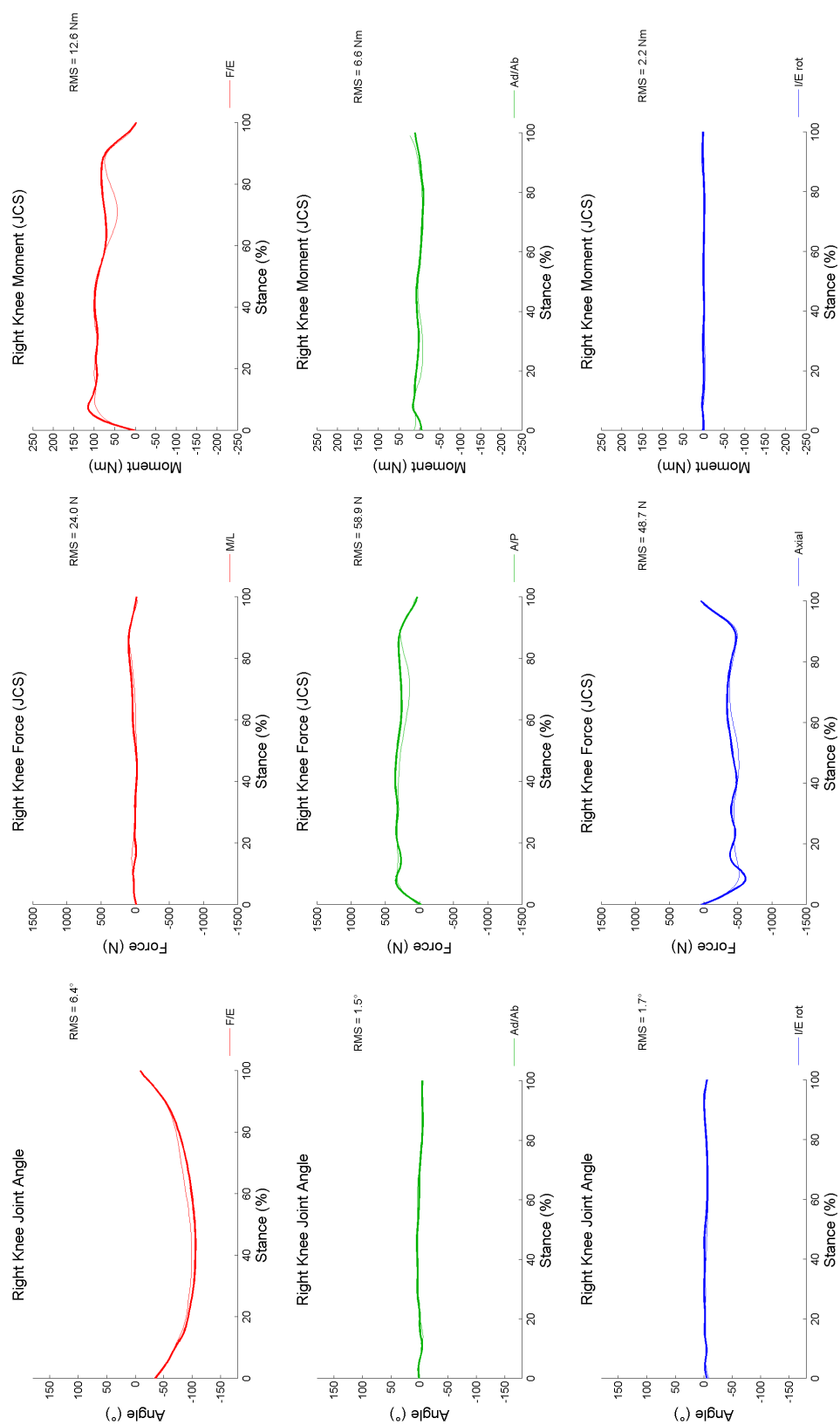


Figure 9.7: Sample Right Knee comparison data between individual repetitions of the same set from the *Vicon System*. Note:

Thin lines 2nd rep, thick lines 1st rep.

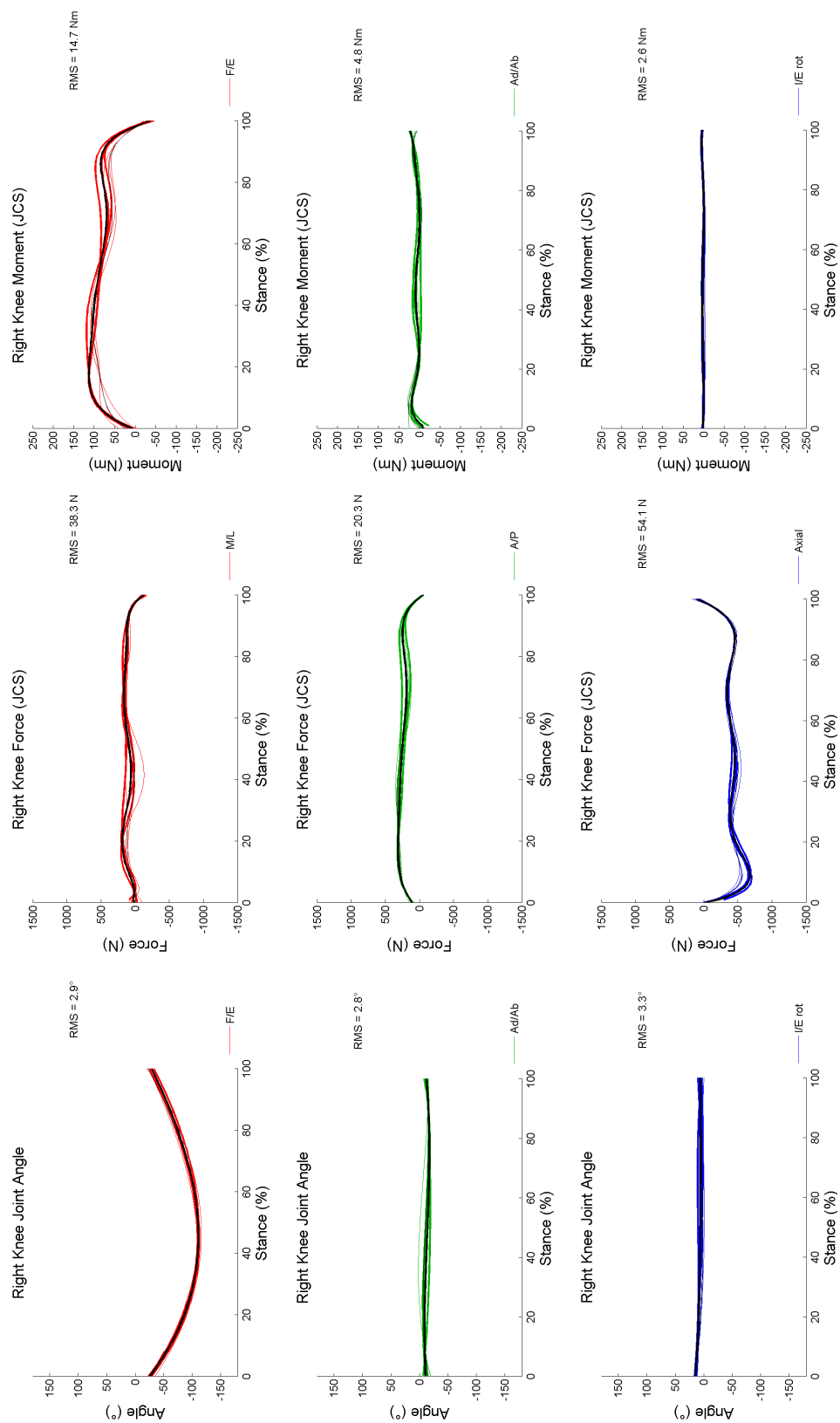


Figure 9.8: Sample Right Knee comparison data between repetition means from two different sets from the LCMAS-Single (Vicon Static, IK). Note: Thin lines Trial F, thick lines Trial D, colored lines individual repetitions, black lines set means.

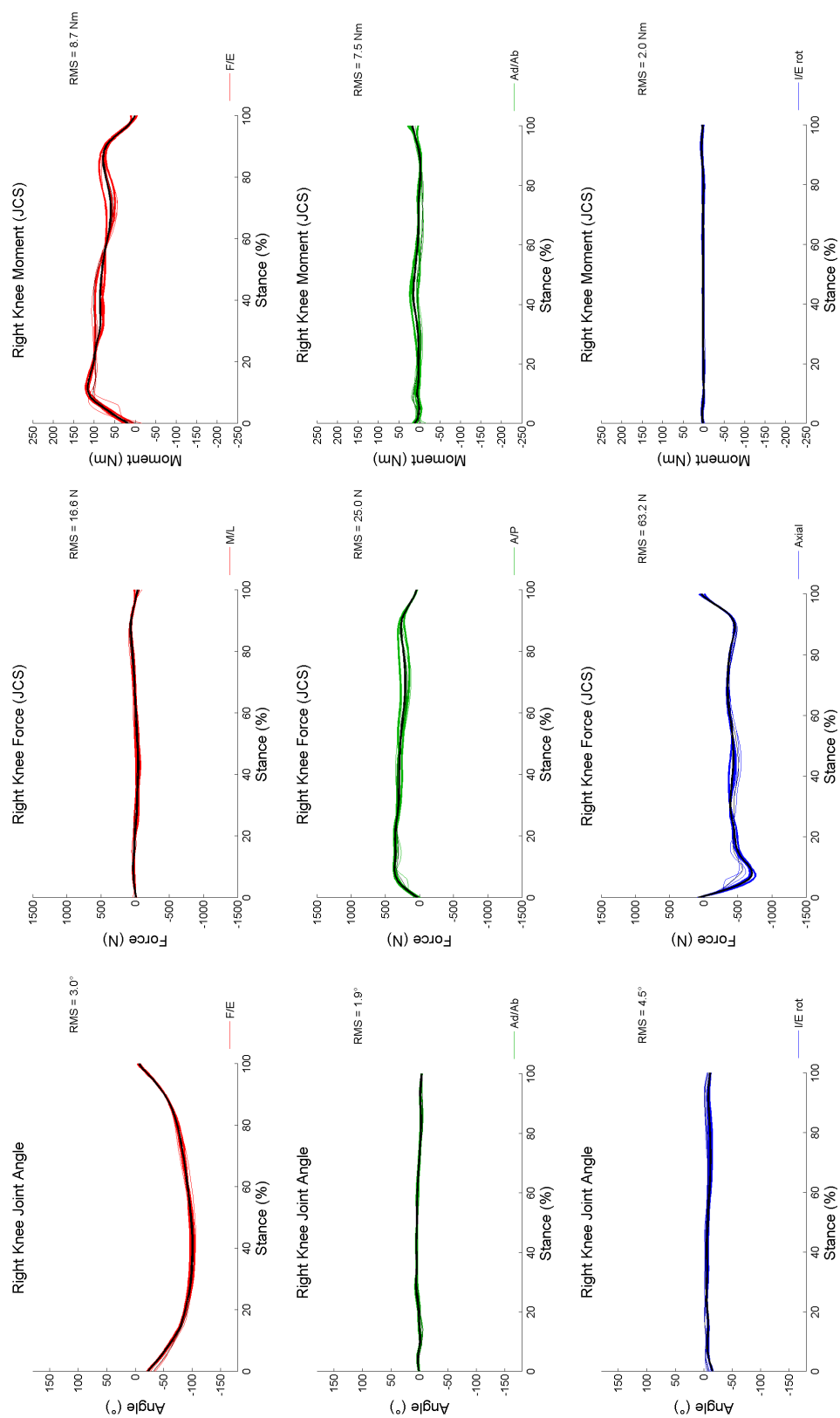


Figure 9.9: Sample Right Knee comparison data between repetition means from two different sets from the Vicon System.

Note: Thin lines Trial D, thick lines Trial F, colored lines individual repetitions, black lines set means.

9.1.3 Bland-Altman Comparisons

Next, we examine the Bland-Altman plots for comparing the extreme metrics detected by our systems. Examples of the eight different Bland-Altman plots generated in our evaluation are shown for the second component of hip angle in the JCS at initial contact (IC) in Figure 9.10. For each plot the average of the measurements being compared is plotted on the x axis and the difference between the measurements is plotted on the y axis. The mean difference, $\bar{d}$, is plotted as a horizontal solid line in the center of the plot, with the 95% confidence interval of $\bar{d}$, $95\%CI_{\bar{d}}$, plotted on either side with a dashed line, and the 95% limits of agreement, $95\%LA$, plotted at the outermost extent of the plot with a dot-dash line. The value for each of these variables is displayed next to the line on the right side of the plot window. The top row of Figure 9.10 contains our inter-system comparisons. The middle row contains intra-system comparisons for the LCMAS-Single, while the bottom row contains intra-system data for the Vicon system. The left-most column contains comparison data from Day 1, while the center column contains data from Day 2. The right-most column contains intra-system data from between days. It should be noted that similar comparisons were performed for all metrics under consideration in this study.

9.1.4 Numerical Results

Numerical results for select metrics are summarized in Table 9.1 and detailed in Tables 9.2 and 9.3. In this summary table, each row contains a metric and the associated inter-system and intra-system comparisons. Each circle is color coded, as detailed in the legend, to visually indicate the level of agreement of ICC and comparison of SDD with the $MCID$ values. The outline of the circle is used to represent ICC agreement and the fill of the circle indicates how the SDD compares to the $MCID$ values. For the inter-system comparisons the two

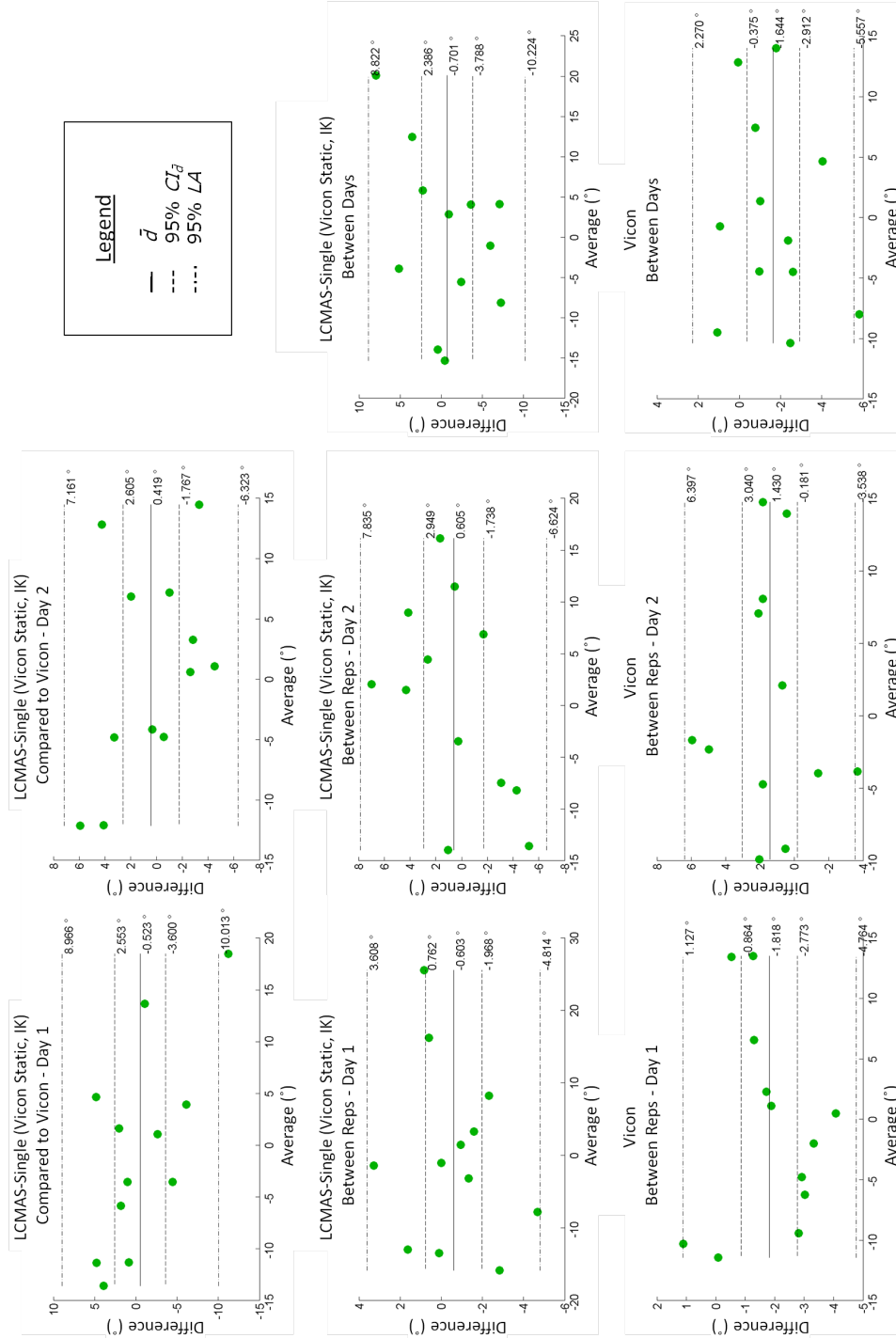


Figure 9.10: Sample Bland-Altman plots for comparison of the LCMAS-Single (Vicon Static, IK) to the Vicon System for the second component of hip angle for JCS based rotations at initial contact (IC).

circles correspond to the Day 1 (left) and Day 2 (right) evaluations. For the intra-system comparisons, the three circles correspond to the between repetitions comparisons, Day 1 (left) and Day 2 (center), and Between Days comparisons (right). Metrics from LCMAS-Single that met our screening criteria are designated with an asterisk. This visual comparison provides a simple platform to compare the metrics detailed in the numerical tables.

Finally, we present numerical tables in which values extracted from the different types of plots are compiled along with *ICC*, *SDD*, and *MCID* values. Primary and secondary variables that passed the screening criteria for LCMAS-Single compared to the corresponding Vicon metric are presented in Table 9.2 and 9.3, respectively. All system comparisons listed in the summary table for these metrics are presented in the numerical tables. Numerical results are compiled in Appendix A.1 for variables from the summary table that did not meet our screening criteria. Five different metrics are presented in Table 9.2 while one metric is presented in Table 9.3.

The tables consist of four different types of comparisons. First, we have comparisons between a version of LCMAS-Single models and the Vicon model. Second, are comparisons between the LCMAS-Single marker based angle and the corresponding Vicon marker based angle. The next type of comparison is LCMAS-Single marker based angle to the corresponding Vicon model or JCS based angle. Finally, we examine the Vicon marker based angle to the corresponding Vicon model or JCS based angle.

For these tables, the inter- and intra-system comparisons for one metric in one version of LCMAS are presented on one half of each page. When looking at the page in landscape orientation, the component is listed on the far left with the type of comparison (i) minimum value (Min), ii) maximum value (Max), iii) range of motion (ROM) of values, iv) value at initial contact (IC), or v) value at maximum knee flexion (MKF)), the component of the parameter of interest

(1st, 2nd, or 3rd), and the parameter of interest (e.g. knee angle corresponding to rotations to align with the JCS). The second main column contains the statistical measurement labels for the data presented in the tables. These labels are comprised of: the *ICC*; the number of comparisons, n , involved in obtaining the statistics; the *SEM*; the *SDD*; the lower and upper bounds for the 95%*SDD*; from the Bland-Altman plots: the $\bar{d}$, the lower and upper bounds for the 95%*CI $\bar{d}$* , and the lower and upper bounds for the 95%*LA*; and from the *RMS* plots the *Fraction* or ratio of comparisons used to comparison captured and the average of the *RMS* values for the comparisons used for both individual curve evaluations and mean curve evaluations. Other statistical output is not presented at this time. The leftmost group of data columns is headed "Inter-System: Vicon" and in this column the inter-system comparison data is presented for each day of testing, with the exception of the *RMS* data where both days are included in the average *RMS* and fraction values. Note that values were obtained for both individual curves and mean curves. The center group of data columns is headed "Intra-System: Between Reps" and contains the intra-system comparisons between repetitions for each day of testing for each system from the inter-system comparison. The next group of data columns is headed "Intra-System: Between Days" and contains the intra-system comparison between days for each system from the inter-system comparison. Finally at the far right of the page, the corresponding *MCID* value from the scientific literature is presented for ease of comparison to each *SDD*. The units listed with the *MCID* values apply to all numbers listed for that metric, with the exception of the *ICC*, n and *Fraction* values.

Note: Inter-system circles represent Day 1 and Day 2; intra-system circles represent Between Repetitions (Day 1, Day 2), and Between Days.

Legend

ICC	SDD	
 = Poor	 = Above MCID	* = Variable meeting screening criteria
 = Adequate	 = Below larger MCID	
 = Excellent	 = Below smaller MCID	

Table 9.2: *Primary Variables - DVJ - LCMAS-Single - Max - 1st Component - Hip Angle.*

Component Parameter	Max 1st Hip Angle JCS	Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Day		MCID
			LCMAS-Single (Vicon Static, IK)		LCMAS-Single (Vicon Static, IK)		Vicon		LCMAS-Single (Vicon Static, IK)		
			Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
ICC			0.936	0.910	0.960	0.887	0.979	0.995	0.956	0.972	
n			12	12	12	12	12	12	12	12	
SEM			7.79	9.13	4.94	8.06	2.85	1.44	7.13	4.73	
SDD			21.60	25.32	13.71	22.35	7.89	3.99	19.76	13.10	
SDDlower bound			-40.63	-47.31	-12.18	-24.51	-7.10	-4.73	-23.96	-14.32	32.3
SDDupper bound			2.58	3.32	15.23	20.19	8.69	3.25	15.57	11.88	degrees
d			-19.02	-21.99	1.52	-2.16	0.80	-0.74	-4.19	-1.22	
d lower bound			-26.03	-30.20	-3.01	-9.59	-1.82	-2.00	-10.28	-5.58	
d upper bound			-12.02	-13.79	6.05	5.27	3.42	0.52	1.89	3.14	
LA lower bound			-40.63	-47.31	-12.45	-25.08	-7.28	-4.62	-22.96	-14.67	
LA upper bound			2.58	3.32	15.49	20.76	8.88	3.14	14.58	12.23	
RMS(individual)			20.63		9.00		3.82				
Fraction(individual)			1.00		1.00		1.00		13.36	6.31	
RMS(mean)			19.78						1.00	1.00	
Fraction(mean)			1.00								

Component Parameter	Max 1st Hip Angle JCS	Comparison System	Inter-System: Vicon (Marker		Intra-System: Between Repts				Intra-System: Between Day		MCID
			LCMAS-Single (Vicon Static, 6DOF)		LCMAS-Single (Vicon Static, 6DOF)		Vicon		LCMAS-Single (Vicon Static, 6DO		
			Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
ICC			0.867	0.840	0.950	0.890	0.979	0.995	0.917	0.972	
n			12	12	12	12	12	12	12	12	
SEM			9.61	10.63	4.68	7.81	2.85	1.44	7.80	4.73	
SDD			26.65	29.47	12.97	21.64	7.89	3.99	21.61	13.10	
SDDlower bound			-35.74	-37.74	-14.53	-19.48	-7.10	-4.73	-22.01	-14.32	32.3
SDDupper bound			17.55	21.20	11.41	23.81	8.69	3.25	21.22	11.88	degrees
d			-9.09	-8.27	-1.56	2.16	0.80	-0.74	-0.40	-1.22	
d lower bound			-17.73	-17.82	-5.83	-5.02	-1.82	-2.00	-7.71	-5.58	
d upper bound			-0.45	1.29	2.71	9.35	3.42	0.52	6.91	3.14	
LA lower bound			-35.74	-37.74	-14.72	-20.01	-7.28	-4.62	-22.96	-14.67	
LA upper bound			17.55	21.20	11.60	24.33	8.88	3.14	22.16	12.23	
RMS(individual)			18.39		12.11		3.82				
Fraction(individual)			0.99		1.00		1.00		16.55	6.31	
RMS(mean)			16.82						1.00	1.00	
Fraction(mean)			1.00								

Table 9.2: (cont.) *Primary Variables - DVJ - LCMAS-Single - Max - 1st Component - Hip Angle.*

Component Parameter		Comparison System	Inter-System: Vicon (Marker)		Intra-System: Between Reps				Intra-System: Between Day		MCID
			LCMAS-Single (Markers)		LCMAS-Single (Markers)		Vicon (Markers)		LCMAS-Single (Markers)		
Max 1st	Hip Angle Marker	Statistic	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
		ICC	0.704	0.710	0.956	0.940	0.979	0.991	0.914	0.951	
		n	11	10	7	8	12	12	9	12	
		SEM	17.58	14.74	6.53	6.29	3.49	2.15	11.14	7.16	
		SDD	48.73	40.85	18.10	17.45	9.68	5.96	30.89	19.86	32.3
		SDDlower bound	-42.47	-26.35	-19.16	-17.82	-8.92	-6.77	-27.72	-20.68	degrees
		SDDupper bound	54.99	55.35	17.03	17.08	10.44	5.15	34.07	19.03	
		$\bar{d}$	6.26	14.50	-1.07	-0.37	0.76	-0.81	3.18	-0.82	
		$\bar{d}$ lower bound	-10.44	-0.41	-10.23	-8.32	-2.48	-2.76	-9.41	-7.52	
		$\bar{d}$ upper bound	22.96	29.41	8.09	7.58	4.00	1.13	15.76	5.88	
		LA lower bound	-42.47	-26.35	-20.48	-19.00	-9.23	-6.81	-28.92	-21.49	
		LA upper bound	54.99	55.35	18.35	18.26	10.75	5.19	35.27	19.85	
		RMS(individual)	20.41		11.40		4.61				
		Fraction(individual)	0.67		0.63		1.00		16.45	8.52	
		RMS(mean)	21.49						0.75	1.00	
		Fraction(mean)	0.88								

Component Parameter		Comparison System	Inter-System: Vicon		Intra-System: Between Reps				Intra-System: Between Day		MCID
			LCMAS-Single (Markers)		LCMAS-Single (Markers)		Vicon (Markers)		LCMAS-Single (Markers)		
Max 1st	Hip Angle	Statistic	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
		ICC	0.583	0.731	0.956	0.940	0.979	0.995	0.914	0.972	
		n	11	10	7	8	12	12	9	12	
		SEM	19.29	13.94	6.53	6.29	2.85	1.44	11.14	4.73	
		SDD	53.47	38.65	18.10	17.45	7.89	3.99	30.89	13.10	32.3
		SDDlower bound	-59.26	-38.92	-19.16	-17.82	-7.10	-4.73	-27.72	-14.32	degrees
		SDDupper bound	47.68	38.38	17.03	17.08	8.69	3.25	34.07	11.88	
		$\bar{d}$	-5.79	-0.27	-1.07	-0.37	0.80	-0.74	3.18	-1.22	
		$\bar{d}$ lower bound	-24.12	-14.37	-10.23	-8.32	-1.82	-2.00	-9.41	-5.58	
		$\bar{d}$ upper bound	12.54	13.84	8.09	7.58	3.42	0.52	15.76	3.14	
		LA lower bound	-59.26	-38.92	-20.48	-19.00	-7.28	-4.62	-28.92	-14.67	
		LA upper bound	47.68	38.38	18.35	18.26	8.88	3.14	35.27	12.23	
		RMS(individual)	19.45		11.40		3.82				
		Fraction(individual)	0.67		0.63		1.00		16.45	6.31	
		RMS(mean)	20.92						0.75	1.00	
		Fraction(mean)	0.88								

Table 9.2: (cont.) *Primary Variables - DVJ - LCMAS-Single - Max - 1st Component - Hip Angle.*

Component Parameter Max 1st Hip Angle	Comparison System	Inter-System: Vicon		Intra-System: Between Reps				Intra-System: Between Day		MCID
		Vicon (Markers)		Vicon (Markers)				Vicon (Markers)	Vicon	
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2			
ICC	Statistic	0.904	0.952	0.979	0.991	0.979	0.995	0.951	0.972	
n		12	12	12	12	12	12	12	12	
SEM		9.22	6.61	3.49	2.15	2.85	1.44	7.16	4.73	
SDD		25.57	18.32	9.68	5.96	7.89	3.99	19.86	13.10	
SDDlower bound		-40.00	-32.35	-8.92	-6.77	-7.10	-4.73	-20.68	-14.32	32.3 degrees
SDDupper bound		11.13	4.28	10.44	5.15	8.69	3.25	19.03	11.88	
d		-14.43	-14.03	0.76	-0.81	0.80	-0.74	-0.82	-1.22	
d lower bound		-22.72	-19.97	-2.48	-2.76	-1.82	-2.00	-7.52	-5.58	
d upper bound		-6.15	-8.10	4.00	1.13	3.42	0.52	5.88	3.14	
LA lower bound		-40.00	-32.35	-9.23	-6.81	-7.28	-4.62	-21.49	-14.67	
LA upper bound		11.13	4.28	10.75	5.19	8.88	3.14	19.85	12.23	
RMS(individual)		10.52		4.61		3.82				
Fraction(individual)		1.00		1.00		1.00				
RMS(mean)		10.46						8.52	6.31	
Fraction(mean)		1.00						1.00	1.00	

Table 9.2: (cont.) *Primary Variables - DVJ - LCMAS-Single - IC - 2nd Component - Hip Angle.*

Component Parameter		Comparison System	Inter-System: Vicon		Intra-System: Between Reps				Intra-System: Between Day		MCID		
			LCMAS-Single (Vicon Static, IK)		LCMAS-Single (Vicon Static, IK)		Vicon		LCMAS-Single (Vicon Static, IK)				
IC 2nd	Hip Angle JCS	Statistic	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2			
		ICC	0.940	0.961	0.985	0.935	0.964	0.945	0.948	0.977	9.41 to 11.14 degrees		
		n	12	12	12	12	12	12	12	12		12	
		SEM	3.42	2.43	1.52	2.53	1.64	1.99	3.33	1.78		1.78	
		SDD	9.49	6.74	4.20	7.02	4.54	5.52	9.22	4.94		4.94	
		SDDlower bound	-10.01	-6.32	-4.81	-6.42	-6.36	-4.09	-9.92	-6.58		-6.58	
		SDDupper bound	8.97	7.16	3.60	7.63	2.73	6.95	8.52	3.30		3.30	
		d	-0.52	0.42	-0.60	0.61	-1.82	1.43	-0.70	-1.64		-1.64	
		d lower bound	-3.60	-1.77	-1.97	-1.74	-2.77	-0.18	-3.79	-2.91		-2.91	
		d upper bound	2.55	2.60	0.76	2.95	-0.86	3.04	2.39	-0.37		-0.37	
		LA lower bound	-10.01	-6.32	-4.81	-6.62	-4.76	-3.54	-10.22	-5.56		-5.56	
		LA upper bound	8.97	7.16	3.61	7.83	1.13	6.40	8.82	2.27		2.27	
		RMS(individual)		3.71		3.84		2.08					
		Fraction(individual)		1.00		1.00		1.00		3.80		2.63	2.63
		RMS(mean)		3.32						1.00		1.00	1.00
		Fraction(mean)		1.00									

Component Parameter		Comparison System	Inter-System: Vicon		Intra-System: Between Reps				Intra-System: Between Day		MCID		
			LCMAS-Single (Vicon Static, 6DOF)		LCMAS-Single (Vicon Static, 6DOF)		Vicon		LCMAS-Single (Vicon Static, 6DO)				
IC 2nd	Hip Angle JCS	Statistic	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2			
		ICC	0.927	0.932	0.960	0.927	0.964	0.945	0.916	0.977	9.41 to 11.14 degrees		
		n	12	12	12	12	12	12	12	12		12	
		SEM	3.66	3.18	2.40	2.72	1.64	1.99	4.11	1.78		1.78	
		SDD	10.15	8.81	6.64	7.54	4.54	5.52	11.40	4.94		4.94	
		SDDlower bound	-10.38	-8.64	-7.70	-7.27	-6.36	-4.09	-12.63	-6.58		-6.58	
		SDDupper bound	9.92	8.99	5.58	7.80	2.73	6.95	10.17	3.30		3.30	
		d	-0.23	0.18	-1.06	0.26	-1.82	1.43	-1.23	-1.64		-1.64	
		d lower bound	-3.52	-2.68	-3.19	-2.28	-2.77	-0.18	-5.01	-2.91		-2.91	
		d upper bound	3.06	3.04	1.08	2.81	-0.86	3.04	2.54	-0.37		-0.37	
		LA lower bound	-10.38	-8.64	-7.65	-7.59	-4.76	-3.54	-12.87	-5.56		-5.56	
		LA upper bound	9.92	8.99	5.53	8.12	1.13	6.40	10.40	2.27		2.27	
		RMS(individual)		4.09		4.35		2.08					
		Fraction(individual)		1.00		1.00		1.00		4.52		2.63	2.63
		RMS(mean)		3.51						1.00		1.00	1.00
		Fraction(mean)		1.00									

Table 9.2: (cont.) Primary Variables - DVJ - LCMAS-Single - IC - 2nd Component - Hip Angle.

Component Parameter	IC 2nd Hip Angle Marker	Comparison System	Inter-System: Vicon (Marker)		Intra-System: Between Reps				Intra-System: Between Day		MCID
			LCMAS-Single (Markers)		LCMAS-Single (Markers)		Vicon (Markers)		LCMAS-Single (Markers)		
			Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
IC 2nd Hip Angle	Hip Angle	ICC	0.785	0.906	0.697	0.787	0.919	0.911	0.721	0.923	9.41 to 11.14 degrees
		n	10	10	8	8	12	12	9	12	
		SEM	3.92	2.05	4.15	2.96	1.49	1.79	4.54	2.01	
		SDD	10.86	5.68	11.50	8.21	4.13	4.96	12.60	5.57	
		SDDlower bound	-8.82	-4.61	-16.41	-8.17	-5.72	-3.71	-14.97	-6.17	
		SDDupper bound	12.91	6.76	6.60	8.25	2.54	6.22	10.22	4.98	
		d	2.04	1.07	-4.91	0.04	-1.59	1.25	-2.37	-0.60	
		d lower bound	-1.92	-1.00	-7.79	-3.70	-2.51	-0.20	-7.24	-2.44	
		d upper bound	6.01	3.15	-2.03	3.79	-0.68	2.71	2.50	1.25	
		LA lower bound	-8.82	-4.61	-11.66	-8.74	-4.42	-3.25	-14.79	-6.29	
		LA upper bound	12.91	6.76	1.84	8.82	1.23	5.76	10.04	5.10	
		RMS(individual)	4.10		3.49		1.97				
		Fraction(individual)	0.78		0.71		1.00		4.41	2.67	
		RMS(mean)	4.03						0.83	1.00	
		Fraction(mean)	0.92								
Component Parameter	IC 2nd Hip Angle	Comparison System	Inter-System: Vicon		Intra-System: Between Reps				Intra-System: Between Day		MCID
			LCMAS-Single (Markers)		LCMAS-Single (Markers)		Vicon		LCMAS-Single (Markers)		
			Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
IC 2nd Hip Angle	Hip Angle	ICC	0.898	0.793	0.697	0.787	0.964	0.945	0.721	0.977	9.41 to 11.14 degrees
		n	10	10	8	8	12	12	9	12	
		SEM	3.3234	3.9565	4.15	2.96	1.64	1.99	4.54	1.78	
		SDD	9.2119	10.9669	11.50	8.21	4.54	5.52	12.60	4.94	
		SDDlower bound	-7.5014	-9.1460	-16.41	-8.17	-6.36	-4.09	-14.97	-6.58	
		SDDupper bound	10.9225	12.7877	6.60	8.25	2.73	6.95	10.22	3.30	
		d	1.7106	1.8209	-4.91	0.04	-1.82	1.43	-2.37	-1.64	
		d lower bound	-1.6516	-2.1818	-7.79	-3.70	-2.77	-0.18	-7.24	-2.91	
		d upper bound	5.0727	5.8236	-2.03	3.79	-0.86	3.04	2.50	-0.37	
		LA lower bound	-7.5014	-9.1460	-11.66	-8.74	-4.76	-3.54	-14.79	-5.56	
		LA upper bound	10.9225	12.7877	1.84	8.82	1.13	6.40	10.04	2.27	
		RMS(individual)	5.8470		3.49		2.08				
		Fraction(individual)	0.7778		0.71		1.00		4.41	2.63	
		RMS(mean)	5.7740						0.83	1.00	
		Fraction(mean)	0.9167								

Table 9.2: (cont.) *Primary Variables - DVJ - LCMAS-Single - IC - 2nd Component - Hip Angle.*

Component Parameter IC 2nd Hip Angle	Comparison System	Inter-System: Vicon		Intra-System: Between Reps				Intra-System: Between Day		MCID
		Vicon (Markers)		Vicon (Markers)		Vicon (Markers)		Vicon (Markers)		
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
ICC	Statistic	0.897	0.916	0.919	0.911	0.964	0.945	0.923	0.977	
n		12	12	12	12	12	12	12	12	
SEM		3.02	2.74	1.49	1.79	1.64	1.99	2.01	1.78	
SDD		8.36	7.60	4.13	4.96	4.54	5.52	5.57	4.94	9.41 to
SDDlower bound		-8.48	-6.66	-5.72	-3.71	-6.36	-4.09	-6.17	-6.58	11.14
SDDupper bound		8.25	8.53	2.54	6.22	2.73	6.95	4.98	3.30	degrees
d		-0.11	0.94	-1.59	1.25	-1.82	1.43	-0.60	-1.64	
d lower bound		-2.82	-1.53	-2.51	-0.20	-2.77	-0.18	-2.44	-2.91	
d upper bound		2.60	3.40	-0.68	2.71	-0.86	3.04	1.25	-0.37	
LA lower bound		-8.48	-6.66	-4.42	-3.25	-4.76	-3.54	-6.29	-5.56	
LA upper bound		8.25	8.53	1.23	5.76	1.13	6.40	5.10	2.27	
RMS(individual)		3.63		1.97		2.08				
Fraction(individual)		1.00		1.00		1.00				
RMS(mean)		3.62						2.67	2.63	
Fraction(mean)		1.00						1.00	1.00	

Table 9.2: (cont.) *Primary Variables - DVJ - LCMAS-Single - Min - 1st Component - Knee Angle.*

Component Parameter		Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Day		MCID
			LCMAS-Single (Vicon Static, IK)		LCMAS-Single (Vicon Static, IK)		Vicon		LCMAS-Single (Vicon Static, IK)		
Min 1st	Knee Angle JCS	Statistic	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
		ICC	0.888	0.884	0.849	0.725	0.935	0.815	0.964	0.989	
		n	12	12	12	12	12	12	12	12	
		SEM	5.52	6.27	5.40	8.59	2.96	5.35	3.73	1.71	
		SDD	15.29	17.38	14.97	23.81	8.22	14.82	10.35	4.73	10.5 to
		SDDlower bound	-11.35	-13.47	-19.49	-22.37	-7.64	-11.68	-9.86	-4.22	46
		SDDupper bound	19.22	21.30	10.46	25.26	8.80	17.96	10.84	5.24	degrees
		d̄	3.93	3.91	-4.51	1.44	0.58	3.14	0.49	0.51	
		d̄ lower bound	-1.02	-1.72	-8.60	-6.56	-2.18	-1.42	-3.00	-1.05	
		d̄ upper bound	8.89	9.55	-0.42	9.45	3.34	7.70	3.98	2.08	
		LA lower bound	-11.35	-13.47	-17.13	-23.25	-7.92	-10.94	-10.27	-4.31	
		LA upper bound	19.22	21.30	8.11	26.14	9.08	17.22	11.25	5.34	
		RMS(individual)	11.67		10.20		4.79				
		Fraction(individual)	1.00		1.00		1.00		10.13	5.40	
		RMS(mean)	10.74						1.00	1.00	
		Fraction(mean)	1.00								

Component Parameter		Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Day		MCID
			LCMAS-Single (Vicon Static, 6DOF)		LCMAS-Single (Vicon Static, 6DOF)		Vicon		LCMAS-Single (Vicon Static, 6DO)		
Min 1st	Knee Angle JCS	Statistic	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
		ICC	0.552	0.637	0.905	0.866	0.935	0.815	0.953	0.989	
		n	12	12	12	12	12	12	12	12	
		SEM	10.54	11.40	4.78	6.85	2.96	5.35	5.04	1.71	
		SDD	29.22	31.60	13.24	19.00	8.22	14.82	13.97	4.73	10.5 to
		SDDlower bound	-32.69	-38.79	-15.47	-15.88	-7.64	-11.68	-17.17	-4.22	46
		SDDupper bound	25.75	24.41	11.01	22.11	8.80	17.96	10.76	5.24	degrees
		d̄	-3.47	-7.19	-2.23	3.11	0.58	3.14	-3.21	0.51	
		d̄ lower bound	-12.94	-17.43	-6.46	-2.98	-2.18	-1.42	-7.43	-1.05	
		d̄ upper bound	6.00	3.05	2.00	9.20	3.34	7.70	1.02	2.08	
		LA lower bound	-32.69	-38.79	-15.29	-15.68	-7.92	-10.94	-16.23	-4.31	
		LA upper bound	25.75	24.41	10.83	21.90	9.08	17.22	9.82	5.34	
		RMS(individual)	16.68		11.10		4.79				
		Fraction(individual)	1.00		1.00		1.00		13.78	5.40	
		RMS(mean)	15.88						1.00	1.00	
		Fraction(mean)	1.00								

Table 9.2: (cont.) *Primary Variables - DVJ - LCMAS-Single - Min - 1st Component - Knee Angle.*

Component Parameter	Min 1st	Knee Angle	Marker	Comparison System	Inter-System: Vicon (Marker)		Intra-System: Between Reprs				Intra-System: Between Day		MCID		
					LCMAS-Single (Markers)		LCMAS-Single (Markers)		Vicon (Markers)		LCMAS-Single (Markers)			Vicon (Markers)	
					Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2		Day 1	Day 2
ICC					0.719	0.907	0.869	0.211	0.937	0.804	0.921	0.982			
n					10	7	7	7	12	12	7	12			
SEM					7.98	5.34	4.11	15.33	2.86	5.43	5.16	2.18			
SDD					22.11	14.79	11.39	42.49	7.93	15.05	14.31	6.04	10.5 to		
SDDlower bound					-26.59	-18.84	-13.72	-47.51	-7.29	-12.20	-11.49	-5.00	46		
SDDupper bound					17.63	10.75	9.06	37.46	8.57	17.89	17.12	7.09	degrees		
d					-4.48	-4.04	-2.33	-5.03	0.64	2.84	2.81	1.04			
d lower bound					-12.55	-11.02	-7.65	-26.09	-2.01	-1.89	-3.91	-0.88			
d upper bound					3.59	2.94	2.99	16.04	3.29	7.58	9.54	2.97			
LA lower bound					-26.59	-18.84	-13.60	-49.67	-7.54	-11.75	-11.44	-4.89			
LA upper bound					17.63	10.75	8.95	39.61	8.82	17.44	17.07	6.98			
RMS(individual)					10.68		10.04		4.74						
Fraction(individual)					0.61		0.58		1.00		8.04	6.18			
RMS(mean)					10.55						0.58	1.00			
Fraction(mean)					0.71										

Component Parameter	Min 1st	Knee Angle	Marker	Comparison System	Inter-System: Vicon		Intra-System: Between Reprs				Intra-System: Between Day		MCID		
					LCMAS-Single (Markers)		LCMAS-Single (Markers)		Vicon (Markers)		LCMAS-Single (Markers)			Vicon (Markers)	
					Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2		Day 1	Day 2
ICC					0.754	0.880	0.869	0.211	0.935	0.815	0.921	0.989			
n					10	7	7	7	12	12	7	12			
SEM					7.54	6.01	4.11	15.33	2.96	5.35	5.16	1.71			
SDD					20.89	16.65	11.39	42.49	8.22	14.82	14.31	4.73	10.5 to		
SDDlower bound					-30.05	-25.81	-13.72	-47.51	-7.64	-11.68	-11.49	-4.22	46		
SDDupper bound					11.74	7.50	9.06	37.46	8.80	17.96	17.12	5.24	degrees		
d					-9.16	-9.15	-2.33	-5.03	0.58	3.14	2.81	0.51			
d lower bound					-16.78	-17.01	-7.65	-26.09	-2.18	-1.42	-3.91	-1.05			
d upper bound					-1.53	-1.30	2.99	16.04	3.34	7.70	9.54	2.08			
LA lower bound					-30.05	-25.81	-13.60	-49.67	-7.92	-10.94	-11.44	-4.31			
LA upper bound					11.74	7.50	8.95	39.61	9.08	17.22	17.07	5.34			
RMS(individual)					12.43		10.04		4.79						
Fraction(individual)					0.61		0.58		1.00		8.04	5.40			
RMS(mean)					12.69						0.58	1.00			
Fraction(mean)					0.71										

Table 9.2: (cont.) *Primary Variables - DVJ - LCMAS-Single - Min - 1st Component - Knee Angle.*

Component Parameter	Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Day		MCID
		Vicon (Markers)		Vicon (Markers)		Vicon (Markers)		Vicon (Markers)		
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
Max 1st Knee Angle	ICC	0.994	0.987	0.937	0.804	0.935	0.815	0.982	0.989	
	n	12	12	12	12	12	12	12	12	
	SEM	1.23	1.96	2.86	5.43	2.96	5.35	2.18	1.71	
	SDD	3.41	5.43	7.93	15.05	8.22	14.82	6.04	4.73	10.5 to 46
	SDDlower bound	-7.77	-9.27	-7.29	-12.20	-7.64	-11.68	-5.00	-4.22	degrees
	SDDupper bound	-0.96	1.59	8.57	17.89	8.80	17.96	7.09	5.24	
	d	-4.37	-3.84	0.64	2.84	0.58	3.14	1.04	0.51	
	d lower bound	-5.47	-5.60	-2.01	-1.89	-2.18	-1.42	-0.88	-1.05	
	d upper bound	-3.26	-2.08	3.29	7.58	3.34	7.70	2.97	2.08	
	LA lower bound	-7.77	-9.27	-7.54	-11.75	-7.92	-10.94	-4.89	-4.31	
	LA upper bound	-0.96	1.59	8.82	17.44	9.08	17.22	6.98	5.34	
	RMS(individual)	3.89		4.74		4.79				
	Fraction(individual)	1.00		1.00		1.00				
	RMS(mean)	3.88						6.18	5.40	
	Fraction(mean)	1.00						1.00	1.00	

Table 9.2: (cont.) *Primary Variables - DVJ - LCMAS-Single - IC - 2nd Component - Knee Angle.*

Component Parameter	IC 2nd	Knee Angle	Marker	Comparison System	Inter-System: Vicon (Marker)		Intra-System: Between Reps				Intra-System: Between Day		MCID																																																																																	
					LCMAS-Single (Markers)		LCMAS-Single (Markers)		Vicon (Markers)		LCMAS-Single (Markers)			Vicon (Markers)																																																																																
					Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2		Day 1	Day 2																																																																															
IC 2nd			ICC	n	0.961	0.948	0.775	0.812	0.933	0.876	0.949	0.947	6.17 to 8.4 degrees																																																																																	
														SEM	8	10	1.64	1.38	0.77	1.02	1.08	0.95																																																																								
																							SDD	2.59	2.83	-5.76	-3.15	-2.13	-1.74	-4.17	-2.98																																																															
																																SDDlower bound	3.94	3.32	3.35	4.51	2.14	3.89	1.82	2.31																																																						
																																									SDDupper bound	1.35	0.49	-1.20	0.68	0.01	1.07	-1.17	-0.33																																													
																																																		d̄	lower bound	0.24	-0.54	-2.98	-1.15	-0.72	0.44	-2.05	-1.20																																			
																																																												d̄ upper bound	2.45	1.53	0.57	2.51	0.73	1.71	-0.30	0.54																										
																																																																					LA lower bound	-1.24	-2.33	-5.37	-3.20	-2.22	-0.88	-3.23	-3.01																	
																																																																														LA upper bound	3.94	3.32	2.96	4.56	2.24	3.03	0.88	2.34								
																																																																																							RMS(individual)	1.55	2.39	2.20	1.00			
																																																																																												Fraction(individual)	0.72	0.67
Fraction(mean)	0.83																																																																																													

Component Parameter	IC 2nd	Knee Angle	Marker	Comparison System	Inter-System: Vicon		Intra-System: Between Reps				Intra-System: Between Day		MCID																																																																												
					LCMAS-Single (Markers)		LCMAS-Single (Markers)		Vicon		LCMAS-Single (Markers)			Vicon																																																																											
					Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2		Day 1	Day 2																																																																										
IC 2nd			ICC	n	0.245	0.411	0.775	0.812	0.933	0.910	0.949	0.973	6.17 to 8.4 degrees																																																																												
														SEM	8	10	1.64	1.38	1.21	1.47	1.08	1.08																																																																			
																							SDD	9.62	9.78	-5.76	-3.15	-2.71	-2.96	-4.17	-2.97																																																										
																																SDDlower bound	11.23	9.66	3.35	4.51	4.02	5.18	1.82	3.03																																																	
																																									SDDupper bound	1.61	-0.12	0.68	0.66	1.11	-1.17	0.03																																									
																																																	d̄	lower bound	-2.50	-3.69	-2.98	-1.15	-0.40	-0.05	-0.99																																
																																																										d̄ upper bound	5.71	3.45	0.57	2.51	1.71	2.27	1.04																								
																																																																		LA lower bound	-8.02	-9.90	-5.37	-3.20	-2.59	-2.48	-3.10																
																																																																										LA upper bound	11.23	9.66	2.96	4.56	3.90	4.70	0.88	3.16							
																																																																																			RMS(individual)	5.03	2.39	1.99			
																																																																																							Fraction(individual)	0.72	1.00
Fraction(mean)	0.83																																																																																								

Table 9.2: (cont.) *Primary Variables - DVJ - LCMAS-Single - IC - 2nd Component - Knee Angle.*

Component Parameter	Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Day		MCID
		Vicon		Vicon		Vicon		Vicon		
		(Markers)		(Markers)		(Markers)		(Markers)		
IC 2nd	Knee Angle	Statistic	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2
		ICC	0.389	0.371	0.933	0.876	0.933	0.910	0.947	0.973
		n	12	12	12	12	12	12	12	12
		SEM	3.40	3.53	0.77	1.02	1.21	1.47	0.95	1.08
		SDD	9.43	9.79	2.13	2.82	3.37	4.07	2.64	3.00
		SDDlower bound	-8.95	-9.67	-2.13	-1.74	-2.71	-2.96	-2.98	-2.97
		SDDupper bound	9.90	9.91	2.14	3.89	4.02	5.18	2.31	3.03
		d	0.48	0.12	0.01	1.07	0.66	1.11	-0.33	0.03
		d lower bound	-2.58	-3.06	-0.72	0.44	-0.40	-0.05	-1.20	-0.99
		d upper bound	3.53	3.29	0.73	1.71	1.71	2.27	0.54	1.04
		LA lower bound	-8.95	-9.67	-2.22	-0.88	-2.59	-2.48	-3.01	-3.10
		LA upper bound	9.90	9.91	2.24	3.03	3.90	4.70	2.34	3.16
		RMS(individual)	4.98		2.20		1.99			
		Fraction(individual)	1.00		1.00		1.00			
		RMS(mean)	4.77						1.91	2.70
		Fraction(mean)	1.00						1.00	1.00

Table 9.2: (cont.) *Primary Variables - DVJ - LCMAS-Single - Max - 2nd Component - Knee Angle.*

Component Parameter	Max 2nd Knee Angle Marker	Comparison System	Inter-System: Vicon (Markers)		Intra-System: Between Reps				Intra-System: Between Days		MCID
			LCMAS-Single (Markers)		LCMAS-Single (Markers)		Vicon (Markers)		LCMAS-Single (Markers)		
			Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
ICC			0.987	0.916	0.785	0.917	0.882	0.910	0.941	0.968	
n			10	10	9	7	12	12	9	12	
SEM			0.79	1.63	2.13	1.37	1.89	1.24	1.69	1.19	
SDD			2.18	4.51	5.90	3.78	5.23	3.45	4.67	3.31	6.2 to
SDD lower bound			-3.08	-4.99	-4.43	-4.35	-4.56	-4.39	-4.48	-3.36	8.72
SDD upper bound			1.29	4.03	7.37	3.22	5.89	2.50	4.87	3.26	degrees
$\bar{d}$			-0.89	-0.48	1.47	-0.56	0.67	-0.95	0.19	-0.05	
$\bar{d}$ lower bound			-1.69	-2.12	-0.67	-2.41	-1.05	-1.93	-1.74	-1.17	
$\bar{d}$ upper bound			-0.10	1.17	3.61	1.28	2.38	0.04	2.13	1.07	
LA lower bound			-3.08	-4.99	-3.99	-4.47	-4.62	-3.98	-4.75	-3.51	
LA upper bound			1.29	4.03	6.93	3.34	5.95	2.09	5.13	3.41	
RMS (individual)			1.55		2.39		2.20				
Fraction (individual)			0.72		0.67		1.00		2.12	1.91	
RMS (mean)			1.54						0.75	1.00	
Fraction (mean)			0.83								

Component Parameter	Max 2nd Knee Angle	Comparison System	Inter-System: Vicon		Intra-System: Between Reps				Intra-System: Between Days		MCID
			LCMAS-Single (Markers)		LCMAS-Single (Markers)		Vicon		LCMAS-Single (Markers)		
			Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
ICC			0.508	0.760	0.785	0.917	0.948	0.968	0.941	0.950	
n			10	10	9	7	12	12	9	12	
SEM			4.14	3.86	2.13	1.37	1.55	1.28	1.69	2.15	
SDD			11.49	10.70	5.90	3.78	4.30	3.54	4.67	5.95	6.2 to
SDD lower bound			-9.80	-7.59	-4.43	-4.35	-4.21	-4.01	-4.48	-6.12	8.72
SDD upper bound			13.17	13.81	7.37	3.22	4.39	3.06	4.87	5.78	degrees
$\bar{d}$			1.69	3.11	1.47	-0.56	0.09	-0.47	0.19	-0.17	
$\bar{d}$ lower bound			-2.51	-0.79	-0.67	-2.41	-1.37	-1.63	-1.74	-2.18	
$\bar{d}$ upper bound			5.88	7.02	3.61	1.28	1.55	0.68	2.13	1.84	
LA lower bound			-9.80	-7.59	-3.99	-4.47	-4.40	-4.04	-4.75	-6.37	
LA upper bound			13.17	13.81	6.93	3.34	4.58	3.09	5.13	6.03	
RMS (individual)			5.03		2.39		1.99				
Fraction (individual)			0.72		0.67		1.00		2.12	2.70	
RMS (mean)			4.57						0.75	1.00	
Fraction (mean)			0.83								

Table 9.2: (cont.) *Primary Variables - DVJ - LCMAS-Single - Max - 2nd Component - Knee Angle.*

Component Parameter		Comparison System	Inter-System: Vicon		Intra-System: Between Reps				Intra-System: Between Days		MCID
			Vicon (Markers)		Vicon (Markers)		Day 1	Day 2	Vicon (Markers)	Vicon	
			Day 1	Day 2	Day 1	Day 2					
Max 2nd	Knee Angle	ICC	0.750	0.660	0.882	0.910	0.948	0.968	0.968	0.950	
		n	12	12	12	12	12	12	12	12	
		SEM	3.75	4.29	1.89	1.24	1.55	1.28	1.19	2.15	
		SDD	10.39	11.88	5.23	3.45	4.30	3.54	3.31	5.95	6.2 to
		SDD lower bound	-7.14	-8.51	-4.56	-4.39	-4.21	-4.01	-3.36	-6.12	8.72
		SDD upper bound	13.64	15.25	5.89	2.50	4.39	3.06	3.26	5.78	degrees
		$\bar{d}$	3.25	3.37	0.67	-0.95	0.09	-0.47	-0.05	-0.17	
		$\bar{d}$ lower bound	-0.12	-0.48	-1.05	-1.93	-1.37	-1.63	-1.17	-2.18	
		$\bar{d}$ upper bound	6.62	7.22	2.38	0.04	1.55	0.68	1.07	1.84	
		LA lower bound	-7.14	-8.51	-4.62	-3.98	-4.40	-4.04	-3.51	-6.37	
		LA upper bound	13.64	15.25	5.95	2.09	4.58	3.09	3.41	6.03	
		RMS (individual)	4.98		2.20		1.99				
		Fraction (individual)	1.00		1.00		1.00				
		RMS (mean)	4.77						1.91	2.70	
		Fraction (mean)	1.00						1.00	1.00	

Table 9.3: *Secondary Variables - DVJ - LCMAS-Single - ROM - 1st Component - COM Position.*

Component Parameter	ROM 1st	Position COM	Comparison System		Inter-System: Vicon				Intra-System: Between Repts				Intra-System: Between Days		MCID
			Statistic	System	LCMAS-Single (Vicon Static, IK)		Day 1	Day 2	LCMAS-Single (Vicon Static, IK)		Vicon		LCMAS-Single (Vicon Static, IK)	Vicon	
					Day 1	Day 2			Day 1	Day 2	Day 1	Day 2			
ROM 1st	Position COM	ICC		0.836	0.959	8	8	0.596	0.514	0.776	0.478	0.432	0.777	0.0404 m	
		n		0.005	0.003	6	6	0.010	0.010	0.005	0.008	0.008	0.005		
		SEM		0.014	0.009	0.027	0.029	-0.024	-0.018	0.014	0.023	-0.025	0.015		
		SDD lower bound		-0.017	-0.014	0.010	0.004	-0.030	0.040	0.014	-0.019	0.020	-0.015		
		SDD upper bound		-0.004	-0.005	0.003	-0.005	0.003	0.011	0.000	0.004	-0.003	0.000		
		$\bar{d}$ lower bound		-0.009	-0.009	-0.013	-0.009	-0.013	0.000	-0.005	-0.004	-0.013	-0.005		
		$\bar{d}$ upper bound		0.002	-0.001	0.018	0.022	0.018	0.022	0.005	0.011	0.007	0.005		
		LA lower bound		-0.017	-0.014	-0.026	-0.009	-0.026	-0.009	-0.015	-0.019	-0.026	-0.016		
		LA upper bound		0.010	0.004	0.032	0.031	0.032	0.031	0.015	0.027	0.021	0.015		
		RMS (individual)		0.005		0.018		0.018		0.019					
		Fraction (individual)		0.556		0.500		0.500		1.000		0.018	0.023		
		RMS (mean)		0.007								0.667	1.000		
		Fraction (mean)		0.667											

Component Parameter	ROM 1st	Position COM	Comparison System		Inter-System: Vicon				Intra-System: Between Repts				Intra-System: Between Days		MCID
			Statistic	System	LCMAS-Single (Vicon Static, 6DOF)		Day 1	Day 2	LCMAS-Single (Vicon Static, 6DOF)		Vicon		LCMAS-Single (Vicon Static, 6DOF)	Vicon	
					Day 1	Day 2			Day 1	Day 2	Day 1	Day 2			
ROM 1st	Position COM	ICC		0.689	0.884	6	6	0.815	0.676	0.776	0.478	0.766	0.777	0.0404 m	
		n		0.005	0.007	4	4	0.006	0.011	0.005	0.008	0.009	0.005		
		SEM		0.015	0.020	0.018	0.030	0.018	0.030	0.014	0.023	0.025	0.015		
		SDD lower bound		-0.011	-0.025	-0.013	-0.025	-0.013	-0.025	-0.014	-0.019	-0.032	-0.015		
		SDD upper bound		0.018	0.014	0.023	0.036	0.023	0.036	0.014	0.027	0.017	0.015		
		$\bar{d}$ lower bound		0.003	-0.006	0.005	0.006	0.005	0.006	0.000	0.004	-0.007	0.000		
		$\bar{d}$ upper bound		-0.005	-0.016	-0.009	-0.011	-0.009	-0.011	-0.005	-0.004	-0.019	-0.005		
		LA lower bound		0.011	0.005	0.019	0.022	0.019	0.022	0.005	0.011	0.004	0.005		
		LA upper bound		-0.011	-0.025	-0.012	-0.025	-0.012	-0.025	-0.015	-0.019	-0.029	-0.016		
		RMS (individual)		0.018	0.014	0.022	0.036	0.022	0.036	0.015	0.027	0.014	0.015		
		Fraction (individual)		0.005		0.017		0.017		0.019					
		Fraction (mean)		0.361		0.417		0.417		1.000		0.017	0.023		
		RMS (mean)		0.006								0.500	1.000		
		Fraction (mean)		0.500											

9.2 Discussion

We will first discuss general points. Then we will step through a discussion of the primary and secondary metrics presented in the numerical tables of the prior section.

9.2.1 General

COM Relative to BOS Interpretation

For understanding and interpretation of the COM relative to BOS plot we look to the example in Figure 9.10. In this figure, the path for the LCMAS-Single COM relative to BOS travels a larger range in the Y -direction and a more similar range in the X -direction when compared to the Vicon COM relative to BOS. This positioning demonstrates greater measurement similarity in the X -direction (medial-lateral) than in the Y -direction (anterior-posterior) or the depth value from the LCMAS-Single system.

Bland-Altman Plots Interpretation

In the Bland-Altman plots the mean difference, $\bar{d}$, represents an estimate of the bias between measurements. If this number is positive or negative, the measurements from one system (for inter-system comparisons) or one test occasion (for intra-system comparisons) tend to be larger or smaller than the other. If the $95\%CI_{\bar{d}}$ does not include zero, it indicates a systematic bias [67]. If the bias is consistent, we can adjust the new method by simply adding or subtracting $\bar{d}$ to match the industry gold standard [10]. It is possible that the variability changes with magnitude and that the $95\%LA$ are too wide or too narrow throughout the measurement range. A logarithmic transformation could be used to address these differences. It is also possible that difference is nonuniform and in one direction for low values and the other direction for larger

values. This relationship could cause the 95%*LA* to be wider than necessary. A linear regression for determining $\bar{d}$ would narrow the bands for the corresponding 95%*CI* and 95%*LA*. [11] For example, this type of analysis could benefit the data shown in the top row left side of Figure 9.10 where values are above $\bar{d}$ on the left side of the plots and below $\bar{d}$ on the right side of the plots. We leave this level of analysis and refinement to future work.

Reliability and Repeatability

Agreement between two systems is impacted by intra-system repeatability [11]. If either system has poor repeatability the result would be poor agreement. For this reason it is important to compare the intra-system repeatability alongside the inter-system reliability in our screening criteria. If we can improve intra-system repeatability for our LCMAS-Single system across additional metrics, we will likely see improved inter-system agreement. While inter-system agreement could be impacted by lack of repeatability from either system, almost all of the data presented here shows the Vicon system to have better repeatability and lower *SDD* than the LCMAS-Single.

The 95%*SDD* is similar to the 95%*LA* and both can be used to estimate the inter-system reliability and intra-system repeatability. If this value is similar between intra-system repeatability for one system and inter-system reliability, a lack of agreement can be attributed to lack of repeatability by that system. If the inter-system bounds are considerably wider than either of the intra-system bounds, then some other factor is impacting the agreement [11]. Most of our data is within the range of the intra-system bounds.

Root Mean Square Analysis

Only a few metrics met our overall criteria. However, we did see that *RMS*

values tended to be smaller than *SDD* values. We suspect this observation indicates that LCMAS-Single is better at representing the curve of a metric over the duration of a repetition rather than the peak metrics. This situation could potentially be improved in future work by refining data processing. These process improvements could include adjustments to filter and polynomial fit parameters, as well as the range of detection based on the Vicon data.

LCMAS-Single Model

The LCMAS-Single (Vicon Static - IK) was the model with the most associated metrics, with three primary (Max 1st component hip angle, IC 2nd component hip angle, and Min 1st knee angle) and one secondary (ROM 1st component COM position) meeting our screening criteria. The LCMAS-Single (Vicon Static - 6DOF) was the second place model for associated metrics, with two primary (Max 1st component hip angle, and Min 1st knee angle,) and one secondary (ROM 1st component COM position) meeting our screening criteria. We suspect the association with the Vicon static over the Kinect static indicates a compounding error when a Kinect static is employed. When the LCMAS-Single uses the Vicon static, the low-cost and Vicon Systems use the same static reference posture. If this set-up yields a positive result with our screening criteria over a set-up using the Kinect static, this situation indicates the low-cost tracking is adequate but the initial assignment calibration in the low-cost system is poor. Possible refinement of defining the static reference posture in our LCMAS-Single system would improve metric detection in a stand alone system. For example, aligning the calibration markers at each joint in the participant's frontal plane and then ensuring both markers have the same value in the anterior-posterior direction in post-processing. We also suspect that the results were better with the IK model over the 6DOF model because of the additional constraints on the system.

Selection of model did not impact marker based angles.

Marker Based Angle Measurements

The LCMAS-Single had two primary (IC 2nd component knee angle, and Max 2nd component knee angle) and zero secondary metrics meet our screening criteria for marker based angle measurements relative to Vicon marker based angle measurements. The LCMAS-Single had zero metrics meet our screening criteria for marker based angle measurements relative to Vicon rotation based angle measurements. The Vicon System had five primary (Max 1st component hip angle, ROM 1st hip angle, IC 2nd component hip angle, Min 1st knee angle, and ROM 1st knee angle) and one secondary (ROM 2nd component knee angle) metric meet our screening criteria for marker based angle measurements relative to Vicon rotation based angle measurements. Only one of these metrics (IC 2nd component knee angle) passed the screening criteria for both LCMAS-Single marker based angle measurements relative to Vicon marker based angle measurements and Vicon marker based angle measurements relative to Vicon rotation based angle measurements. However, we did see good intra-system reliability and low *SDD* from several LCMAS-Single marker based angle measurements (Max 1st component hip angle, ROM 1st knee angle, IC 2nd component knee angle, Min 2nd component knee angle, and Max 2nd component knee angle) reported in the summary table. This observation indicates a potential to use marker based angle measurements as a injury risk screening metric in the future, after we conduct a prospective study to establish metric thresholds.

Coordinate System for Reporting Moment

None of the moment metrics met our screening criteria. In general, the Vicon system showed adequate to excellent intra-system correlation and the intra-system *SDD* was smaller than the *MCID*. The intra-system LCMAS-Single (Vicon Static - IK, Vicon - 6DOF, and Kinect Static - IK) had mixed intra-system results as did each systems' inter-system comparison to Vicon. We had more of the

systems close to passing our screening criteria for the 2nd component of Knee Moment in the JCS. Pending future work, currently the JCS is coordinate system of choice.

9.2.2 Primary Variables DVJ - LCMAS-Single Compared to Vicon

This section covers the primary metrics summarized in Table 9.1 and detailed in Tables 9.2.

Max - 1st Component - Hip Angle

First, we examine the rotation based angle comparisons. For the inter-system comparison for this metric, the data captured with the LCMAS-Single, using the Vicon Static reference posture and both the IK and 6DOF models, were excellently correlated to the corresponding Vicon System data for both Day 1 and Day 2. For intra-system comparisons, these systems also had excellent correlation for each day of between repetition comparisons and between days comparisons. Also, all of the data was validly collected with these systems for each day of testing. When evaluating the *SDD*, we see larger values for the inter-system comparisons and smaller values for the intra-system comparisons. For the between days comparison, the Vicon *SDD* was about half of the LCMAS-Single (Vicon Static - IK and Vicon - 6DOF) *SDDs*. For these systems all inter- and intra-system comparisons yielded *SDD* values were less than the *MCID* from the scientific literature. The Bland-Altman plots showed a bias, $\bar{d}$, of around 20 degrees for the LCMAS-Single (Vicon Static - IK) to Vicon inter-system comparison, and around 9 degrees for the LCMAS-Single (Vicon Static - 6DOF) to Vicon inter-system comparison. All intra-system comparisons for these systems displayed a $\bar{d}$, of less than 4.2 degrees. In addition, the 95%*LA* were similar to the 95%*SDD*, with larger spread on the inter-system comparisons than the intra-system comparisons.

Now, we examine the marker based angle comparison. For the inter-system comparisons for this metric, the LCMAS-Single (Markers) based data was adequately correlated to the corresponding Vicon (Markers) data. The intra-system comparisons for LCMAS-Single (Markers) and Vicon (Markers) were excellently correlated. About two-thirds of the data was validly detected in LCMAS-Single (Markers), while all the data was detected in Vicon (Markers). For LCMAS-Single (Markers) and Vicon (Markers) the intra-system *SDD* values were less than the *MCID* from the scientific literature. However, the inter-system *SDD* values were below the *MCID* value, thus not meeting our screening criteria.

Finally, we examine the Vicon and LCMAS-Single marker based angles to the Vicon rotation based angle. For the inter-system comparisons for this metric, the Vicon (Markers) and LCMAS-Single (Markers) based data were adequately correlated to the corresponding Vicon System rotation based data. The intra-system comparisons were discussed above. The inter-system *SDD* values for Vicon (Markers) to Vicon rotation based angle comparisons were smaller than the *MCID* values, showing potential for the marker based metric to be a surrogate measure for the rotation based metric after accounting for the 14 degree measurement bias, $\bar{d}$. However, the inter-system *SDD* values for LCMAS-Single (Markers) to Vicon rotation based angle comparisons were greater than the *MCID* values, thus not meeting our screening criteria. This LCMAS-Single (Markers) metric has potential to be used in clinical evaluations following system improvements and/or a prospective study.

For all comparisons, the *RMS* values were smaller than the corresponding *SDD* values and the *MCID* values.

IC - 2nd Component - Hip Angle

Again we start with examining the rotation based angle comparisons. For the inter-system comparison for this metric, the data captured with the LCMAS-

Single, using the Vicon Static reference posture and both the IK and 6DOF models, were excellently correlated to the corresponding Vicon System data for both Day 1 and Day 2. For intra-system comparisons, these systems also had excellent correlation for each day of between repetition comparisons and between days comparisons. Also, all of the data was validly collected with the LCMAS-Single (Vicon Static - IK and Vicon Static - 6DOF) for each day of testing. When evaluating the *SDD*, we see all values for the LCMAS-Single (Vicon Static - IK) comparison are less than the smaller *MCID*, with the exception of inter-system comparison Day 1 *SDD* which is less than the larger *MCID* value. For the LCMAS-Single (Vicon Static - 6DOF) comparison, all *SDD* values are less than the smaller *MCID*, with the exception of inter-system comparison Day 1 *SDD* which is less than the larger *MCID* value, and intra-system LCMAS-Single (Vicon Static - 6DOF) between days Day 1 *SDD* which exceeds both *MCID* values. LCMAS-Single (Vicon Static - 6DOF) does not meet our screening criteria but LCMAS-Single (Vicon Static - IK) passes the evaluation. For the LCMAS-Single (Vicon Static - IK), the Bland-Altman plots showed a bias, $\bar{d}$, of less than 2 degrees across all comparisons. In addition, the 95%*LA* were similar to the 95%*SDD*.

Now, we examine the marker based angle comparisons. For the LCMAS-Single (Markers) based data and the corresponding Vicon (Markers) data, all *ICC* values were adequate or excellent. However, the the intra-system *SDD* value for LCMAS-Single (Markers) between repetitions Day 1 and between days were above the larger *MCID* value, thus not meeting our screening criteria.

Finally, we examine the Vicon and LCMAS-Single marker based angles to the Vicon rotation based angle. For the inter-system comparisons for this metric, the Vicon (Markers) and LCMAS-Single (Markers) based data was excellently correlated to the corresponding Vicon System rotation based data. The intra-system comparisons were discussed above. The LCMAS-Single marker based angle compared to the Vicon rotation based angle did not meet our screening criteria

for the same reason the LCMAS-Single (Markers) based data compared to the corresponding Vicon (Markers) data did not meet our screening criteria, LCMAS-Single (Markers) intra-system *SDD*. However, the inter-system *SDD* values for Vicon (Markers) to the Vicon rotation based angle were smaller than the *MCID*, which again shows the potential of the marker based angle as a surrogate for the corresponding rotation based angle with future work.

For all comparisons, the *RMS* values were smaller than the corresponding *SDD* values and the *MCID* values.

Min - 1st Component - Knee Angle

We begin with an examination of the rotation based angle comparisons. For this metric the JCS based rotation from the LCMAS-Single (Vicon Static - IK and Vicon Static - 6DOF) met the screening criteria relative to their Vicon counterpart. For the inter-system comparison for this metric, the data captured with the LCMAS-Single (Vicon Static - IK), was excellently correlated to the corresponding Vicon System data for both Day 1 and Day 2. For intra-system comparisons, each system also had excellent correlation for each day of between repetition comparisons and between days comparisons, with the exception of between repetitions Day 2 for the LCMAS-Single (Vicon Static - IK) which had adequate correlation. The LCMAS-Single (Vicon Static - 6DOF) was excellently correlated for all intra-system comparisons and adequately correlated to the corresponding Vicon System data for inter-system comparisons. All of the data was validly collected with these three systems for each day of testing. The between repetition *SDD* tended to be larger than the between days *SDD* in each system, indicating a benefit to using a mean value from multiple repetitions. All *SDD* values were less than the larger *MCID* from the scientific literature. This comparison indicates that maneuvers scored with large differences between groups such as the deep squat in a Functional Movement Screen (FMS) may be an appropriate use of our system while it

may lack the accuracy for more sensitive comparisons. However, it is interesting to note that the between days LCMAS-Single (Vicon Static - IK) SDD was slightly smaller than the smaller $MCID$, as were the intra-system between repetitions Day 1 and between days SDD s for the Vicon system. This comparison indicates promise for the low-cost system to be used in more sensitive comparisons once a normative database has been established with the low-cost system. The Bland-Altman plots showed a bias, $\bar{d}$, of less than 7.2 degrees across all comparisons. In addition, 95% LA were similar to the corresponding 95% SDD . The RMS values were smaller than the SDD values for all comparisons with the exception of the between days comparison for Vicon data where the values were similar. However, LCMAS-Single (Vicon Static - IK) and Vicon intra-system RMS values were less than the smaller $MCID$ value while the intra-system LCMAS-Single (Vicon Static - 6DOF) and all inter-system RMS values were only slightly larger than the smaller $MCID$ value. Both LCMAS-Single (Vicon Static - IK) and LCMAS-Single (Vicon Static - 6DOF) meet our screening criteria.

Now, we examine the marker based angle comparison for LCMAS-Single (Markers) and Vicon (Markers). For the inter-system comparisons, Day 1 was adequately correlated and Day 2 was excellently correlated. In the intra-system comparisons for these systems all data was excellently correlated with the exception of the poor intra-system LCMAS-Single (Markers) between repetitions on Day 2. Almost two-thirds of the data in LCMAS-Single (Markers) was validly detected. All SDD values were below the larger $MCID$ value and the intra-system Vicon (Markers) between repetitions Day 1 and between days SDD values were also below the smaller $MCID$ values. Unfortunately, we just miss meeting our screening criteria do to the lack of correlation for LCMAS-Single (Markers) between repetitions Day 2. Again, this metric has potential and system improvements could bring this variable into the range of meeting our criteria.

We round out our analysis with an examination of the Vicon and LCMAS-

Single marker based angles to the Vicon rotation based angle. For all inter-system comparisons for this metric, the Vicon (Markers) and LCMAS-Single (Markers) based data was excellently correlated to the corresponding Vicon System rotation based data. The intra-system comparisons for this metric were discussed above. When evaluating the *SDD*, for the inter-system comparisons between Vicon (Markers) and Vicon (Rotation) we see values smaller than the inter-system comparisons between LCMAS-Single (Markers) and Vicon (Rotation), with the *SDD* values from Vicon (Markers) and Vicon (Rotation) less than the smaller *MCID* value and the *SDD* values from LCMAS-Single (Markers) and Vicon (Rotation) less than the larger *MCID* value. All of the *RMS* values were less than the smaller *MCID* value with the exception of inter-system LCMAS-Single (Markers) and Vicon (Rotations) that were slightly larger than the smaller *MCID* value and well below the larger *MCID* value. Again, we just miss meeting our screening criteria for the LCMAS-Single (Markers) due to the lack of correlation between repetitions Day 2. However, the positive outcome of the Vicon (Markers) to Vicon (Rotation) indicates the potential for the marker based angle to be a good surrogate measure for the rotation based measure.

IC - 2nd Component - Knee Angle

For this metric we start with the marker based angle comparison for LCMAS-Single (Markers) and Vicon (Markers) which met our screening criteria. For the inter-system comparison for this metric, the data captured with the LCMAS-Single (Markers), was excellently correlated to the corresponding Vicon System data for both Day 1 and Day 2. For intra-system comparisons, each system also had excellent correlation for each day of between repetition comparisons and between days comparisons. It is also important to note over two-thirds of the data was validly collected with the LCMAS-Single (Markers) for each day of testing. When evaluating the *SDD*, we see similar values for the inter-system comparisons, intra-

system between days comparisons, and intra-system between repetitions comparisons for Vicon (Markers). We see slightly larger values for intra-system between repetitions comparisons for LCMAS-Single (Markers). All *SDD* values were less than the smaller *MCID* from the scientific literature. The Bland-Altman plots showed a bias, $\bar{d}$, of less than 1.5 degrees across all comparisons. In addition, the intra-system 95%*LA* were similar to the 95%*SDD*.

Next, we look at the Vicon and LCMAS-Single marker based angles compared to the Vicon rotation based angle. All inter-system comparisons were poorly correlated and the *SDD* values were greater than the *MCID* values, with the exception of inter-system Day 2 LCMAS-Single (Markers) to Vicon (Rotation) which was adequately correlated. The intra-system comparisons for Vicon (Rotation) were excellently correlated with *SDD* values less than the smaller *MCID* value. The intra-system comparisons for LCMAS-Single (Markers) and Vicon (Markers) were discussed above.

The *RMS* values were smaller than the *MCID* values for all all comparisons.

So we have a successful screening criteria result for the LCMAS-Single (Markers) to Vicon (Markers) evaluation, however the negative result when comparing each of these systems to the Vicon (Rotation) data indicates the marker based data is not a surrogate measure for the rotation based data and a prospective study should be performed to establish thresholds for this metric.

Max - 2nd Component - Knee Angle

For this metric we start with the marker based angle comparison for LCMAS-Single (Markers) and Vicon (Markers) which also met our screening criteria. All inter- and intra-system comparisons were excellently correlated. About three-quarters of the data was validly collected with the LCMAS-Single (Markers) for each day of testing. When evaluating the *SDD*, we see similar values for all

comparisons. All *SDD* values were less than the *MCID* from the scientific literature. The Bland-Altman plots showed a bias, $\bar{d}$, of less than 1.5 degrees across all comparisons. In addition, the intra-system 95%*LA* were similar to the 95%*SDD*.

To complete our analysis of this metric we look at the Vicon and LCMAS-Single marker based angles compared to the Vicon rotation based angle. The inter-system correlation was excellent between LCMAS-Single (Markers) and Vicon (Rotation) for Day 2 and adequate for Day 1. The inter-system correlation was excellent between Vicon (Markers) and Vicon (Rotation) for Day 1 and adequate for Day 2. The intra-system correlation for Vicon (Rotation) was excellent for all comparisons and the other intra-system comparisons were discussed above. The inter-system *SDD* values were larger than the *MCID* for both sets of system comparisons. All intra-system *SDD* values were less than the smaller *MCID*.

The *RMS* values were smaller than all the corresponding *SDD* values and *MCID* values. It is also important to note that these *RMS* values are the same as those discussed in the prior metric because the *RMS* is calculated over the duration of the repetition of this component.

The screening criteria result was positive for the LCMAS-Single (Markers) to Vicon (Markers) evaluation, however the negative result when comparing each of these systems to the Vicon (Rotation) data indicates the marker based data is not a surrogate measure for the rotation based data. The excellent correlation within systems with low *SDD* values indicate good repeatability within the systems and potential viability as the low-cost system to be able to use this metric in evaluating maneuvers. Again, a prospective study should be performed to establish thresholds for this metric.

9.2.3 Secondary Variables DVJ - LCMAS-Single Compared to Vicon

This section covers the secondary metrics summarized in Table 9.1 and detailed in Tables 9.3.

ROM - 1st Component - COM - Position

For this metric both the LCMAS-Single (Vicon Static - IK) and the LCMAS-Single (Vicon Static - 6DOF) had good screening criteria results relative to the Vicon counterpart. For the inter-system comparison for this metric, the data captured with LCMAS-Single (Vicon Static - IK) and was excellently correlated to the Vicon data for both Day 1 and Day 2, while the data captured with LCMAS-Single (Vicon Static - 6DOF) was adequately correlated to the Vicon data for Day 1 and excellently correlated for Day 2. For intra-system between repetition comparisons, the LCMAS-Single (Vicon Static - IK) data was adequately correlated for both days, the LCMAS-Single (Vicon Static - 6DOF) and Vicon data were both excellently correlated for Day 1 and adequately correlated for Day 2. For intra-system between days comparisons, the LCMAS-Single (Vicon Static - IK) data was adequately correlated, the LCMAS-Single (Vicon Static - 6DOF) and Vicon data were both excellently correlated. When evaluating the *SDD*, we see values below the *MCID* ranging from 0.9 to 3.0 cm. For the inter-system comparison, the LCMAS-Single (Vicon Static - IK) Day 2 had the smallest *SDD* value. For the intra-system comparisons each LCMAS-Single (Vicon Static - IK and Vicon Static - 6DOF) had slightly larger values than the Vicon system. The LCMAS-Single (Vicon Static - IK) also has more valid repetitions (over half) than the LCMAS-Single (Vicon Static - 6DOF).

The Bland-Altman plots showed a bias, $\bar{d}$, of 1.1 cm or less for all comparisons. In addition, the 95%*LA* were similar to the 95%*SDD*.

The *RMS* values were similar to or smaller than the *SDD* values and smaller

than the *MCID* value for all comparisons. The inter-system *RMS* values were smaller than the intra-system *RMS* values.

Both systems LCMAS-Single (Vicon Static - IK and Vicon Static - 6DOF) met the screening criteria for this metric. This result suggests the systems ability to detect medial-lateral movement of the whole body and consistency of the participants' range of medial-lateral movement through repetitions and between days.

9.2.4 Conclusions

For each system we were able to assess the within-day and between-day repeatability for the full repetition time profiles as well as the peak value of each metric. These intra-system reliability measures are also known as test-retest reliability and help us evaluate the “consistency of a test or measure” [121]. Additionally, we were able to compare the reliability of each LCMAS to the industry gold standard Vicon system. Inter-system evaluations help us quantify the agreement between two methods of clinical measurement [11]. We also determined: 1) which marker based angles are good surrogate measures for the corresponding rotation based angle measurements; and 2) the JCS is the best to report moment data.

Two of our Low-Cost Movement Assessment Systems models have repeatable measures and *SDD* smaller than the *MCID* values from the scientific literature for some of the metrics (2 for LCMAS-Single Markers relative to Vicon Markers, 4 for Vicon Static - IK, and 3 for Vicon Static - 6DOF) between at-risk and normal populations, enabling use of the system as a screening tool for ACL injury risk and rehabilitation. To expand the number of metrics and the clinical relevance of this screening tool we propose continued system improvements and a prospective study to establish a normative database and identification of abnormal movement thresholds.

CHAPTER 10

Low-Cost Movement Assessment System-2

Compared to Vicon

Using the methods detailed in Chapter 8, we have processed and analyzed the LCMAS-2 and Vicon data for the drop vertical jump (DVJ), double leg squat (DLS), and single leg squat (SLS). In this chapter we present the Results and Discussion for the inter-system reliability and the intra-system repeatability study for these systems.

10.1 Results

We first present a sample of the plots generated in our study. Again, our intent is to provide the reader with a comprehensive view of the scope of comparisons as well as a feel for the numerical values. The three types of plots are 1) center of mass (COM) relative to base of support (BOS), 2) root mean square (RMS), and 3) Bland-Altman. Details of COM relative to BOS and RMS plots are explained below. Bland-Altman plots were covered in detail in Chapter 9.1.3 and that description applies to the statistics presented in this chapter also. Then, we present tables of numerical data for variables that passed the screening criteria for both the low-cost system compared to Vicon and for angle measurement comparisons between markers, from either the the low-cost or Vicon system, and rotations calculated in the Vicon system for DVJ, DLS, and SLS maneuvers, respectively.

10.1.1 Center of Mass Relative to Base of Support

The description given for this plot in Chapter 9.1.1 also applies to the sample COM relative to BOS plot is shown in Figure 10.1. However in this version of the plot we present data from the three different maneuvers examined in this study. The sample repetition of DVJ in Figure 10.1 is the same repetition previously shown in Figure 9.1, therefore the Vicon path is the same in the two figures while the LCMAS data in this section is from the LCMAS-2 and the LCMAS data presented previously is from the LCMAS-Single. Examination of the different maneuvers in Figure 10.1 is detailed in the Discussion section.

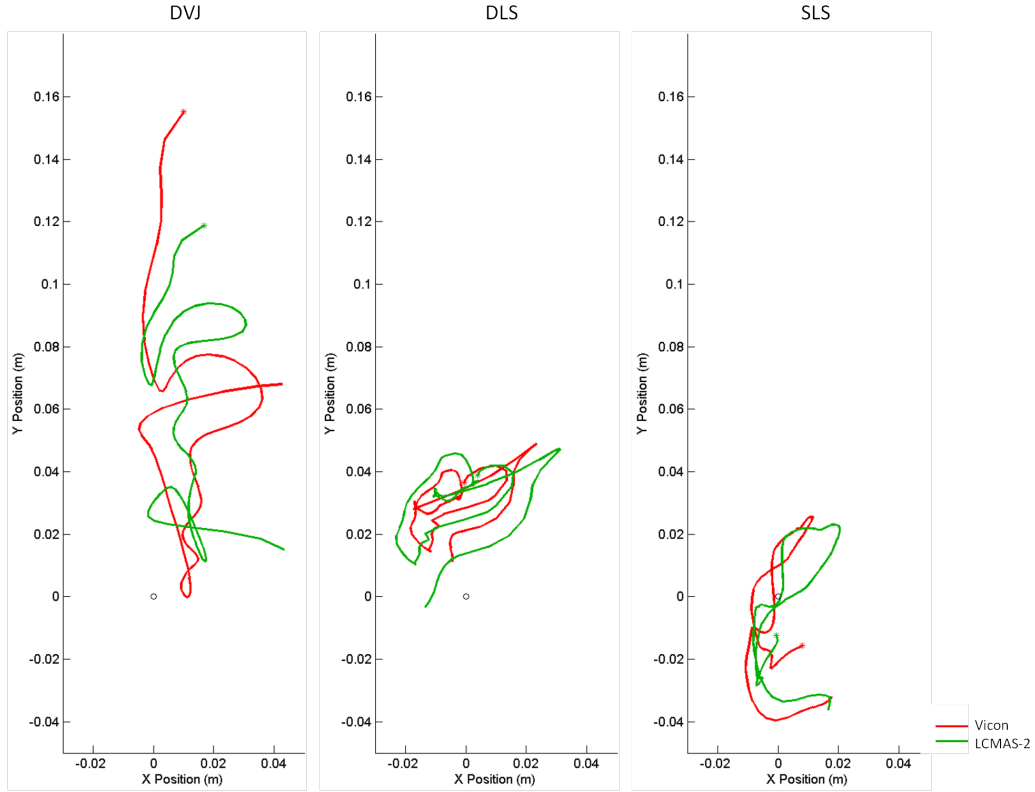


Figure 10.1: *Sample plot: center of mass relative to base of support for DVJ (left), DLS (center), and SLS (right). Note: Stars represent initial contact, circle represents base of support, decreasing Y is towards the participant's anterior direction.*

10.1.2 Root Mean Square Comparisons

All of the same types of RMS plots for inter- and intra-system comparisons presented in Chapter 9.1.2 were also created in the evaluations presented in this chapter. For the inter-system comparisons these types of plots are the individual and mean of repetition plots. For the intra-system comparisons these types of plots are between repetition and mean of repetitions between days. The plots in this chapter are to be interpreted in the same manner.

To provide the reader with a feel for the different maneuvers in this chapter, we have included sample individual repetition inter-system RMS plots. For each maneuver we present the angle (left column), force (center column) and moment (right column) plots for the right hip, knee, and ankle. The DVJ is shown in Figures 10.2 to 10.4. Again this data is from the same repetition presented in the LCMAS-Single Figures 9.2 to 9.4. The Vicon data will be the same between the two sets of plots, however the LCMAS data presented in this chapter is from the LCMAS-2 . The DLS is shown in Figures 10.5 to 10.7. Finally, the SLS is shown in Figures 10.8 to 10.10.

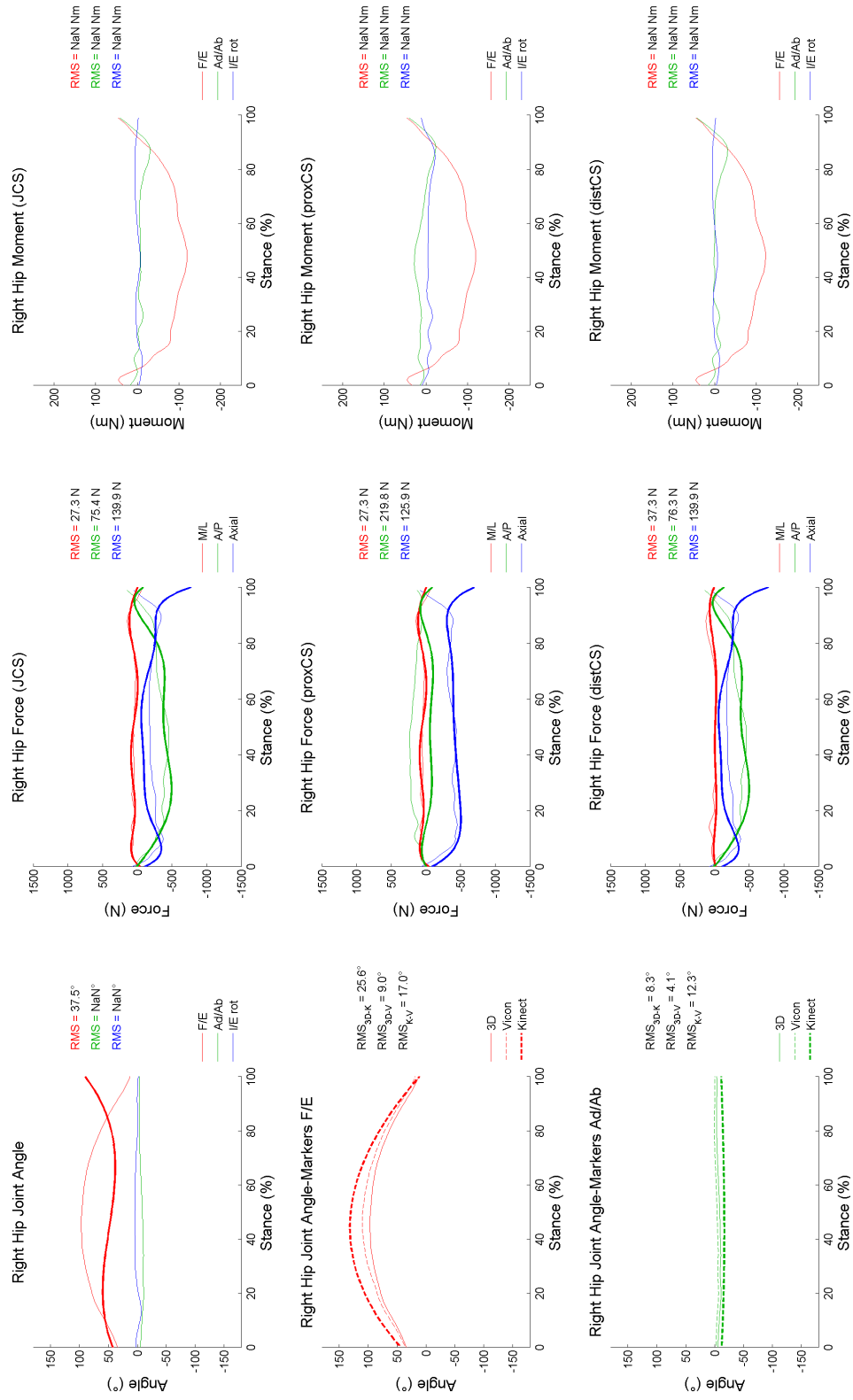


Figure 10.2: Sample Right Hip comparison data between individual repetitions of DVJ from the LCMAS-2 and Vicron System.

Note: Thin lines Vicron, thick lines LCMAS-2.

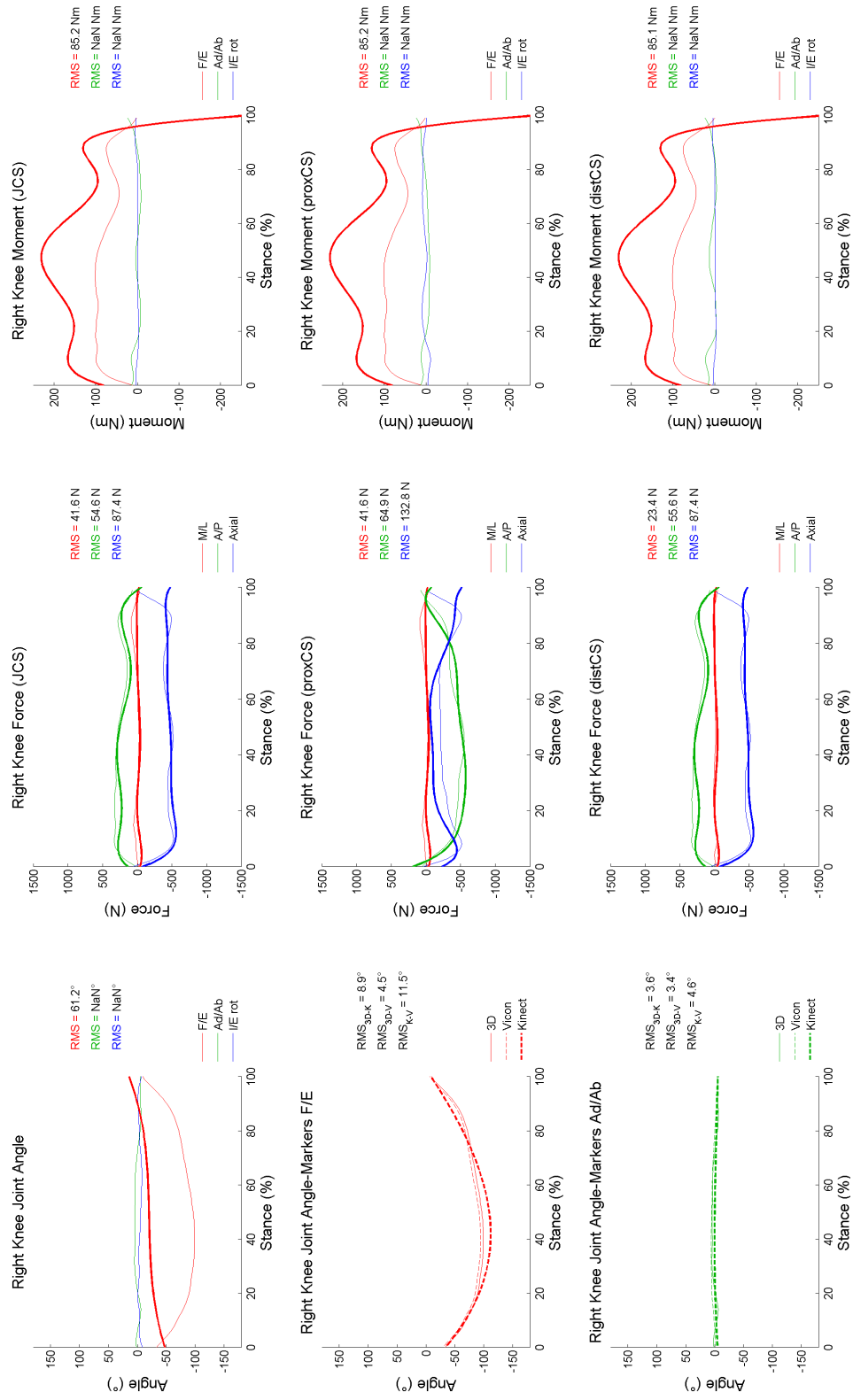


Figure 10.3: Sample Right Knee comparison data between individual repetitions of DVJ from the LCMAS-2 and Vicon System.. Note: Thin lines Vicon, thick lines LCMAS-2.

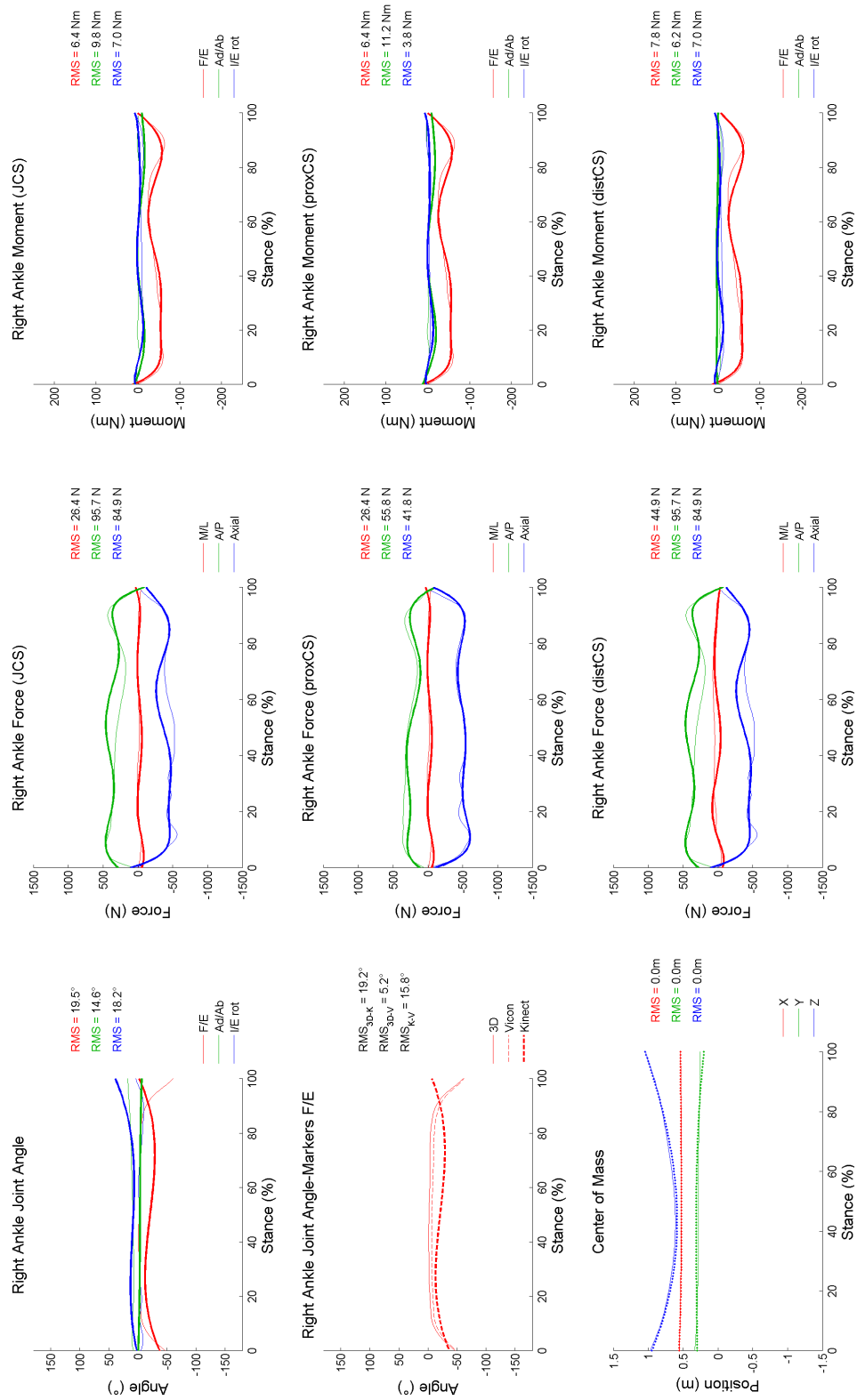


Figure 10.4: Sample Right Ankle comparison data between individual repetitions of DVJ from the LCMAS-2 and Vicon System. Note: Thin lines Vicon, thick lines LCMAS-2.

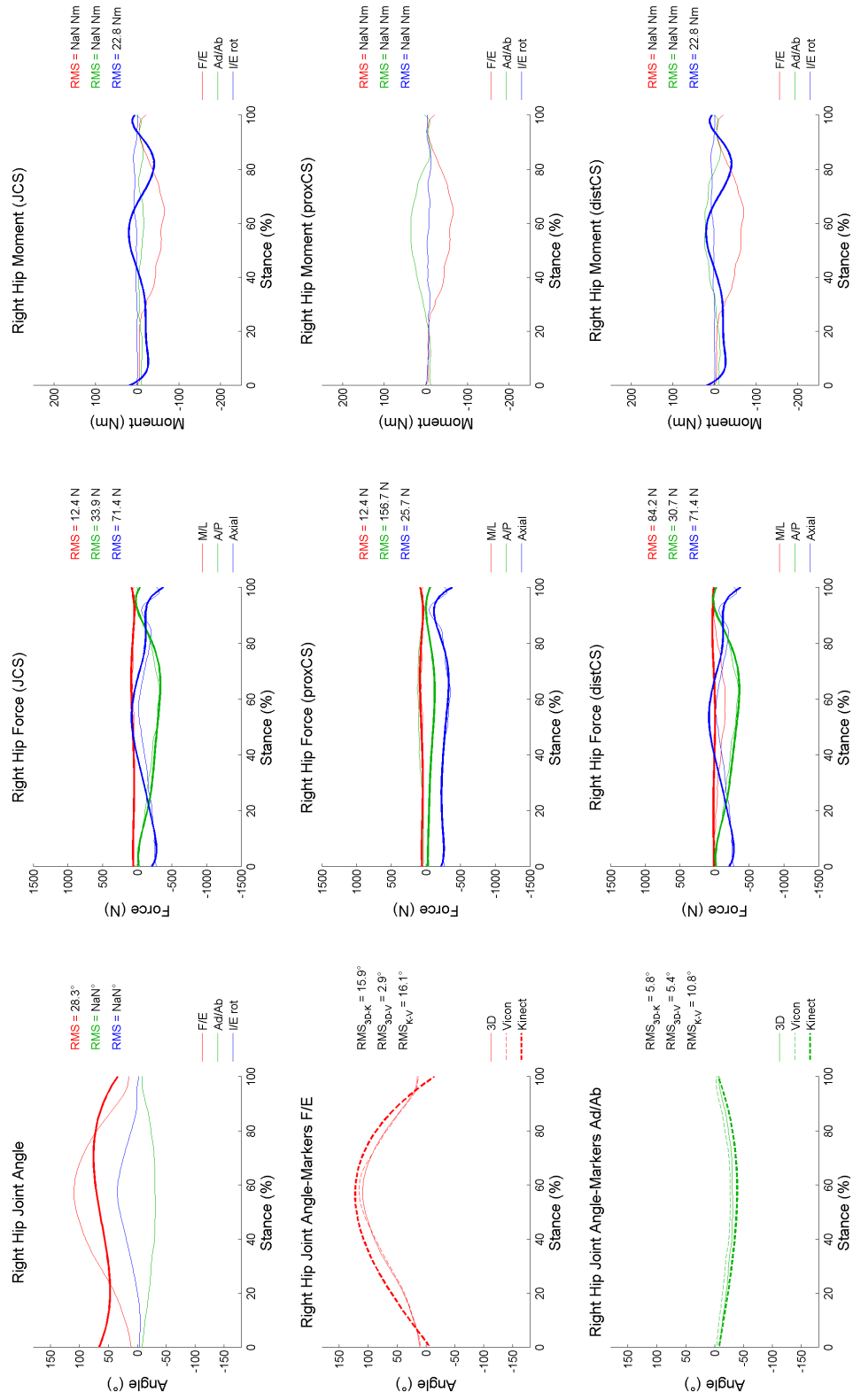


Figure 10.5: Sample Right Hip comparison data between individual repetitions of DLS from the LCMAS-2 and Vicon System.

Note: Thin lines Vicon, thick lines LCMAS-2.

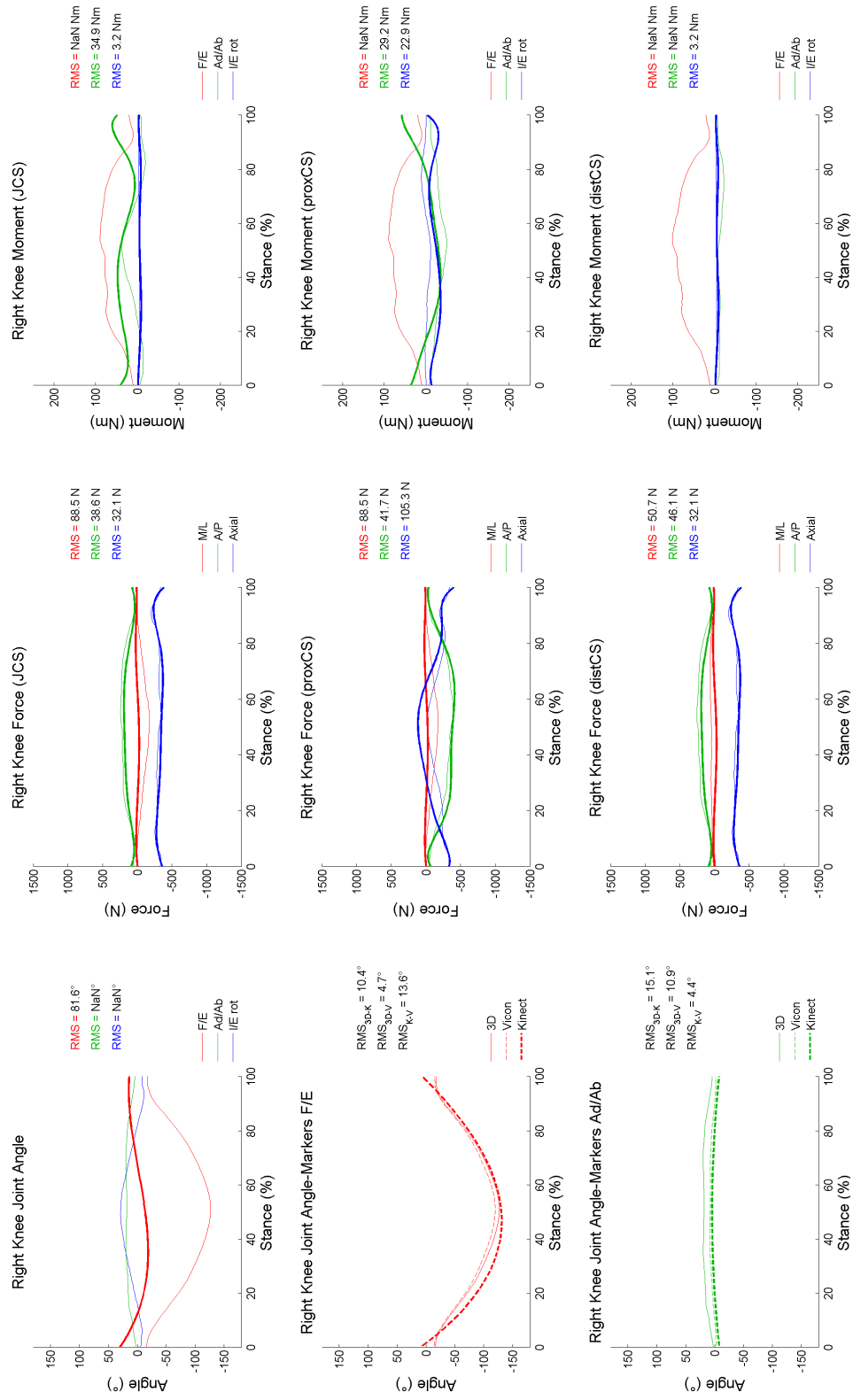


Figure 10.6: Sample Right Knee comparison data between individual repetitions of DLS from the LCMAS-2 and Vicron System.. Note: Thin lines Vicron, thick lines LCMAS-2.

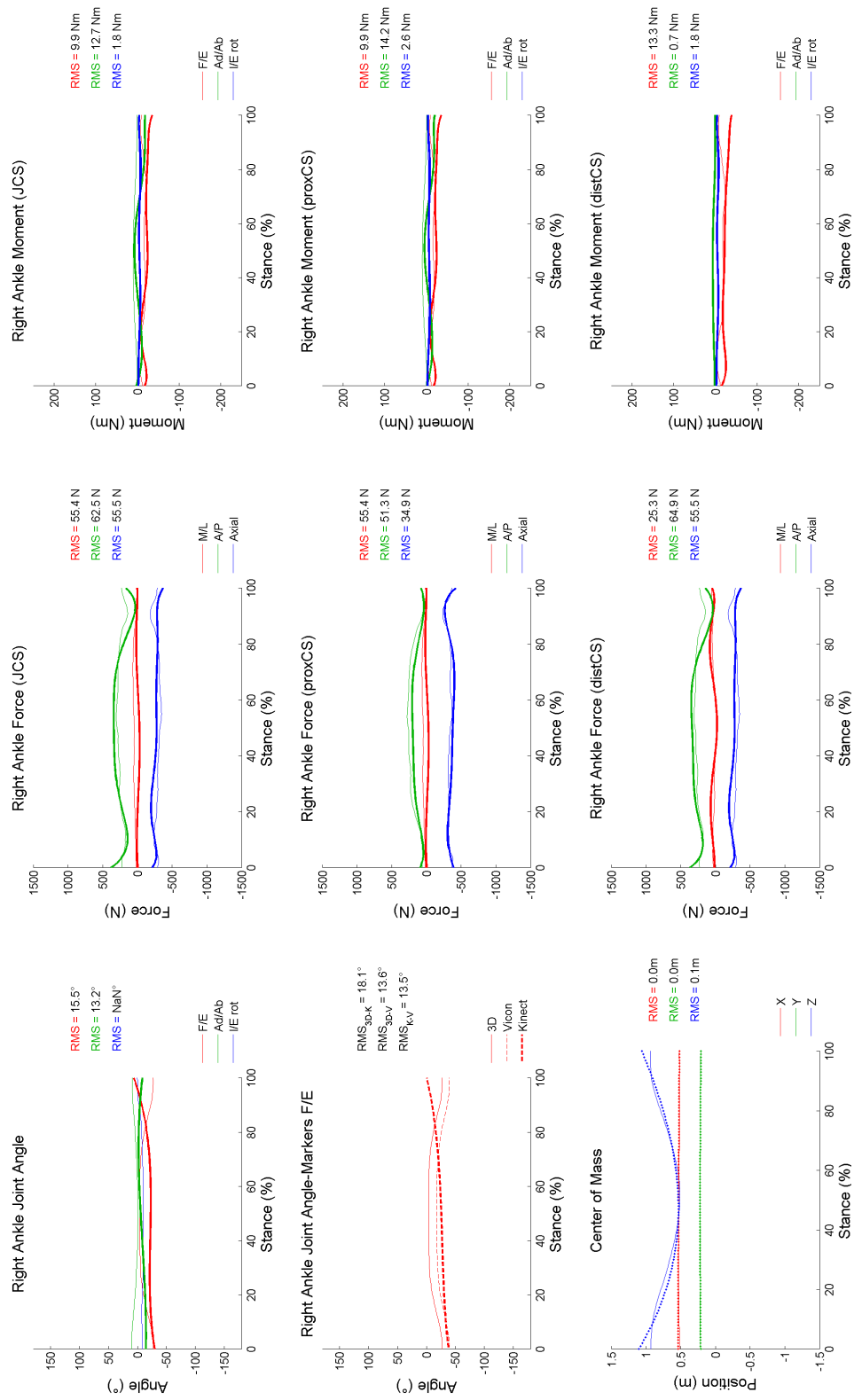


Figure 10.7: Sample Right Ankle comparison data between individual repetitions of DLS from the LCMAS-2 and Vicon System. Note: Thin lines Vicon, thick lines LCMAS-2.

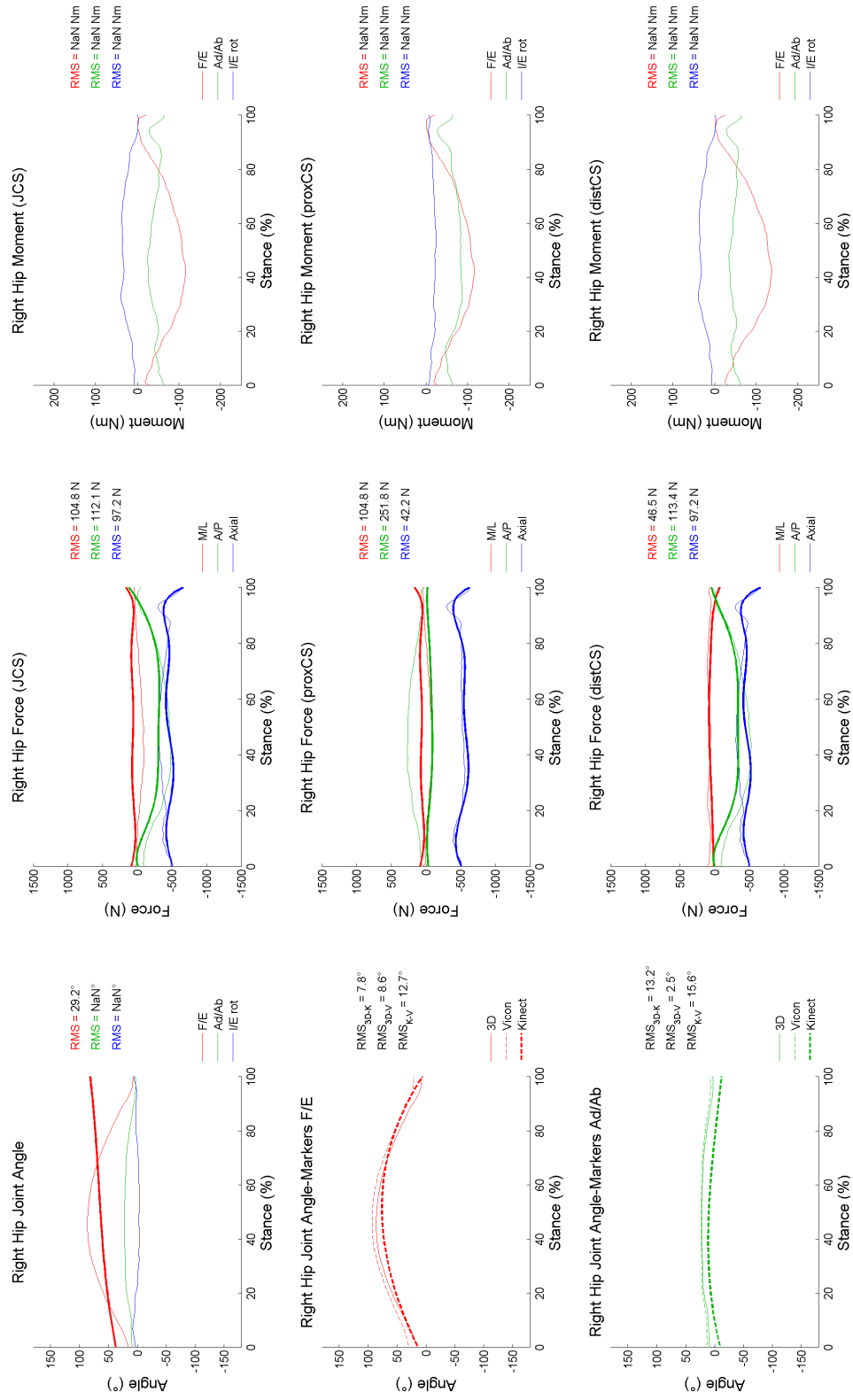


Figure 10.8: Sample Right Hip comparison data between individual repetitions of SLS from the LCMAS-2 and Vicron System.

Note: Thin lines Vicron, thick lines LCMAS-2.

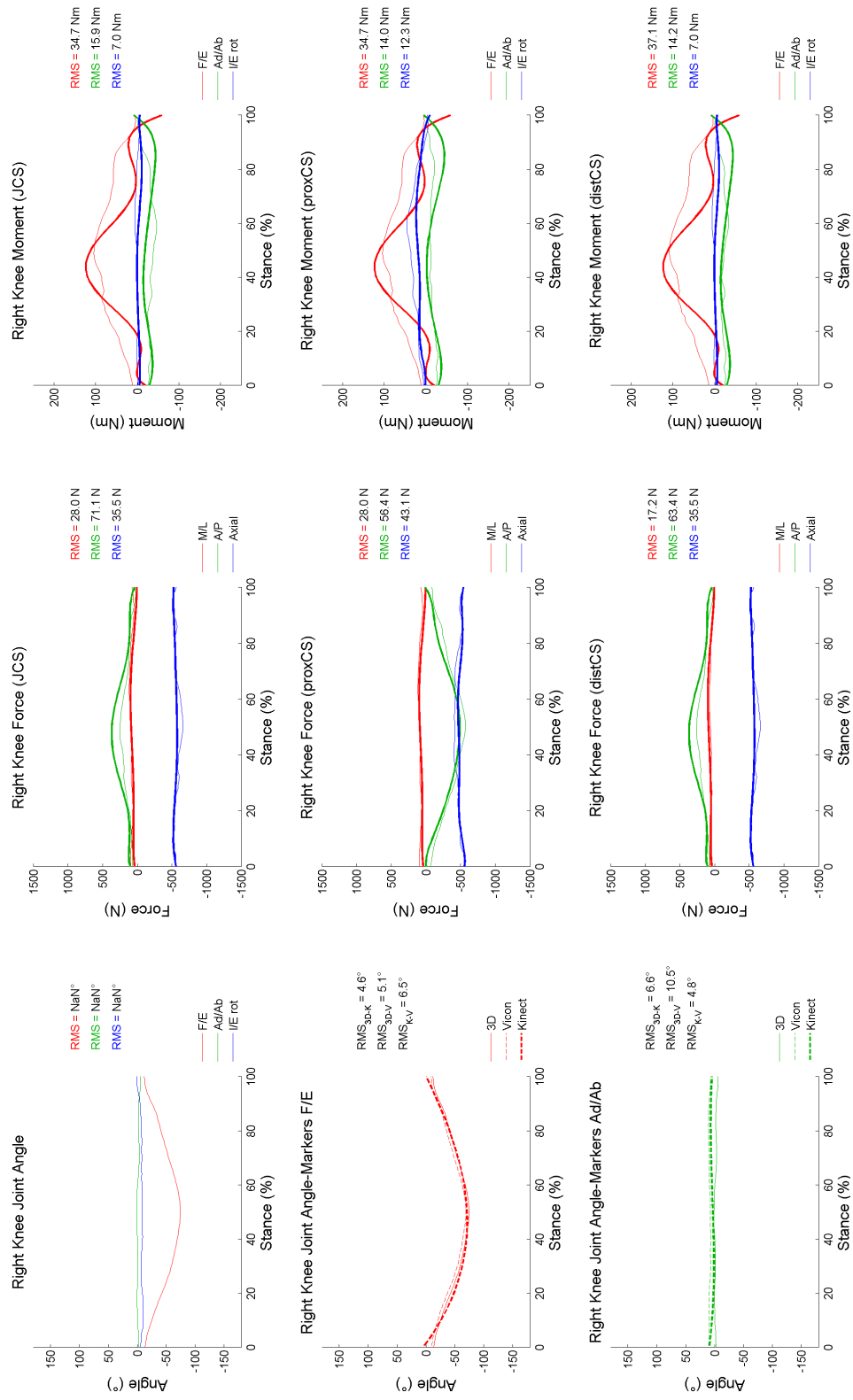


Figure 10.9: Sample Right Knee comparison data between individual repetitions of SLS from the LCMAS-2 and Vicon System.

Note: Thin lines Vicon, thick lines LCMAS-2.

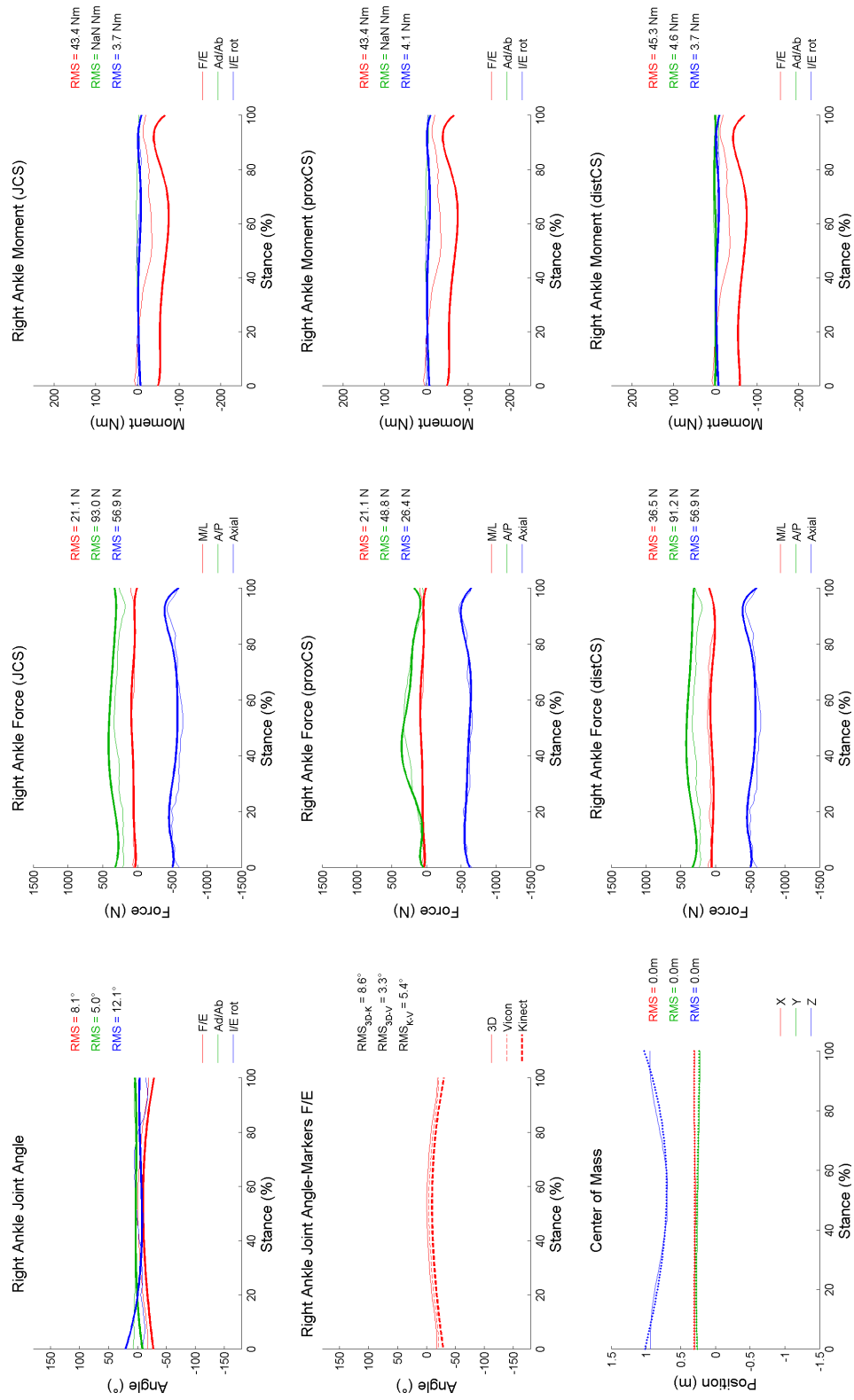


Figure 10.10: Sample Right Ankle comparison data between individual repetitions of SLS from the LCMAS-2 and Vicon System. Note: Thin lines Vicon, thick lines LCMAS-2.

10.1.3 Numerical Results

For each maneuver, results for select metrics are presented in summary tables and detailed in numerical tables. We remind the reader that interpretations of these two types of tables were presented in Chapter 9.1.4.

The tables consist of three different types of comparisons. First, we have comparisons between the LCMAS-2 marker based angle and the corresponding Vicon marker based angle. The next type of comparison is LCMAS-2 marker based angle to the corresponding Vicon model or JCS based angle. Finally, we examine the Vicon marker based angle to the corresponding Vicon model or JCS based angle.

10.1.3.1 Drop Vertical Jump

For the DVJ, numerical results for select metrics are summarized in Table 10.1. Variables that passed the screening criteria for LCMAS-2 compared to the corresponding Vicon metric are presented in Table 10.2. All system comparisons listed in the summary table for these metrics are presented in the numerical tables. Numerical results are compiled in Appendix A.2 for variables from the summary table that did not meet our screening criteria. Three different metrics are presented in Table 10.2.

Table 10.1: *Summary of ICC and SDD for DVJ metrics in LCMAS-2 and associated systems. Note: Inter-system circles represent Day 1 and Day 2; intra-system circles represent Between Repetitions (Day 1, Day 2), and Between Days.*

	Joint	Metric	Peak	Component	Inter-System Comparison	Intra-System Comparisons			
						Model		to	Model
						LCMAS-2	Vicon		Vicon
						Markers/Model	Markers		Vicon Static 6DOF
Primary	Hip	Angle	Max	1	*   	  	  		  
	Hip	Angle	ROM	1	  	  	  		  
	Hip	Angle	IC	2	  	  	  		  
	Knee	Angle	Min	1	*   	  	  		  
	Knee	Angle	ROM	1	*   	  	  		  
	Knee	Angle	IC	2	  	  	  		  
	Knee	Angle	Min	2	  	  	  		  
	Knee	Angle	Max	2	  	  	  		  
	Knee	Moment PCS	Min	2	  	  	  		  
	COM	Position	ROM	1	  	  	  		  
Secondary	Hip	Angle	MKF	2	  	  	  		  
	Knee	Angle	ROM	2	  	  	  		  
	Knee	Angle	MKF	2	  	  	  		  

Legend

ICC

 = Poor

 = Adequate

 = Excellent

SDD

 = Above MCID

 = Below larger MCID

 = Below Smaller MCID

* = Variable meeting screening criteria

Table 10.2: Primary Variables - DVJ - LCMAS-2 - Max - 1st Component - Hip Angle.

Component Parameter		Comparison System	Inter-System: Vicon (Markers)		Intra-System: Between Repts				Intra-System: Between Days		MCID
			LCMAS-2 (Markers)		LCMAS-2 (Markers)		Vicon (Markers)		LCMAS-2 (Markers)		
Max 1st	Hip Angle Marker	Statistic	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
		ICC	0.919	0.974	0.975	0.946	0.979	0.991	0.964	0.951	
		n	12	12	12	12	12	12	12	12	
		SEM	10.95	5.46	4.88	5.78	3.49	2.15	7.74	7.16	
		SDD	30.36	15.12	13.53	16.02	9.68	5.96	21.45	19.86	32.3
		SDD lower bound	-42.97	-33.62	-13.35	-20.31	-8.92	-6.77	-28.15	-20.68	degrees
		SDD upper bound	17.74	-3.37	13.71	11.74	10.44	5.15	14.74	19.04	
		$\bar{d}$	-12.62	-18.50	0.18	-4.29	0.76	-0.81	-6.70	-0.82	
		$\bar{d}$ lower bound	-22.46	-23.40	-4.40	-8.91	-2.48	-2.76	-12.44	-7.52	
		$\bar{d}$ upper bound	-2.77	-13.60	4.76	0.33	4.00	1.13	-0.96	5.88	
		LA lower bound	-42.97	-33.62	-13.95	-18.54	-9.23	-6.81	-24.41	-21.49	
		LA upper bound	17.74	-3.37	14.31	9.96	10.75	5.19	11.00	19.85	
		RMS (individual)	18.68		6.94		4.64				
		Fraction (individual)	1.00		1.00		1.00				
		RMS (mean)	18.01						14.67	8.51	
		Fraction (mean)	1.00						1.00	1.00	

Component Parameter		Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID
			LCMAS-2 (Markers)		LCMAS-2 (Markers)		Vicon		LCMAS-2 (Markers)		
Max 1st	Hip Angle	Statistic	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
		ICC	0.867	0.948	0.975	0.946	0.979	0.995	0.964	0.972	
		n	12	12	12	12	12	12	12	12	
		SEM	12.88	7.30	4.88	5.78	2.85	1.44	7.74	4.73	
		SDD	35.70	20.23	13.53	16.02	7.89	3.99	21.45	13.10	32.3
		SDD lower bound	-62.76	-52.77	-13.35	-20.31	-7.10	-4.73	-28.15	-14.32	degrees
		SDD upper bound	8.65	-12.30	13.71	11.74	8.69	3.25	14.74	11.88	
		$\bar{d}$	-27.05	-32.53	0.18	-4.29	0.80	-0.74	-6.70	-1.22	
		$\bar{d}$ lower bound	-38.63	-39.09	-4.40	-8.91	-1.82	-2.00	-12.44	-5.58	
		$\bar{d}$ upper bound	-15.48	-25.97	4.76	0.33	3.42	0.52	-0.96	3.14	
		LA lower bound	-62.76	-52.77	-13.95	-18.54	-7.28	-4.62	-24.41	-14.67	
		LA upper bound	8.65	-12.30	14.31	9.96	8.88	3.14	11.00	12.23	
		RMS (individual)	23.69		6.94		3.83				
		Fraction (individual)	1.00		1.00		1.00				
		RMS (mean)	23.14						14.67	6.31	
		Fraction (mean)	1.00						1.00	1.00	

Table 10.2: (cont.) *Primary Variables - DVJ - LCMAS-2 - Max - 1st Component - Hip Angle.*

Component Parameter	Comparison System	Inter-System: Vicon		Intra-System: Between Reps				Intra-System: Between Days		MCID
		Vicon (Markers)		Vicon (Markers)		Vicon (Markers)		Vicon (Markers)		
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
Max 1st Hip Angle	ICC	0.904	0.952	0.979	0.991	0.979	0.995	0.951	0.972	
	n	12	12	12	12	12	12	12	12	
	SEM	9.22	6.61	3.49	2.15	2.85	1.44	7.16	4.73	
	SDD	25.57	18.32	9.68	5.96	7.89	3.99	19.86	13.10	
	SDD lower bound	-40.00	-32.35	-8.92	-6.77	-7.10	-4.73	-20.68	-14.32	32.3 degrees
	SDD upper bound	11.13	4.28	10.44	5.15	8.69	3.25	19.04	11.88	
	$\bar{d}$	-14.44	-14.03	0.76	-0.81	0.80	-0.74	-0.82	-1.22	
	$\bar{d}$ lower bound	-22.72	-19.97	-2.48	-2.76	-1.82	-2.00	-7.52	-5.58	
	$\bar{d}$ upper bound	-6.15	-8.10	4.00	1.13	3.42	0.52	5.88	3.14	
	LA lower bound	-40.00	-32.35	-9.23	-6.81	-7.28	-4.62	-21.49	-14.67	
	LA upper bound	11.13	4.28	10.75	5.19	8.88	3.14	19.85	12.23	
	RMS (individual)	10.51		4.64		3.83				
	Fraction (individual)	1.00		1.00		1.00				
	RMS (mean)	10.46						8.51	6.31	
	Fraction (mean)	1.00						1.00	1.00	

Table 10.2: (cont.) *Primary Variables - DVJ - LCMAS-2 - Min - 1st Component - Knee Angle.*

Component Parameter	Min 1st	Knee Angle Marker	Comparison System	Inter-System: Vicon (Markers)		Intra-System: Between Repts				Intra-System: Between Days		MCID		
				LCMAS-2 (Markers)		LCMAS-2 (Markers)		Vicon (Markers)		LCMAS-2 (Markers)			Vicon (Markers)	
				Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2		Day 1	Day 2
Min 1st	Knee Angle	ICC		0.820	0.891	0.903	0.965	0.937	0.804	0.912	0.982	10.5 to 46 degrees		
		n		12	12	12	12	12	12	12	12		12	
		SEM		9.71	7.75	6.82	4.16	2.86	5.43	8.92	2.18		6.04	
		SDD		26.93	21.48	18.90	11.53	7.93	15.05	24.72	5.00		7.09	
		SDD lower bound		-17.75	-6.17	-20.63	-9.41	-7.29	-12.20	-17.54	-5.00		1.04	
		SDD upper bound		36.11	36.79	17.18	13.65	8.57	17.89	31.89	7.09		-0.88	
		$\bar{d}$		9.18	15.31	-1.72	2.12	0.64	2.84	7.18	1.04		2.97	
		$\bar{d}$ lower bound		0.45	8.35	-8.02	-1.52	-2.01	-1.89	0.29	-0.88		-4.89	
		$\bar{d}$ upper bound		17.91	22.27	4.58	5.76	3.29	7.58	14.06	2.97		6.98	
		LA lower bound		-17.75	-6.17	-21.15	-9.12	-7.54	-11.75	-14.05	-4.89			
		LA upper bound		36.11	36.79	17.71	13.36	8.82	17.44	28.41	6.98			
		RMS (individual)		14.68		7.96		4.76						
Fraction (individual)		1.00		1.00		1.00								
		RMS (mean)		13.89						17.31	6.18			
		Fraction (mean)		1.00						1.00	1.00			

Component Parameter	Min 1st	Knee Angle	Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID		
				LCMAS-2 (Markers)		LCMAS-2 (Markers)		Vicon		LCMAS-2 (Markers)			Vicon	
				Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2		Day 1	Day 2
Min 1st	Knee Angle	ICC		0.849	0.884	0.903	0.965	0.935	0.815	0.912	0.989	10.5 to 46 degrees		
		n		12	12	12	12	12.00	12.00	12	12.00		12	
		SEM		9.02	8.06	6.82	4.16	2.96	5.35	8.92	1.71		4.73	
		SDD		25.00	22.35	18.90	11.53	8.22	14.82	24.72	4.73		-4.22	
		SDD lower bound		-20.18	-10.87	-20.63	-9.41	-7.64	-11.68	-17.54	-4.22		5.24	
		SDD upper bound		29.81	33.82	17.18	13.65	8.80	17.96	31.89	5.24		0.51	
		$\bar{d}$		4.81	11.47	-1.72	2.12	0.58	3.14	7.18	0.51		-1.05	
		$\bar{d}$ lower bound		-3.29	4.23	-8.02	-1.52	-2.17	-1.42	0.29	-1.05		2.08	
		$\bar{d}$ upper bound		12.92	18.72	4.58	5.76	3.34	7.70	14.06	2.08		-4.31	
		LA lower bound		-20.18	-10.87	-21.15	-9.12	-7.92	-10.94	-14.05	-4.31		5.34	
		LA upper bound		29.81	33.82	17.71	13.36	9.08	17.22	28.41	5.34			
		RMS (individual)		13.75		7.96		4.81						
Fraction (individual)		1.00		1.00		1.00								
		RMS (mean)		12.86						17.31	5.40			
		Fraction (mean)		1.00						1.00	1.00			

Table 10.2: (cont.) *Primary Variables - DVJ - LCMAS-2 - Min - 1st Component - Knee Angle.*

Component Parameter Min 1st Knee Angle	Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID
		Vicon (Markers)		Vicon (Markers)		Vicon (Markers)		Vicon (Markers)		
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
ICC	Statistic	0.994	0.987	0.937	0.804	0.935	0.815	0.982	0.989	
n		12	12	12	12	12	12	12	12	
SEM		1.23	1.96	2.86	5.43	2.96	5.35	2.18	1.71	
SDD		3.41	5.43	7.93	15.05	8.22	14.82	6.04	4.73	10.5 to
SDD lower bound		-7.77	-9.27	-7.29	-12.20	-7.64	-11.68	-5.00	-4.22	46
SDD upper bound		-0.96	1.59	8.57	17.89	8.80	17.96	7.09	5.24	degrees
$\bar{d}$		-4.37	-3.84	0.64	2.84	0.58	3.14	1.04	0.51	
$\bar{d}$ lower bound		-5.47	-5.60	-2.01	-1.89	-2.17	-1.42	-0.88	-1.05	
$\bar{d}$ upper bound		-3.26	-2.08	3.29	7.58	3.34	7.70	2.97	2.08	
LA lower bound		-7.77	-9.27	-7.54	-11.75	-7.92	-10.94	-4.89	-4.31	
LA upper bound		-0.96	1.59	8.82	17.44	9.08	17.22	6.98	5.34	
RMS (individual)		3.89		4.76		4.81				
Fraction (individual)		1.00		1.00		1.00				
RMS (mean)		3.88						6.18	5.40	
Fraction (mean)		1.00						1.00	1.00	

Table 10.2: (cont.) Primary Variables - DVJ - LCMAS-2 - ROM - 1st Component - Knee Angle.

Component Parameter		Comparison System	Inter-System: Vicon (Markers)			Intra-System: Between Repts				Intra-System: Between Days		MCID		
			LCMAS-2 (Markers)		Day 2	LCMAS-2 (Markers)		Vicon (Markers)		LCMAS-2 (Markers)	Vicon (Markers)			
ROM 1st	Knee Angle Marker	Statistic	Day 1	Day 2		Day 1	Day 2	Day 1	Day 2			Day 1	Day 2	
ROM 1st	Knee Angle Marker	ICC	0.827	0.803								0.892	51.4 degrees	
		n	12	12										12
		SEM	12.32	7.79			7.93	7.74	3.34	6.25	14.55	6.76		
		SDD	34.16	21.60			21.98	21.44	9.26	17.34	40.33	18.74		
		SDD lower bound	-47.95	-40.62			-19.94	-24.52	-9.56	-16.32	-40.27	-13.45		
		SDD upper bound	20.38	2.58			24.03	18.36	8.96	18.36	40.39	24.04		
		$\bar{d}$	-13.79	-19.02			2.04	-3.08	-0.30	1.02	0.06	5.29		
		$\bar{d}$ lower bound	-24.86	-26.02			-5.28	-10.05	-3.43	-4.81	-13.60	0.01		
		$\bar{d}$ upper bound	-2.71	-12.02			9.36	3.89	2.83	6.85	13.72	10.58		
		LA lower bound	-47.95	-40.62			-20.53	-24.57	-9.95	-16.97	-42.06	-11.01		
		LA upper bound	20.38	2.58			24.62	18.41	9.35	19.01	42.18	21.60		
		RMS (individual)	14.68				7.96		4.76					
		Fraction (individual)	1.00				1.00		1.00		17.31	6.18		
		RMS (mean)	13.89								1.00	1.00		
		Fraction (mean)	1.00											
Component Parameter		Comparison System	Inter-System: Vicon			Intra-System: Between Repts				Intra-System: Between Days		MCID		
			LCMAS-2 (Markers)		Day 2	LCMAS-2 (Markers)		Vicon		LCMAS-2 (Markers)	Vicon			
ROM 1st	Knee Angle	Statistic	Day 1	Day 2		Day 1	Day 2	Day 1	Day 2			Day 1	Day 2	
ROM 1st	Knee Angle	ICC	0.837	0.810								0.897	51.4 degrees	
		n	12	12			12	12	12	12	12	12		
		SEM	12.05	7.72			7.93	7.74	3.44	6.15	14.55	6.75		
		SDD	33.41	21.41			21.98	21.44	9.55	17.05	40.33	18.72		
		SDD lower bound	-45.78	-39.60			-19.94	-24.52	-9.66	-16.18	-40.27	-12.84		
		SDD upper bound	21.04	3.22			24.03	18.36	9.43	17.92	40.39	24.60		
		$\bar{d}$	-12.37	-18.19			2.04	-3.08	-0.11	0.87	0.06	5.88		
		$\bar{d}$ lower bound	-23.20	-25.13			-5.28	-10.05	-3.34	-4.87	-13.60	0.88		
		$\bar{d}$ upper bound	-1.54	-11.25			9.36	3.89	3.12	6.62	13.72	10.88		
		LA lower bound	-45.78	-39.60			-20.53	-24.57	-10.08	-16.85	-42.06	-9.53		
		LA upper bound	21.04	3.22			24.62	18.41	9.86	18.59	42.18	21.29		
		RMS (individual)	13.75				7.96		4.81					
		Fraction (individual)	1.00				1.00		1.00		17.31	5.40		
		RMS (mean)	12.86								1.00	1.00		
		Fraction (mean)	1.00											

Table 10.2: (cont.) *Primary Variables - DVJ - LCMAS-2 - ROM - 1st Component - Knee Angle.*

Component Parameter	Comparison System	Inter-System: Vicon		Intra-System: Between Reps				Intra-System: Between Days		MCID
		Vicon (Markers)		Vicon (Markers)		Vicon (Markers)		Vicon		
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2			
ROM 1st	Knee Angle	ICC	0.998	0.998	0.998	0.952	0.825	0.952	0.831	0.897
		n	12	12	12	12	12	12	12	12
		SEM	1.05	1.05	1.05	1.05	6.25	3.44	6.15	6.75
		SDD	2.92	2.91	2.91	2.91	17.34	9.55	17.05	18.72
		SDD lower bound	-1.51	-2.09	-2.09	-2.09	-16.32	-9.66	-16.18	-12.84
		SDD upper bound	4.34	3.74	3.74	3.74	18.36	9.43	17.92	24.60
		$\bar{d}$	1.41	0.83	0.83	1.02	1.02	-0.11	0.87	5.88
		$\bar{d}$ lower bound	0.47	-0.12	-0.12	-3.43	-4.81	-3.34	-4.87	0.01
		$\bar{d}$ upper bound	2.36	1.77	1.77	2.83	6.85	3.12	6.62	10.88
		LA lower bound	-1.51	-2.09	-2.09	-9.95	-16.97	-10.08	-16.85	-9.53
		LA upper bound	4.34	3.74	3.74	9.35	19.01	9.86	18.59	21.29
		RMS (individual)	3.89			4.76		4.81		
		Fraction (individual)	1.00			1.00		1.00		
		RMS (mean)	3.88					6.18		5.40
		Fraction (mean)	1.00					1.00		1.00

10.1.3.2 Double Leg Squat

For the DLS, numerical results for select metrics are summarized in Table 10.3. Primary and secondary variables that passed the screening criteria for LCMAS-2 compared to the corresponding Vicon metric are presented in Tables 10.4 and 10.5, respectively. All system comparisons listed in the summary table for these metrics are presented in the numerical tables. Numerical results are compiled in Appendix A.3 for variables from the summary table that did not meet our screening criteria. Four different metrics are presented in Table 10.4 and one metric is presented in Table 10.5.

Table 10.3: Summary of ICC and SDD for DLS metrics in LCMAS-2 and associated systems. Note: Inter-system circles represent Day 1 and Day 2; intra-system circles represent Between Repetitions (Day 1, Day 2), and Between Days.

	Joint	Metric	Peak	Component	Inter-System Comparison	Intra-System Comparisons				
						Model		to	Model	
						LCMAS-2	Vicon		Vicon	
						Markers/Model	Markers		Vicon Static 6DOF	Markers
Primary	Hip	Angle	Max	1	* 					
	Hip	Angle	ROM	1						
	Hip	Angle	IC	2	* 					
	Knee	Angle	Min	1	* 					
	Knee	Angle	ROM	1	* 					
	Knee	Angle	IC	2						
	Knee	Angle	Min	2						
	Knee	Angle	Max	2						
	Knee	Moment PCS	Min	2						
Secondary	COM	Position	ROM	1						
	COM	Position to BOS	ROM	2	* 					
	Hip	Angle	MKF	2						
	Knee	Angle	ROM	2						
	Knee	Angle	MKF	2						

ICC

= Poor

= Adequate

= Excellent

SDD

= Above MCID

= Below larger MCID

= Below Smaller MCID

Legend

* = Variable meeting screening criteria

Table 10.4: *Primary Variables - DLS - LCMAS-2 - Max - 1st Component - Hip Angle.*

Component Parameter	Max 1st	Hip Angle Marker	Comparison System	Inter-System: Vicon (Markers)				Intra-System: Between Repts				Intra-System: Between Days		MCID
				LCMAS-2 (Markers)		Vicon (Markers)		LCMAS-2 (Markers)		Vicon (Markers)				
				Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2			
ICC				0.911	0.903	12	12	0.971	0.936	0.992	0.994	0.933	0.983	
n				12	12	12	12	12	12	12	12	12	12	
SEM				13.64	12.87	12.87	12.87	5.55	6.59	3.11	2.59	10.77	6.20	
SDD				37.80	35.67	35.67	35.67	15.39	18.27	8.61	7.19	29.85	17.18	
SDD lower bound				-28.31	-33.32	-33.32	-33.32	-12.81	-16.01	-10.75	-9.29	-34.39	-14.58	32.3 degrees
SDD upper bound				47.29	38.02	38.02	38.02	17.97	20.52	6.47	5.08	25.31	19.78	
$\bar{d}$				9.49	2.35	2.35	2.35	2.58	2.26	-2.14	-2.10	-4.54	2.60	
$\bar{d}$ lower bound				-2.76	-9.22	-9.22	-9.22	-2.34	-3.74	-4.69	-4.10	-14.19	-2.95	
$\bar{d}$ upper bound				21.74	13.91	13.91	13.91	7.50	8.26	0.41	-0.11	5.11	8.16	
LA lower bound				-28.31	-33.32	-33.32	-33.32	-12.60	-16.26	-9.99	-8.25	-34.30	-14.53	
LA upper bound				47.29	38.02	38.02	38.02	17.76	20.77	5.71	4.04	25.22	19.74	
RMS (individual)				15.12				8.59		7.21				
Fraction (individual)				1.00				1.00		1.00				
RMS (mean)				14.53								10.23	7.27	
Fraction (mean)				1.00								1.00	1.00	

Component Parameter	Max 1st	Hip Angle	Comparison System	Inter-System: Vicon				Intra-System: Between Repts				Intra-System: Between Days		MCID
				LCMAS-2 (Markers)		Vicon		LCMAS-2 (Markers)		Vicon				
				Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2			
ICC				0.957	0.934	12	12	0.971	0.936	0.994	0.997	0.933	0.982	
n				12	12	12	12	12	12	12	12	12	12	
SEM				8.71	9.41	9.41	9.41	5.55	6.59	1.98	1.45	10.77	4.99	
SDD				24.15	26.09	26.09	26.09	15.39	18.27	5.50	4.02	29.85	13.84	
SDD lower bound				-33.59	-41.11	-41.11	-41.11	-12.81	-16.01	-6.21	-4.89	-34.39	-12.80	32.3 degrees
SDD upper bound				14.70	11.06	11.06	11.06	17.97	20.52	4.79	3.16	25.31	14.89	
$\bar{d}$				-9.44	-15.03	-15.03	-15.03	2.58	2.26	-0.71	-0.87	-4.54	1.04	
$\bar{d}$ lower bound				-17.27	-23.48	-23.48	-23.48	-2.34	-3.74	-2.51	-2.10	-14.19	-3.59	
$\bar{d}$ upper bound				-1.62	-6.57	-6.57	-6.57	7.50	8.26	1.09	0.37	5.11	5.68	
LA lower bound				-33.59	-41.11	-41.11	-41.11	-12.60	-16.26	-6.27	-4.68	-34.30	-13.26	
LA upper bound				14.70	11.06	11.06	11.06	17.76	20.77	4.85	2.94	25.22	15.34	
RMS (individual)				14.47				8.59		4.85				
Fraction (individual)				1.00				1.00		1.00				
RMS (mean)				13.92								10.23	6.10	
Fraction (mean)				1.00								1.00	1.00	

Table 10.4: (cont.) *Primary Variables - DLS - LCMAS-2 - Max - 1st Component - Hip Angle.*

Component Parameter	Comparison System	Inter-System: Vicon		Intra-System: Between Reps				Intra-System: Between Days		MCID
		Vicon (Markers)		Vicon (Markers)		Vicon (Markers)		Vicon (Markers)		
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
Max 1st Hip Angle	ICC	0.927	0.961	0.992	0.994	0.994	0.997	0.983	0.982	
	n	12	12	12	12	12	12	12	12	
	SEM	11.21	8.42	3.11	2.59	1.98	1.45	6.20	4.99	
	SDD	31.07	23.34	8.61	7.19	5.50	4.02	17.18	13.84	32.3
	SDD lower bound	-50.00	-40.72	-10.75	-9.29	-6.21	-4.89	-14.58	-12.80	degrees
	SDD upper bound	12.14	5.97	6.47	5.08	4.79	3.16	19.78	14.89	
	$\bar{d}$	-18.93	-17.37	-2.14	-2.10	-0.71	-0.87	2.60	1.04	
	$\bar{d}$ lower bound	-29.00	-24.94	-4.69	-4.10	-2.51	-2.10	-2.95	-3.59	
	$\bar{d}$ upper bound	-8.86	-9.81	0.41	-0.11	1.09	0.37	8.16	5.68	
	LA lower bound	-50.00	-40.72	-9.99	-8.25	-6.27	-4.68	-14.53	-13.26	
	LA upper bound	12.14	5.97	5.71	4.04	4.85	2.94	19.74	15.34	
	RMS (individual)	11.42		7.21		4.85				
	Fraction (individual)	1.00		1.00		1.00				
	RMS (mean)	11.12						7.27	6.10	
	Fraction (mean)	1.00						1.00	1.00	

Table 10.4: (cont.) *Primary Variables - DLS - LCMAS-2 - IC - 2nd Component - Hip Angle.*

Component Parameter IC 2nd Hip Angle Marker	Comparison System Statistic	Inter-System: Vicon (Markers)		Intra-System: Between Repts				Intra-System: Between Days		MCID
		LCMAS-2 (Markers)		LCMAS-2 (Markers)		Vicon (Markers)		LCMAS-2 (Markers)		
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
ICC	ICC	0.644	0.673	0.968	0.955	0.938	0.990	0.991	0.953	
n	n	12	12	12	12	12	12	12	12	
SEM	SEM	4.94	5.00	1.67	2.05	0.77	0.35	1.27	0.99	
SDD	SDD	13.71	13.87	4.63	5.69	2.13	0.96	3.53	2.75	9.41 to
SDD lower bound	SDD lower bound	-13.17	-13.02	-3.83	-5.36	-1.94	-0.87	-3.29	-2.82	11.14
SDD upper bound	SDD upper bound	14.24	14.71	5.42	6.02	2.31	1.05	3.76	2.68	degrees
$\bar{d}$	$\bar{d}$	0.53	0.84	0.79	0.33	0.19	0.09	0.24	-0.07	
$\bar{d}$ lower bound	$\bar{d}$ lower bound	-3.91	-3.65	-0.68	-1.58	-0.52	-0.23	-0.95	-1.00	
$\bar{d}$ upper bound	$\bar{d}$ upper bound	4.97	5.34	2.27	2.24	0.90	0.41	1.42	0.86	
LA lower bound	LA lower bound	-13.17	-13.02	-3.76	-5.57	-2.00	-0.90	-3.41	-2.94	
LA upper bound	LA upper bound	14.24	14.71	5.34	6.23	2.38	1.08	3.89	2.79	
RMS (individual)	RMS (individual)	13.48		2.30		1.41				
Fraction (individual)	Fraction (individual)	1.00		1.00		1.00				
RMS (mean)	RMS (mean)	13.43						3.58	2.98	
Fraction (mean)	Fraction (mean)	1.00						1.00	1.00	

Component Parameter IC 2nd Hip Angle	Comparison System Statistic	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID
		LCMAS-2 (Markers)		LCMAS-2 (Markers)		Vicon		LCMAS-2 (Markers)		
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
ICC	ICC	0.949	0.948	0.968	0.955	0.982	0.997	0.991	0.980	
n	n	12	12	12	12	12	12	12	12	
SEM	SEM	2.50	2.58	1.67	2.05	0.91	0.37	1.27	1.34	
SDD	SDD	6.93	7.16	4.63	5.69	2.53	1.02	3.53	3.71	9.41 to
SDD lower bound	SDD lower bound	-6.68	-5.83	-3.83	-5.36	-2.37	-0.91	-3.29	-4.55	11.14
SDD upper bound	SDD upper bound	7.18	8.48	5.42	6.02	2.68	1.13	3.76	2.88	degrees
$\bar{d}$	$\bar{d}$	0.25	1.32	0.79	0.33	0.16	0.11	0.24	-0.84	
$\bar{d}$ lower bound	$\bar{d}$ lower bound	-1.99	-1.00	-0.68	-1.58	-0.69	-0.23	-0.95	-1.96	
$\bar{d}$ upper bound	$\bar{d}$ upper bound	2.50	3.65	2.27	2.24	1.00	0.45	1.42	0.29	
LA lower bound	LA lower bound	-6.68	-5.83	-3.76	-5.57	-2.46	-0.93	-3.41	-4.32	
LA upper bound	LA upper bound	7.18	8.48	5.34	6.23	2.77	1.15	3.89	2.65	
RMS (individual)	RMS (individual)	9.94		2.30		1.54				
Fraction (individual)	Fraction (individual)	1.00		1.00		1.00				
RMS (mean)	RMS (mean)	9.88						3.58	2.64	
Fraction (mean)	Fraction (mean)	1.00						1.00	1.00	

Table 10.4: (cont.) *Primary Variables - DLS - LCMA5-2 - IC - 2nd Component - Hip Angle.*

Component Parameter	Comparison System	Inter-System: Vicon				Intra-System: Between Repts				Intra-System: Between Days		MCID	
		Statistic	Vicon (Markers)		Day 1	Day 2	Vicon (Markers)		Day 1	Day 2	Vicon (Markers)		Vicon
			Day 1	Day 2			Day 1	Day 2					
IC 2nd Hip Angle	ICC		0.813	0.849	0.938	0.990	0.982	0.997	0.953	0.980			
	n		12	12	12	12	12	12	12	12			
	SEM		2.94	2.78	0.77	0.35	0.91	0.37	0.99	1.34			
	SDD		8.15	7.72	2.13	0.96	2.53	1.02	2.75	3.71	9.41 to		
	SDD lower bound		-8.43	-7.24	-1.94	-0.87	-2.37	-0.91	-2.82	-4.55	11.14		
	SDD upper bound		7.87	8.20	2.31	1.05	2.68	1.13	2.68	2.88	degrees		
	$\bar{d}$		-0.28	0.48	0.19	0.09	0.16	0.11	-0.07	-0.84			
	$\bar{d}$ lower bound		-2.92	-2.02	-0.52	-0.23	-0.69	-0.23	-1.00	-1.96			
	$\bar{d}$ upper bound		2.36	2.99	0.90	0.41	1.00	0.45	0.86	0.29			
	LA lower bound		-8.43	-7.24	-2.00	-0.90	-2.46	-0.93	-2.94	-4.32			
	LA upper bound		7.87	8.20	2.38	1.08	2.77	1.15	2.79	2.65			
	RMS (individual)		3.68		1.41		1.54						
Fraction (individual)		1.00		1.00		1.00							
RMS (mean)		3.68						2.98	2.64				
Fraction (mean)		1.00						1.00	1.00				

Table 10.4: (cont.) *Primary Variables - DLS - LCMAS-2 - Min - 1st Component - Knee Angle.*

Component Parameter		Comparison System	Inter-System: Vicon (Markers)		Intra-System: Between Repts				Intra-System: Between Days		MCID																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																
			LCMAS-2 (Markers)		LCMAS-2 (Markers)		Vicon (Markers)		LCMAS-2 (Markers)			Vicon (Markers)																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																															
Min	1st	Knee Angle Marker	Statistic	ICC	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																															
			n	12	0.897	0.887	12	12	0.991	0.958	0.989	0.937																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																															
			SEM	9.71	8.16			12	12			12	12																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																														
			SDD	26.91	22.62	26.91	22.62	2.50	4.47	1.78	3.48	12.93	5.89																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																														
			SDD lower bound	-28.99	-16.77	-28.99	-16.77	6.93	12.39	4.92	9.65	35.84	16.33																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																														
			SDD upper bound	24.83	28.46	24.83	28.46	-9.25	-11.59	-4.00	-8.07	-27.71	-16.12																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																														
			$\bar{d}$	-2.08	5.84	-2.08	5.84	4.61	13.19	5.85	11.24	43.97	16.54																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																														
			$\bar{d}$ lower bound	-10.80	-1.49	-10.80	-1.49	-2.32	0.80	0.92	1.59	8.13	0.21																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																														
			$\bar{d}$ upper bound	6.64	13.18	6.64	13.18	-4.09	-3.36	-0.63	-1.51	-2.74	-5.32																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																														
			LA lower bound	-28.99	-16.77	-28.99	-16.77	-0.54	4.96	2.47	4.68	19.00	5.73																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																														
			LA upper bound	24.83	28.46	24.83	28.46	-7.79	-12.04	-3.86	-7.96	-25.40	-16.84																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																														
			RMS (individual)	12.61				6.71			6.41																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																
			Fraction (individual)	1.00				1.00			1.00																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																
			RMS (mean)	12.32																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																							
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Table 10.4: (cont.) *Primary Variables - DLS - LCMAS-2 - Min - 1st Component - Knee Angle.*

Component Parameter Min 1st	Comparison System	Inter-System: Vicon		Intra-System: Between Repts		Intra-System: Between Days		MCID
		Vicon (Markers)		Vicon		Vicon (Markers)		
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
ICC	Statistic	0.997	0.988	0.989	0.937	0.988	0.935	0.936
n		12	12	12	12	12	12	12
SEM		1.37	2.20	1.78	3.48	1.93	3.68	5.57
SDD		3.79	6.10	4.92	9.65	5.34	10.21	15.45
SDD lower bound		-9.40	-11.46	-4.00	-8.07	-4.37	-8.32	-15.49
SDD upper bound		-1.83	0.73	5.85	11.24	6.32	12.10	15.40
$\bar{d}$		-5.62	-5.37	0.92	1.59	0.98	1.89	-0.04
$\bar{d}$ lower bound		-6.84	-7.34	-0.63	-1.51	-0.71	-1.33	-5.27
$\bar{d}$ upper bound		-4.39	-3.39	2.47	4.68	2.66	5.11	5.19
LA lower bound		-9.40	-11.46	-3.86	-7.96	-4.24	-8.05	-16.18
LA upper bound		-1.83	0.73	5.71	11.13	6.19	11.83	16.09
RMS (individual)		4.26		6.41		6.56		
Fraction (individual)		1.00		1.00		1.00		
RMS (mean)		4.24						5.40
Fraction (mean)		1.00						1.00

Table 10.4: (cont.) Primary Variables - DLS - LCMAS-2 - ROM - 1st Component - Knee Angle.

Component Parameter		Comparison System	Inter-System: Vicon (Markers)		Intra-System: Between Repts				Intra-System: Between Days		MCID	
			LCMAS-2 (Markers)		LCMAS-2 (Markers)		Vicon (Markers)		LCMAS-2 (Markers)	Vicon (Markers)		
ROM 1st	Knee Angle Marker	Statistic	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2		
ROM 1st	Knee Angle	ICC	0.833	0.831	0.946	0.900	0.958	0.830	0.853	0.940	51.4 degrees	
		n	12	12	12	12	12	12	12	12		12
		SEM	13.36	10.94	6.73	8.01	3.13	5.38	14.84	4.57		4.57
		SDD	37.04	30.32	18.65	22.20	8.68	14.90	41.15	12.65		12.65
		SDD lower bound	-53.68	-54.67	-16.30	-20.80	-11.06	-16.61	-48.41	-12.20		-12.20
		SDD upper bound	20.41	5.97	21.00	23.59	6.31	13.19	33.89	13.11		13.11
		$\bar{d}$	-16.64	-24.35	2.35	1.39	-2.37	-1.71	-7.26	0.45		0.45
		$\bar{d}$ lower bound	-28.65	-34.18	-3.77	-6.06	-4.85	-6.63	-20.33	-3.82		-3.82
		$\bar{d}$ upper bound	-4.63	-14.52	8.47	8.85	0.11	3.20	5.81	4.73		4.73
		LA lower bound	-53.68	-54.67	-16.52	-21.61	-10.03	-16.88	-47.59	-12.73		-12.73
		LA upper bound	20.41	5.97	21.23	24.40	5.29	13.45	33.07	13.64		13.64
		RMS (individual)	12.61		6.71		6.41					
		Fraction (individual)	1.00		1.00		1.00					
		RMS (mean)	12.32									
		Fraction (mean)	1.00									
Component Parameter		Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID	
			LCMAS-2 (Markers)		LCMAS-2 (Markers)		Vicon		LCMAS-2 (Markers)	Vicon		
ROM 1st	Knee Angle	Statistic	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2		
ROM 1st	Knee Angle	ICC	0.841	0.854	0.946	0.900	0.974	0.910	0.853	0.934	51.4 degrees	
		n	12	12	12	12	12	12	12	12		12
		SEM	13.18	10.54	6.73	8.01	2.53	4.22	14.84	5.16		5.16
		SDD	36.52	29.22	18.65	22.20	7.01	11.69	41.15	14.31		14.31
		SDD lower bound	-50.11	-51.74	-16.30	-20.80	-8.90	-14.21	-48.41	-12.63		-12.63
		SDD upper bound	22.94	6.69	21.00	23.59	5.12	9.16	33.89	16.00		16.00
		$\bar{d}$	-13.58	-22.53	2.35	1.39	-1.89	-2.52	-7.26	1.69		1.69
		$\bar{d}$ lower bound	-25.42	-32.00	-3.77	-6.06	-3.91	-6.11	-20.33	-3.03		-3.03
		$\bar{d}$ upper bound	-1.74	-13.06	8.47	8.85	0.12	1.06	5.81	6.40		6.40
		LA lower bound	-50.11	-51.74	-16.52	-21.61	-8.11	-13.58	-47.59	-12.86		-12.86
		LA upper bound	22.94	6.69	21.23	24.40	4.33	8.53	33.07	16.23		16.23
		RMS (individual)	11.59		6.71		6.56					
		Fraction (individual)	1.00		1.00		1.00					
		RMS (mean)	11.32									
		Fraction (mean)	1.00									

Table 10.4: (cont.) *Primary Variables - DLS - LCMAS-2 - ROM - 1st Component - Knee Angle.*

Component Parameter	ROM 1st Knee Angle	Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID
			Vicon (Markers)		Vicon (Markers)		Vicon (Markers)		Vicon (Markers)		
			Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
ICC			0.992	0.991	0.958	0.830	0.974	0.910	0.940	0.934	
n			12	12	12	12	12	12	12	12	
SEM			1.87	1.78	3.13	5.38	2.53	4.22	4.57	5.16	
SDD			5.19	4.95	8.68	14.90	7.01	11.69	12.65	14.31	
SDD lower bound			-2.14	-3.13	-11.06	-16.61	-8.90	-14.21	-12.20	-12.63	51.4
SDD upper bound			8.24	6.77	6.31	13.19	5.12	9.16	13.11	16.00	degrees
$\bar{d}$			3.05	1.82	-2.37	-1.71	-1.89	-2.52	0.45	1.69	
$\bar{d}$ lower bound			1.37	0.22	-4.85	-6.63	-3.91	-6.11	-3.82	-3.03	
$\bar{d}$ upper bound			4.74	3.42	0.11	3.20	0.12	1.06	4.73	6.40	
LA lower bound			-2.14	-3.13	-10.03	-16.88	-8.11	-13.58	-12.73	-12.86	
LA upper bound			8.24	6.77	5.29	13.45	4.33	8.53	13.64	16.23	
RMS (individual)			4.26		6.41		6.56				
Fraction (individual)			1.00		1.00		1.00				
RMS (mean)			4.24						6.42	5.67	
Fraction (mean)			1.00						1.00	1.00	

Table 10.5: Secondary Variables - DLS - LCMAS-2 - ROM - 2nd Component - COM relative to BOS Position.

Component Parameter ROM 2nd Position COM relative to BOS	Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID
		LCMAS-2 (Model)		LCMAS-2 (Model)		Vicon		LCMAS-2 (Model)		
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
ICC	Statistic	0.862	0.718	0.971	0.889	0.561	0.850	0.947	0.692	
n		12	12	12	12	12	12	12	12	
SEM		0.010	0.010	0.004	0.007	0.010	0.005	0.007	0.008	
SDD		0.028	0.029	0.011	0.019	0.028	0.014	0.020	0.023	
SDD lower bound		-0.039	-0.040	-0.013	-0.018	-0.033	-0.014	-0.018	-0.021	
SDD upper bound		0.017	0.017	0.008	0.020	0.022	0.014	0.022	0.025	
$\bar{d}$		-0.011	-0.011	-0.003	0.001	-0.005	0.000	0.002	0.002	
$\bar{d}$ lower bound		-0.020	-0.021	-0.006	-0.005	-0.014	-0.005	-0.005	-0.006	
$\bar{d}$ upper bound		-0.002	-0.002	0.001	0.008	0.003	0.005	0.008	0.010	
LA lower bound		-0.039	-0.040	-0.013	-0.019	-0.032	-0.014	-0.019	-0.022	
LA upper bound		0.017	0.017	0.008	0.021	0.021	0.014	0.022	0.026	
RMS (individual)		0.010		0.012		0.011				
Fraction (individual)		1.000		1.000		1.000				
RMS (mean)		0.009						0.014	0.013	
Fraction (mean)		1.000						1.000	1.000	

10.1.3.3 Single Leg Squat

For the SLS, numerical results for select metrics are summarized in Table 10.6. Variables that passed the screening criteria for LCMAS-2 compared to the corresponding Vicon metric are presented in Table 10.7. All system comparisons listed in the summary table for these metrics are presented in the numerical tables. Numerical results are compiled in Appendix A.4 for variables from the summary table that did not meet our screening criteria. Six different metrics are presented in Table 10.7.

We remind the reader that in the SLS there is a switch in primary and secondary variables. For consistency and ease in comparison we have left the metrics in the same order in the presented tables and simply changed the heading of the sections to correspond to the correct assignment. A few metrics had *MCID* values in both the primary and secondary category. For the SLS the primary *MCID* was lower. In all cases the LCMAS-2 did not meet the screening criteria for this lower *MCID* so the metric was converted into a secondary metric and evaluated in the screening criteria with the secondary *MCID*. Two of these metrics (ROM 1st component hip angle and Min 1st component knee angle) are reported in these tables.

Table 10.6: Summary of ICC and SDD for SLS metrics in LCMAS-2 and associated systems. Note: Inter-system circles represent Day 1 and Day 2; intra-system circles represent Between Repetitions (Day 1, Day 2), and Between Days.

	Joint	Metric	Peak	Component	Inter-System Comparison	Intra-System Comparisons			
						Model		to	Model
						LCMAS-2	Vicon		Vicon
						Markers/Model	Markers		Vicon Static 6DOF
Secondary	Hip	Angle	Max	1	*				
	Hip	Angle	ROM	1					
	Hip	Angle	IC	2					
	Knee	Angle	Min	1	*				
	Knee	Angle	ROM	1	*				
	Knee	Angle	IC	2					
	Knee	Angle	Min	2	*				
	Knee	Angle	Max	2	*				
	Knee	Moment	JCS	Max	*				
	Knee	Moment	PCS	Max	*				
	Knee	Moment	DCS	Max	*				
	COM	Position	ROM	1					
Primary	COM	Position	ROM	2					
	COM	Position to BOS	ROM	1					
	COM	Position to BOS	ROM	2					
	Hip	Angle	MKF	2					
	Knee	Angle	ROM	2					
	Knee	Angle	MKF	2					

Legend		
ICC	SDD	
= Poor	= Above MCID	* = Variable meeting screening criteria
= Adequate	= Below larger MCID	
= Excellent	= Below Smaller MCID	

Table 10.7: *Secondary Variables - SLS - LCMAS-2 - Max - 1st Component - Hip Angle.*

Component Parameter Max 1st Hip Angle Marker	Comparison System	Inter-System: Vicon (Markers)		Intra-System: Between Repts				Intra-System: Between Days		MCID
		LCMAS-2 (Markers)		LCMAS-2 (Markers)		Vicon (Markers)		LCMAS-2 (Markers)		
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
ICC		0.876	0.944	0.959	0.932	0.978	0.993	0.960	0.939	
n		12	12	12	12	12	12	12	12	
SEM		13.21	7.99	5.92	6.61	3.90	2.03	7.59	8.62	
SDD		36.63	22.16	16.40	18.32	10.82	5.63	21.05	23.90	
SDD lower bound		-31.56	-22.53	-15.66	-17.21	-12.09	-5.67	-26.23	-23.65	32.3
SDD upper bound		41.69	21.80	17.14	19.43	9.55	5.59	15.86	24.14	degrees
$\bar{d}$		5.06	-0.36	0.74	1.11	-1.27	-0.04	-5.18	0.24	
$\bar{d}$ lower bound		-6.81	-7.55	-4.79	-5.05	-4.84	-1.94	-11.42	-7.85	
$\bar{d}$ upper bound		16.93	6.82	6.27	7.27	2.29	1.87	1.06	8.33	
LA lower bound		-31.56	-22.53	-16.32	-17.89	-12.27	-5.92	-24.43	-24.71	
LA upper bound		41.69	21.80	17.80	20.11	9.72	5.84	14.07	25.20	
RMS (individual)		12.80		6.33		5.73				
Fraction (individual)		1.00		1.00		1.00				
RMS (mean)		12.09						9.74	8.98	
Fraction (mean)		1.00						1.00	1.00	

Component Parameter Max 1st Hip Angle	Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID
		LCMAS-2 (Markers)		LCMAS-2 (Markers)		Vicon		LCMAS-2 (Markers)		
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
ICC		0.963	0.988	0.959	0.932	0.987	0.993	0.960	0.985	
n		12	12	12	12	12	12	12	12	
SEM		7.46	3.86	5.92	6.61	2.90	2.01	7.59	4.40	
SDD		20.68	10.71	16.40	18.32	8.05	5.58	21.05	12.19	
SDD lower bound		-21.66	-14.89	-15.66	-17.21	-7.37	-4.98	-26.23	-14.17	32.3
SDD upper bound		19.69	6.52	17.14	19.43	8.73	6.17	15.86	10.20	degrees
$\bar{d}$		-0.99	-4.19	0.74	1.11	0.68	0.59	-5.18	-1.98	
$\bar{d}$ lower bound		-7.69	-7.66	-4.79	-5.05	-2.01	-1.26	-11.42	-5.89	
$\bar{d}$ upper bound		5.72	-0.72	6.27	7.27	3.37	2.44	1.06	1.93	
LA lower bound		-21.66	-14.89	-16.32	-17.89	-7.61	-5.11	-24.43	-14.05	
LA upper bound		19.69	6.52	17.80	20.11	8.97	6.29	14.07	10.08	
RMS (individual)		7.71		6.33		4.36				
Fraction (individual)		1.00		1.00		1.00				
RMS (mean)		7.15						9.74	6.10	
Fraction (mean)		1.00						1.00	1.00	

Table 10.7: (cont.) *Secondary Variables - SLS - LCMAS-2 - Max - 1st Component - Hip Angle.*

Component Parameter	Comparison System	Inter-System: Vicon		Intra-System: Between Repts		Intra-System: Between Days		MCID	
		Vicon (Markers)		Vicon (Markers)		Vicon (Markers)			
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2		
Max 1st Hip Angle	ICC	0.947	0.981	0.978	0.993	0.987	0.993	0.939	0.985
	n	12	12	12	12	12	12	12	12
	SEM	8.36	4.75	3.90	2.03	2.90	2.01	8.62	4.40
	SDD	23.17	13.15	10.82	5.63	8.05	5.58	23.90	12.19
	SDD lower bound	-29.22	-16.98	-12.09	-5.67	-7.37	-4.98	-23.65	-14.17
	SDD upper bound	17.12	9.33	9.55	5.59	8.73	6.17	24.14	10.20
	$\bar{d}$	-6.05	-3.82	-1.27	-0.04	0.68	0.59	0.24	-1.98
	$\bar{d}$ lower bound	-13.56	-8.09	-4.84	-1.94	-2.01	-1.26	-7.85	-5.89
	$\bar{d}$ upper bound	1.46	0.44	2.29	1.87	3.37	2.44	8.33	1.93
	LA lower bound	-29.22	-16.98	-12.27	-5.92	-7.61	-5.11	-24.71	-14.05
	LA upper bound	17.12	9.33	9.72	5.84	8.97	6.29	25.20	10.08
	RMS (individual)	8.49		5.73		4.36			
	Fraction (individual)	1.00		1.00		1.00			
	RMS (mean)	8.07						8.98	6.10
	Fraction (mean)	1.00						1.00	1.00

Table 10.7: (cont.) Secondary Variables - SLS - LCMAS-2 - Min - 1st Component - Knee Angle.

Component Parameter		Comparison System	Inter-System: Vicon (Markers)		Intra-System: Between Repts				Intra-System: Between Days		MCID		
			LCMAS-2 (Markers)		LCMAS-2 (Markers)		Vicon (Markers)		LCMAS-2 (Markers)			Vicon (Markers)	
Min	1st	Knee Angle Marker	Statistic	ICC	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2			
			n		0.957	12	0.966	12	0.944	0.951	0.967	12	0.975
			SEM		6.27	4.60			12	12	12	12	12
			SDD		17.38	12.74			5.90	4.39	3.14	1.67	3.79
			SDD lower bound		-19.47	-10.71			16.34	12.17	8.71	4.64	10.50
			SDD upper bound		15.30	14.78			-19.07	-12.35	-11.07	-4.60	-7.22
			$\bar{d}$		-2.08	2.03			13.61	11.98	6.35	4.68	13.78
			$\bar{d}$ lower bound		-7.72	-2.10			-2.73	-0.19	-2.36	0.04	3.28
			$\bar{d}$ upper bound		3.55	6.16			-7.96	-4.31	-4.86	-1.53	0.47
			LA lower bound		-19.47	-10.71			2.50	3.93	0.14	1.61	6.09
			LA upper bound		15.30	14.78			-18.86	-12.89	-10.07	-4.81	-5.39
			RMS (individual)		7.64				13.40	12.51	5.36	4.89	11.95
			Fraction (individual)		1.00				5.59				
			RMS (mean)		7.02			1.00					6.26
			Fraction (mean)		1.00								1.00
Component Parameter		Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID		
			LCMAS-2 (Markers)		LCMAS-2 (Markers)		Vicon		LCMAS-2 (Markers)			Vicon	
Min	1st	Knee Angle	Statistic	ICC	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2			
			n		0.950	12	0.957	12	0.944	0.951	0.968	12	0.974
			SEM		6.76	5.19			12	12	12	12	12
			SDD		18.73	14.38			5.90	4.39	3.18	1.62	3.91
			SDD lower bound		-24.16	-15.68			16.34	12.17	8.80	4.49	10.84
			SDD upper bound		13.29	13.08			-19.07	-12.35	-11.17	-4.40	-7.58
			$\bar{d}$		-5.43	-1.30			13.61	11.98	6.44	4.59	14.11
			$\bar{d}$ lower bound		-11.50	-5.96			-2.73	-0.19	-2.37	0.10	3.27
			$\bar{d}$ upper bound		0.64	3.37			-7.96	-4.31	-4.90	-1.42	0.30
			LA lower bound		-24.16	-15.68			2.50	3.93	0.16	1.62	6.23
			LA upper bound		13.29	13.08			-18.86	-12.89	-10.18	-4.59	-5.87
			RMS (individual)		8.27				13.40	12.51	5.45	4.78	12.41
			Fraction (individual)		1.00				5.59		4.81		
			RMS (mean)		7.69			1.00			1.00		5.99
			Fraction (mean)		1.00								1.00

Table 10.7: (cont.) Secondary Variables - SLS - LCMAS-2 - Min - 1st Component - Knee Angle.

Component Parameter	Min 1st	Knee Angle	Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID
				Vicon (Markers)		Vicon (Markers)		Vicon (Markers)		Vicon (Markers)		
				Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
ICC				0.997	0.993	0.967	0.988	0.968	0.989	0.975	0.974	
n				12	12	12	12	12	12	12	12	
SEM				1.33	1.89	3.14	1.67	3.18	1.62	3.79	3.91	
SDD				3.69	5.24	8.71	4.64	8.80	4.49	10.50	10.84	10.5 to
SDD lower bound				-7.04	-8.57	-11.07	-4.60	-11.17	-4.40	-7.22	-7.58	46
SDD upper bound				0.34	1.91	6.35	4.68	6.44	4.59	13.78	14.11	degrees
$\bar{d}$				-3.35	-3.33	-2.36	0.04	-2.37	0.10	3.28	3.27	
$\bar{d}$ lower bound				-4.54	-5.03	-4.86	-1.53	-4.90	-1.42	0.47	0.30	
$\bar{d}$ upper bound				-2.15	-1.63	0.14	1.61	0.16	1.62	6.09	6.23	
LA lower bound				-7.04	-8.57	-10.07	-4.81	-10.18	-4.59	-5.39	-5.87	
LA upper bound				0.34	1.91	5.36	4.89	5.45	4.78	11.95	12.41	
RMS (individual)				3.12		4.77		4.81				
Fraction (individual)				1.00		1.00		1.00				
RMS (mean)				3.09						6.26	5.99	
Fraction (mean)				1.00						1.00	1.00	

Table 10.7: (cont.) Secondary Variables - SLS - LCMAS-2 - ROM - 1st Component - Knee Angle.

Component Parameter	ROM 1st	Knee Angle Marker	Comparison System	Inter-System: Vicon (Markers)		Intra-System: Between Repts				Intra-System: Between Days		MCID	
				Statistic	LCMAS-2 (Markers)	Day 1	Day 2	LCMAS-2 (Markers)		Vicon (Markers)			
								Day 1	Day 2				
ROM 1st	Knee Angle	Marker	ICC		0.889	0.869	0.902	0.889	0.939	0.964	0.933	0.966	51.4 degrees
			n		12	12	12	12	12	12	12	12	
			SEM		9.55	10.12	8.50	8.84	3.53	2.66	9.48	3.69	
			SDD		26.48	28.04	23.55	24.49	9.79	7.38	26.28	10.23	
			SDD lower bound		-35.75	-43.97	-24.21	-26.36	-11.91	-8.42	-35.90	-13.19	
			SDD upper bound		17.21	12.12	22.89	22.63	7.67	6.34	16.67	7.27	
			$\bar{d}$		-9.27	-15.92	-0.66	-1.86	-2.12	-1.04	-9.62	-2.96	
			$\bar{d}$ lower bound		-17.85	-25.01	-8.62	-10.06	-5.12	-3.44	-15.82	-5.81	
			$\bar{d}$ upper bound		-0.68	-6.83	7.30	6.34	0.88	1.36	-3.42	-0.11	
			LA lower bound		-35.75	-43.97	-25.22	-27.16	-11.38	-8.45	-28.75	-11.76	
			LA upper bound		17.21	12.12	23.90	23.43	7.14	6.37	9.51	5.84	
			RMS (individual)		7.64		5.59		4.77				
			Fraction (individual)		1.00		1.00		1.00				
			RMS (mean)		7.02						9.21	6.26	
			Fraction (mean)		1.00						1.00	1.00	

Component Parameter	ROM 1st	Knee Angle	Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID	
				Statistic	LCMAS-2 (Markers)	Day 1	Day 2	LCMAS-2 (Markers)		Vicon			
								Day 1	Day 2				
ROM 1st	Knee Angle	Marker	ICC		0.897	0.876	0.902	0.889	0.942	0.972	0.933	0.977	51.4 degrees
			n		12	12	12	12	12	12	12	12	
			SEM		9.28	9.95	8.50	8.84	3.56	2.44	9.48	3.13	
			SDD		25.74	27.57	23.55	24.49	9.88	6.77	26.28	8.67	
			SDD lower bound		-33.65	-42.50	-24.21	-26.36	-11.66	-7.98	-35.90	-11.28	
			SDD upper bound		17.82	12.65	22.89	22.63	8.10	5.55	16.67	6.06	
			$\bar{d}$		-7.92	-14.92	-0.66	-1.86	-1.78	-1.21	-9.62	-2.61	
			$\bar{d}$ lower bound		-16.26	-23.86	-8.62	-10.06	-4.91	-3.36	-15.82	-4.98	
			$\bar{d}$ upper bound		0.43	-5.98	7.30	6.34	1.35	0.93	-3.42	-0.24	
			LA lower bound		-33.65	-42.50	-25.22	-27.16	-11.43	-7.83	-28.75	-9.92	
			LA upper bound		17.82	12.65	23.90	23.43	7.87	5.40	9.51	4.70	
			RMS (individual)		8.27		5.59		4.81				
			Fraction (individual)		1.00		1.00		1.00				
			RMS (mean)		7.69						9.21	5.99	
			Fraction (mean)		1.00						1.00	1.00	

Table 10.7: (cont.) *Secondary Variables - SLS - LCMAS-2 - ROM - 1st Component - Knee Angle.*

Component Parameter ROM 1st Knee Angle	Comparison System	Inter-System: Vicon		Intra-System: Between Reps				Intra-System: Between Days		MCID
		Vicon (Markers)		Vicon (Markers)		Vicon (Markers)		Vicon (Markers)		
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2			
ICC	Statistic	0.998	0.999	0.939	0.964	0.942	0.972	0.966	0.977	
n		12	12	12	12	12	12	12	12	
SEM		1.00	0.65	3.53	2.66	3.56	2.44	3.69	3.13	
SDD		2.77	1.80	9.79	7.38	9.88	6.77	10.23	8.67	
SDD lower bound		-1.42	-0.80	-11.91	-8.42	-11.66	-7.98	-13.19	-11.28	51.4 degrees
SDD upper bound		4.12	2.80	7.67	6.34	8.10	5.55	7.27	6.06	
$\bar{d}$		1.35	1.00	-2.12	-1.04	-1.78	-1.21	-2.96	-2.61	
$\bar{d}$ lower bound		0.45	0.42	-5.12	-3.44	-4.91	-3.36	-5.81	-4.98	
$\bar{d}$ upper bound		2.25	1.58	0.88	1.36	1.35	0.93	-0.11	-0.24	
LA lower bound		-1.42	-0.80	-11.38	-8.45	-11.43	-7.83	-11.76	-9.92	
LA upper bound		4.12	2.80	7.14	6.37	7.87	5.40	5.84	4.70	
RMS (individual)		3.12		4.77		4.81				
Fraction (individual)		1.00		1.00		1.00				
RMS (mean)		3.09						6.26	5.99	
Fraction (mean)		1.00						1.00	1.00	

Table 10.7: (cont.) *Secondary Variables - SLS - LCMAS-2 - Min - 2nd Component - Knee Angle.*

Component Parameter	Min 2nd	Knee Angle Marker	Comparison System	Inter-System: Vicon (Markers)		Intra-System: Between Repts				Intra-System: Between Days		MCID		
				Statistic	LCMAS-2 (Markers)	Day 1	Day 2	LCMAS-2 (Markers)		Vicon (Markers)				
								Day 1	Day 2					
Knee Angle	Min 2nd	Knee Angle Marker	ICC		0.890	0.844	0.818	0.903	0.832	0.990	0.790	0.934	6.35 to 7.6 degrees	
			n		12	12	12	12	12	12	12	12		12
			SEM		1.40	1.60	1.20	0.79	1.46	0.33	1.59	1.23		1.23
			SDD		3.87	4.45	3.32	2.20	4.05	0.92	4.40	3.40		3.40
			SDD lower bound		-0.36	-1.38	-2.68	-1.62	-3.93	-1.03	-5.11	-3.67		-3.67
			SDD upper bound		7.39	7.52	3.97	2.79	4.17	0.82	3.69	3.14		3.14
			$\bar{d}$		3.52	3.07	0.65	0.58	0.12	-0.10	-0.71	-0.27		-0.27
			$\bar{d}$ lower bound		2.26	1.63	-0.40	-0.05	-1.25	-0.41	-2.12	-1.41		-1.41
			$\bar{d}$ upper bound		4.77	4.51	1.69	1.22	1.49	0.20	0.70	0.87		0.87
			LA lower bound		-0.36	-1.38	-2.56	-1.38	-4.10	-1.04	-5.07	-3.78		-3.78
			LA upper bound		7.39	7.52	3.86	2.55	4.35	0.84	3.64	3.25		3.25
			RMS (individual)		3.77		1.48		1.57					
			Fraction (individual)		1.00		1.00		1.00					
			RMS (mean)		3.67						1.71	1.41		1.41
			Fraction (mean)		1.00						1.00	1.00		1.00

Component Parameter	Min 2nd	Knee Angle	Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID		
				Statistic	LCMAS-2 (Markers)	Day 1	Day 2	LCMAS-2 (Markers)		Vicon				
								Day 1	Day 2					
Knee Angle	Min 2nd	Knee Angle	ICC		0.457	0.488	0.818	0.903	0.943	0.940	0.790	0.934	6.35 to 7.6 degrees	
			n		12	12	12	12	12	12	12	12		12
			SEM		2.34	2.19	1.20	0.79	0.66	0.70	1.59	0.97		0.97
			SDD		6.50	6.07	3.32	2.20	1.83	1.94	4.40	2.70		2.70
			SDD lower bound		-12.06	-12.42	-2.68	-1.62	-1.74	-2.11	-5.11	-2.62		-2.62
			SDD upper bound		0.94	-0.28	3.97	2.79	1.92	1.76	3.69	2.78		2.78
			$\bar{d}$		-5.56	-6.35	0.65	0.58	0.09	-0.17	-0.71	0.08		0.08
			$\bar{d}$ lower bound		-7.67	-8.32	-0.40	-0.05	-0.53	-0.82	-2.12	-0.83		-0.83
			$\bar{d}$ upper bound		-3.45	-4.38	1.69	1.22	0.71	0.47	0.70	0.99		0.99
			LA lower bound		-12.06	-12.42	-2.56	-1.38	-1.81	-2.16	-5.07	-2.74		-2.74
			LA upper bound		0.94	-0.28	3.86	2.55	2.00	1.81	3.64	2.90		2.90
			RMS (individual)		5.90		1.48		1.70					
			Fraction (individual)		1.00		1.00		1.00					
			RMS (mean)		5.75						1.71	2.36		2.36
			Fraction (mean)		1.00						1.00	1.00		1.00

Table 10.7: (cont.) *Secondary Variables - SLS - LCMAS-2 - Min - 2nd Component - Knee Angle.*

Component Parameter	Comparison System	Inter-System: Vicon		Intra-System: Between Repts		Intra-System: Between Days		MCID
		Vicon (Markers)		Vicon		Vicon (Markers)		
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
Min 2nd Knee Angle	ICC	0.126	-0.174	0.832	0.990	0.943	0.940	0.934
	n	12	12	12	12	12	12	12
	SEM	3.05	3.26	1.46	0.33	0.66	0.70	0.97
	SDD	8.46	9.03	4.05	0.92	1.83	1.94	2.70
	SDD lower bound	-17.54	-18.45	-3.93	-1.03	-1.74	-2.11	-2.62
	SDD upper bound	-0.61	-0.39	4.17	0.82	1.92	1.76	2.78
	$\bar{d}$	-9.07	-9.42	0.12	-0.10	0.09	-0.17	0.08
	$\bar{d}$ lower bound	-11.82	-12.35	-1.25	-0.41	-0.53	-0.82	-0.83
	$\bar{d}$ upper bound	-6.33	-6.49	1.49	0.20	0.71	0.47	0.99
	LA lower bound	-17.54	-18.45	-4.10	-1.04	-1.81	-2.16	-2.74
	LA upper bound	-0.61	-0.39	4.35	0.84	2.00	1.81	2.90
	RMS (individual)	8.59		1.57		1.70		
	Fraction (individual)	1.00		1.00		1.00		
	RMS (mean)	8.51						2.36
	Fraction (mean)	1.00						1.00

Table 10.7: (cont.) Secondary Variables - SLS - LCMAS-2 - Max - 2nd Component - Knee Angle.

Component Parameter	Max 2nd	Knee Angle Marker	Comparison System	Inter-System: Vicon (Markers)		Intra-System: Between Reps				Intra-System: Between Days		MCID	
				Statistic	LCMAS-2 (Markers)	LCMAS-2 (Markers)		Vicon (Markers)		LCMAS-2 (Markers)	Vicon (Markers)		
						Day 1	Day 2	Day 1	Day 2				
Max 2nd	Knee Angle	Marker	ICC		0.818	0.889	0.705	0.924	0.929	0.915	0.813	0.944	6.2 to 8.72 degrees
			n		12	12	12	12	12	12	12	12	
			SEM		1.22	1.01	1.11	0.75	0.65	0.61	1.28	0.72	
			SDD		3.38	2.79	3.08	2.08	1.80	1.68	3.54	1.99	
			SDD lower bound		1.71	1.30	-2.73	-1.91	-2.25	-1.43	-4.43	-1.88	
			SDD upper bound		8.47	6.89	3.44	2.24	1.36	1.94	2.66	2.10	
			$\bar{d}$		5.09	4.09	0.36	0.17	-0.44	0.25	-0.89	0.11	
			$\bar{d}$ lower bound		4.00	3.19	-0.66	-0.53	-0.98	-0.29	-1.93	-0.56	
			$\bar{d}$ upper bound		6.18	5.00	1.37	0.86	0.09	0.80	0.16	0.78	
			LA lower bound		1.71	1.30	-2.78	-1.98	-2.09	-1.43	-4.11	-1.95	
			LA upper bound		8.47	6.89	3.49	2.31	1.20	1.93	2.34	2.17	
			RMS (individual)		3.77		1.48		1.57				
			Fraction (individual)		1.00		1.00		1.00		1.71	1.41	
			RMS (mean)		3.67						1.00	1.00	
			Fraction (mean)		1.00								
Max 2nd	Knee Angle	Marker	ICC		0.424	0.622	0.705	0.924	0.941	0.974	0.813	0.922	6.2 to 8.72 degrees
			n		12	12	12	12	12	12	12	12	
			SEM		3.82	3.35	1.11	0.75	1.46	0.97	1.28	2.26	
			SDD		10.58	9.28	3.08	2.08	4.04	2.69	3.54	6.26	
			SDD lower bound		-9.39	-8.89	-2.73	-1.91	-3.58	-2.74	-4.43	-6.35	
			SDD upper bound		11.77	9.67	3.44	2.24	4.50	2.64	2.66	6.17	
			$\bar{d}$		1.19	0.39	0.36	0.17	0.46	-0.05	-0.89	-0.09	
			$\bar{d}$ lower bound		-2.24	-2.61	-0.66	-0.53	-0.88	-0.96	-1.93	-2.21	
			$\bar{d}$ upper bound		4.62	3.40	1.37	0.86	1.79	0.86	0.16	2.03	
			LA lower bound		-9.39	-8.89	-2.78	-1.98	-3.66	-2.86	-4.11	-6.62	
			LA upper bound		11.77	9.67	3.49	2.31	4.57	2.76	2.34	6.45	
			RMS (individual)		5.90		1.48		1.70				
			Fraction (individual)		1.00		1.00		1.00		1.71	2.36	
			RMS (mean)		5.75						1.00	1.00	
			Fraction (mean)		1.00								

Table 10.7: (cont.) *Secondary Variables - SLS - LCMAS-2 - Max - 2nd Component - Knee Angle.*

Component Parameter Max 2nd Knee Angle		Comparison System	Inter-System: Vicon		Intra-System: Between Reps				Intra-System: Between Days		MCID
			Vicon		Vicon		Vicon		Vicon (Markers)	Vicon	
			Day 1	Day 2	Day 1	Day 2	Day 1	Day 2			
ICC			0.650	0.539	0.929	0.915	0.941	0.974	0.944	0.922	
n			12	12	12	12	12	12	12	12	
SEM			3.29	3.49	0.65	0.61	1.46	0.97	0.72	2.26	
SDD			9.11	9.67	1.80	1.68	4.04	2.69	1.99	6.26	
SDD lower bound			-13.01	-13.37	-2.25	-1.43	-3.58	-2.74	-1.88	-6.35	6.2 to
SDD upper bound			5.22	5.97	1.36	1.94	4.50	2.64	2.10	6.17	8.72
$\bar{d}$			-3.90	-3.70	-0.44	0.25	0.46	-0.05	0.11	-0.09	degrees
$\bar{d}$ lower bound			-6.85	-6.84	-0.98	-0.29	-0.88	-0.96	-0.56	-2.21	
$\bar{d}$ upper bound			-0.94	-0.57	0.09	0.80	1.79	0.86	0.78	2.03	
LA lower bound			-13.01	-13.37	-2.09	-1.43	-3.66	-2.86	-1.95	-6.62	
LA upper bound			5.22	5.97	1.20	1.93	4.57	2.76	2.17	6.45	
RMS (individual)			8.59		1.57		1.70				
Fraction (individual)			1.00		1.00		1.00				
RMS (mean)			8.51						1.41	2.36	
Fraction (mean)			1.00						1.00	1.00	

Table 10.7: (cont.) Secondary Variables - SLS - LCMAS-2 - Max - 2nd Component - Knee Moment.

Component Parameter		Comparison System	Inter-System: Vicon		Intra-System: Between Repts		Intra-System: Between Days		MCID	
			LCMAS-2 (Model)		Vicon		LCMAS-2 (Model)			
Max 2nd	Knee Moment JCS	Statistic	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2		
Max 2nd	Knee Moment JCS	ICC	0.897	0.807	0.768	0.894	0.893	0.916	0.951	26.9 Nm
		n	7	8	6	7	12	12	7	
		SEM	6.45	9.54	5.74	7.70	3.83	3.02	8.95	
		SDD	17.87	26.45	15.90	21.33	10.61	8.36	24.81	
		SDD lower bound	-14.95	-20.60	-8.59	-24.46	-10.93	-9.87	-21.21	
		SDD upper bound	20.80	32.30	23.21	18.21	10.28	6.86	28.42	
		$\bar{d}$	2.92	5.85	7.31	-3.13	-0.32	-1.51	3.60	
		$\bar{d}$ lower bound	-5.51	-5.43	3.27	-13.54	-3.91	-4.15	-8.52	
		$\bar{d}$ upper bound	11.36	17.13	11.35	7.29	3.26	1.14	15.73	
		LA lower bound	-14.95	-20.60	-0.24	-25.20	-11.38	-9.68	-22.09	
		LA upper bound	20.80	32.30	14.86	18.95	10.73	6.67	29.30	
		RMS (individual)	42.06		21.26		5.96			
Fraction (individual)	0.53		0.54		1.00					
RMS (mean)	44.68						27.53	6.59		
Fraction (mean)	0.63						0.58	1.00		

Component Parameter		Comparison System	Inter-System: Vicon		Intra-System: Between Repts		Intra-System: Between Days		MCID	
			LCMAS-2 (Model)		Vicon		LCMAS-2 (Model)			
Max 2nd	Knee Moment PCS	Statistic	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2		
Max 2nd	Knee Moment PCS	ICC	0.827	0.807	0.918	0.908	0.954	0.933	0.940	26.9 Nm
		n	7	8	6	7	12	12	7	
		SEM	9.24	8.49	5.72	5.93	2.67	2.67	5.66	
		SDD	25.61	23.54	15.85	16.45	7.41	7.41	15.69	
		SDD lower bound	-27.82	-26.98	-12.05	-16.89	-8.68	-8.15	-16.76	
		SDD upper bound	23.39	20.10	19.65	16.01	6.15	6.66	14.63	
		$\bar{d}$	-2.22	-3.44	3.80	-0.44	-1.27	-0.74	-1.06	
		$\bar{d}$ lower bound	-14.30	-13.48	-4.40	-8.81	-3.63	-3.20	-8.99	
		$\bar{d}$ upper bound	9.87	6.60	12.00	7.93	1.10	1.72	6.86	
		LA lower bound	-27.82	-26.98	-11.52	-18.18	-8.56	-8.33	-17.86	
		LA upper bound	23.39	20.10	19.12	17.30	6.03	6.84	15.73	
		RMS (individual)	41.71		20.35		5.76			
Fraction (individual)	0.53		0.54		1.00					
RMS (mean)	44.12						25.97	7.78		
Fraction (mean)	0.63						0.58	1.00		

10.2 Discussion

We will first discuss general points. Then we will step through a discussion of the metrics presented in the numerical tables for the three maneuvers in the prior section.

10.2.1 General

The Bland-Altman Plots Interpretation, Repeatability, and Root Mean Square Analysis were discussed in Chapter 9.2.1 and also apply to this data analysis.

COM Relative to BOS Interpretation

For understanding and interpretation of the COM relative to BOS plot for our three maneuvers, we look to the example in Figure 10.1. In this figure, the path for the LCMAS-2 COM relative to BOS travels a similarly shaped trajectory for all three maneuvers when compared to the Vicon COM relative to BOS. For the DVJ, the path for the LCMAS-2 COM relative to BOS travels a smaller range in the Y -direction and a more similar range in the X -direction when compared to the Vicon COM relative to BOS. This positioning demonstrates greater measurement similarity in the X -direction (medial-lateral) than in the Y -direction (anterior-posterior) or the depth value from the LCMAS-2 system. For the DLS and SLS we see a smaller range in X and Y values than for the DVJ. This discrepancy is understandable based on the dynamic nature of the maneuver and the fact that the participant is not in contact with the force plates immediately before and after the repetition. We also observe that both double legged maneuvers have data posterior to the origin, indicating the COM is to the posterior of the BOS. In the SLS we notice that in contrast, the path of the COM is more evenly distributed between the anterior and posterior sides of the BOS. For the SLS we also note the path curving around the origin on the participant's right

side (decreasing X direction). This maneuver was the SLS on the right leg. We suspect this curved feature may be mirrored for the same maneuver on the left leg.

LCMAS-2 Model

Several measurements depend on the model we created in the LCMAS-2 system. The COM and COM relative to BOS rely not only on the segment mass assignments but also the model orientation within the capture volume. So the evaluation of these metrics is also in part an evaluation of how well we were able to spatially and temporally match the LCMAS-2 data to the Vicon data. Another layer of difficulty is added when evaluating the moments and forces. These metrics also depend on spatial and temporal synchronization in addition to segment coordinate system definitions and relative movement of the different segments to each other and between captured frames used in the inverse dynamic calculations. No force metrics were compared to *MCID* values. However, from looking at the *RMS* plots in Figures 10.2 to 10.10, force curves from the LCMAS-2 appear to closely approximate the corresponding Vicon values indicating potential for use in a screening tool for ACL injury risk and rehabilitation. Force metrics should be included in a normative database and prospective studies.

The model was not used to evaluate rotation based angles.

Marker Based Angle Measurements

All evaluated angle measurements for the LCMAS-2 were marker based angle measurements. While these metrics do not depend on the spacial synchronization to the gold standard system, temporal synchronization is still important for repetition identification. The corresponding metrics, for both marker based and rotation based angles, were reported and evaluated from the Vicon system.

For the DVJ, the LCMAS-2 had three primary (Max 1st component hip angle,

Min 1st knee angle, and ROM 1st knee angle) and zero secondary metrics meet our screening criteria for marker based angle measurements relative to Vicon marker based angle measurements. For the DVJ, the LCMAS-2 had two primary (Min 1st knee angle, and ROM 1st knee angle) and zero secondary metrics meet our screening criteria for marker based angle measurements relative to Vicon rotation based angle measurements. For the DVJ, the Vicon System had five primary (Max 1st component hip angle, ROM 1st hip angle, IC 2nd component hip angle, Min 1st knee angle, and ROM 1st knee angle) and one secondary (ROM 2nd component knee angle) metric meet our screening criteria for marker based angle measurements relative to Vicon rotation based angle measurements. All three metrics that passed the screening criteria for LCMAS-2 marker based angle measurements relative to Vicon marker based angle measurements also passed Vicon marker based angle measurements relative to Vicon rotation based angle measurements.

For the DLS, the LCMAS-2 had two primary (Min 1st knee angle and ROM 1st knee angle) and zero secondary metrics meet our screening criteria for marker based angle measurements relative to Vicon marker based angle measurements. For the DLS, the LCMAS-2 had four primary (Max 1st component hip angle, IC 2nd component hip angle, Min 1st knee angle, and ROM 1st knee angle) and zero secondary metrics meet our screening criteria for marker based angle measurements relative to Vicon rotation based angle measurements. For the DLS, the Vicon System had six primary (Max 1st component hip angle, ROM 1st hip angle, IC 2nd component hip angle, Min 1st knee angle, ROM 1st knee angle, and IC 2nd component knee angle) and zero secondary metrics meet our screening criteria for marker based angle measurements relative to Vicon rotation based angle measurements. Both metrics that passed the screening criteria for LCMAS-2 marker based angle measurements relative to Vicon marker based angle measurements also passed Vicon marker based angle measurements relative to Vicon rotation based angle measurements.

For the SLS, the LCMAS-2 had four secondary (Min 1st knee angle, ROM 1st knee angle, Min 2nd component knee angle, and Max 2nd component knee angle) and zero primary metrics meet our screening criteria for marker based angle measurements relative to Vicon marker based angle measurements. For the SLS, the LCMAS-2 had four secondary (Max 1st component hip angle, Min 1st knee angle, ROM 1st knee angle, and Min 2nd component knee angle) and zero primary metrics meet our screening criteria for marker based angle measurements relative to Vicon rotation based angle measurements. For the SLS, the Vicon System had five secondary (Max 1st component hip angle, ROM 1st hip angle, IC 2nd component hip angle, Min 1st knee angle, and ROM 1st knee angle) and zero primary metrics meet our screening criteria for marker based angle measurements relative to Vicon rotation based angle measurements. Two metrics (Min 1st knee angle and ROM 1st knee angle) that passed the screening criteria for LCMAS-2 marker based angle measurements relative to Vicon marker based angle measurements also passed Vicon marker based angle measurements relative to Vicon rotation based angle measurements.

For all three maneuvers, three metrics (Max 1st component hip angle, ROM 1st hip angle, and IC 2nd component hip angle) passed the screening criteria for Vicon marker based angle measurements relative to Vicon rotation based angle measurements. Two metrics (Min 1st knee angle and ROM 1st knee angle) passed the screening criteria for all three types of comparisons for all three maneuvers.

The metrics where only the Vicon marker based measurements passed the criteria indicate a potential to use marker based angle measurements as a injury risk screening metric in the future, after we conduct a prospective study to establish metric thresholds.

Coordinate System for Reporting Moment

For the DVJ and DLS maneuvers, the PCS had the best result; however, no

moment metric met the screening criteria. In the SLS, we saw positive results for all three coordinate systems, JCS, PCS, and DCS. We will explore these results in more detail in 10.2.4. Remember that when we defined segment coordinate system for LCMAS-2 in Chapter 6.2.1.4 the JCS was equivalent to the DCS. However, these coordinate systems are different from each other in the Vicon model so comparisons of moment in each of the three different coordinate systems may yield different results.

10.2.2 Drop Vertical Jump

10.2.2.1 Primary Variables DVJ - LCMAS-2 Compared to Vicon

This section covers the primary metrics summarized in Table 10.1 and detailed in Table 10.2.

Max - 1st Component - Hip Angle

For this metric we start with the marker based angle comparison for LCMAS-2 (Markers) and Vicon (Markers) which met our screening criteria. For the inter-system comparison for this metric, the data captured with the LCMAS-2 (Markers), was excellently correlated to the corresponding Vicon System data for both Day 1 and Day 2. For intra-system comparisons, each system also had excellent correlation for each day of between repetition comparisons and between days comparisons. All SDD values were less than the smaller $MCID$ from the scientific literature. The Bland-Altman plots showed a bias, $\bar{d}$, of less than 19 degrees for inter-system comparisons, less than 7 degrees for LCMAS-2 intra-system comparisons, and less than 1 degree for Vicon intra-system comparisons. In addition, the intra-system 95% LA were similar to the 95% SDD .

Next, we look at the Vicon and LCMAS-Single marker based angles compared to the Vicon rotation based angle. All inter-system and intra-system comparisons

were excellently correlated and the *SDD* values were less than the *MCID* values, with the exception of inter-system Day 1 LCMAS-2 (Markers) to Vicon (Rotation) *SDD* which was larger than the *MCID*.

The *RMS* values were smaller than the *MCID* values for all comparisons.

We have a successful screening criteria result for the LCMAS-2 (Markers) to Vicon (Markers) and Vicon (Markers) to Vicon (Rotation) evaluations, indicating the potential for the marker based data to be a surrogate measure for the rotation based data. However, a negative result when comparing LCMAS-2 (Markers) to the Vicon (Rotation) data indicates a prospective study should be performed to establish thresholds for this metric.

Min - 1st Component - Knee Angle

For this metric all three types of comparisons had excellent inter- and intra-system correlation.

The marker based angle comparison for LCMAS-2 (Markers) and Vicon (Markers) met our screening criteria. All *SDD* values were less than the larger *MCID* from the scientific literature and Vicon (Markers) between repetitions Day 1 and between days *SDD* values were less than the smaller *MCID* value. The Bland-Altman plots showed a bias, $\bar{d}$, of less than 15 degrees for inter-system comparisons, less than 7.2 degrees for LCMAS-2 (Markers) intra-system comparisons, and less than 3 degrees for Vicon (Markers) intra-system comparisons. In addition, the intra-system 95%*LA* were similar to the 95%*SDD*.

Next, we look at the Vicon and LCMAS-2 marker based angles compared to the Vicon rotation based angle. All *SDD* values were less than the larger *MCID* from the scientific literature and Vicon (Rotation) between repetitions Day 1 and between days *SDD* values were less than the smaller *MCID* value. Vicon (Markers) and Vicon (Rotation) inter-system *SDD* values were also less

than the smaller *MCID* value. For the LCMAS-2 (Markers) to Vicon (Rotation) comparison, the Bland-Altman plots showed a bias, $\bar{d}$, of less than 11.5 degrees for inter-system comparisons, less than 7.2 degrees for LCMAS-2 (Markers) intra-system comparisons, and less than 2.2 degrees for Vicon (Rotation) intra-system comparisons. In addition, the intra-system 95%*LA* were similar to the 95%*SDD*.

The *RMS* values were smaller than the *MCID* values for all comparisons.

So we have a successful screening criteria result for the LCMAS-2 (Markers) to Vicon (Markers) evaluation and when comparing each of these systems to the Vicon (Rotation) data. This outcome indicates the marker based data is a surrogate measure for the rotation based data for this metric.

ROM - 1st Component - Knee Angle

For this metric all three types of comparisons had excellent inter- and intra-system correlation, with the exception of LCMAS-2 (Marker) intra-system between days which was adequately correlated. All three types of comparisons had inter- and intra-system *SDD* values smaller than the *MCID* value.

The marker based angle comparison for LCMAS-2 (Markers) and Vicon (Markers) met our screening criteria. The Bland-Altman plots showed a bias, $\bar{d}$, of less than 20 degrees for inter-system comparisons, less than 3.1 degrees for LCMAS-2 (Markers) intra-system comparisons, and less than 5.3 degrees for Vicon (Markers) intra-system comparisons. In addition, the intra-system 95%*LA* were similar to the 95%*SDD*.

The comparison for LCMAS-2 (Markers) and Vicon (Rotation) also met our screening criteria. The Bland-Altman plots showed a bias, $\bar{d}$, of less than 19 degrees for inter-system comparisons, less than 3.1 degrees for LCMAS-2 (Markers) intra-system comparisons, and less than 6 degrees for Vicon (Rotation) intra-system comparisons. In addition, the intra-system 95%*LA* were similar to the

95%*SDD*.

The *RMS* values were smaller than the *MCID* values for all comparisons.

We have a successful screening criteria result for the LCMAS-2 (Markers) to Vicon (Markers) evaluation and when comparing each of these systems to the Vicon (Rotation) data. This outcome indicates the marker based data is a surrogate measure for the rotation based data for this metric. We do acknowledge however, that for this metric the *MCID* value is rather large. This comparison indicates that maneuvers scored with large differences between groups such as the deep squat in a Functional Movement Screen (FMS) may be an appropriate use of our system while the accuracy for more sensitive comparisons requires more exploration.

10.2.3 Double Leg Squat

10.2.3.1 Primary Variables DLS - LCMAS-2 Compared to Vicon

This section covers the primary metrics summarized in Table 10.3 and detailed in Table 10.4.

Max - 1st Component - Hip Angle

For this metric all three types of comparisons had excellent inter- and intra-system correlation. All three types of comparisons had inter- and intra-system *SDD* values smaller than the *MCID* value, with the exception of LCMAS-2 (Marker) to Vicon (Markers) inter-system comparison.

The marker based angle comparison for LCMAS-2 (Markers) and Vicon (Markers) did not meet our screening criteria.

The comparison for LCMAS-2 (Markers) and Vicon (Rotation) met our screening criteria. The Bland-Altman plots showed a bias, $\bar{d}$, of less than 15.1 degrees

for inter-system comparisons, less than 4.5 degrees for LCMAS-2 intra-system comparisons, and less than 1.1 degrees for Vicon intra-system comparisons. In addition, the intra-system 95%*LA* were similar to the 95%*SDD*.

The *RMS* values were less than the *MCID* values for all comparisons.

We have a successful screening criteria result for the LCMAS-2 (Markers) to Vicon (Rotation) evaluation. This outcome indicates our system can use this metric in evaluating maneuvers.

IC - 2nd Component - Hip Angle

For this metric all three types of comparisons had excellent inter- and intra-system correlation, with the exception of LCMAS-2 (Marker) to Vicon (Markers) inter-system comparison which was adequately correlated for both Day 1 and Day 2. All three types of comparisons had inter- and intra-system *SDD* values less than the smaller *MCID* value, with the exception of LCMAS-2 (Marker) to Vicon (Markers) inter-system comparison which had an *SDD* value above the larger *MCID* value.

The marker based angle comparison for LCMAS-2 (Markers) and Vicon (Markers) did not meet our screening criteria.

The comparison for LCMAS-2 (Markers) and Vicon (Rotation) met our screening criteria. The Bland-Altman plots showed a bias, $\bar{d}$, of less than 1.4 degrees for inter-system comparisons, less than 1 degree for LCMAS-2 intra-system comparisons, and less than 1 degree for Vicon intra-system comparisons. In addition, the intra-system 95%*LA* were similar to the 95%*SDD*.

The *RMS* values were smaller than the larger *MCID* values for all comparisons, with the exception of LCMAS-2 (Marker) to Vicon (Markers) inter-system comparison.

We have a successful screening criteria result for the LCMAS-2 (Markers) to

Vicon (Rotation) evaluation. This outcome indicates our system can use this metric in evaluating maneuvers.

Min - 1st Component - Knee Angle

For this metric all three types of comparisons had excellent inter- and intra-system correlation. All three types of comparisons had inter- and intra-system *SDD* values smaller than the larger *MCID* value. Intra-system comparisons had *SDD* values less than the smaller *MCID* value for LCMAS-2 (Markers) between repetitions Day 1, Vicon (Markers) between repetitions Day 1 and Day 2, and Vicon (Rotation) between repetitions Day 1 and Day 2. Inter-system comparisons had *SDD* values less than the smaller *MCID* value for Vicon (Markers) to Vicon (Rotation).

The marker based angle comparison for LCMAS-2 (Markers) and Vicon (Markers) met our screening criteria. The Bland-Altman plots showed a bias, $\bar{d}$, of less than 6 degrees for inter-system comparisons, less than 8.2 degrees for LCMAS-2 (Markers) intra-system comparisons, and less than 1.6 degrees for Vicon (Markers) intra-system comparisons. In addition, the intra-system 95%*LA* were similar to the 95%*SDD*.

The comparison for LCMAS-2 (Markers) and Vicon (Rotation) met our screening criteria. The Bland-Altman plots showed a bias, $\bar{d}$, of less than 8 degrees for inter-system comparisons, less than 8.2 degrees for LCMAS-2 intra-system comparisons, and less than 2 degrees for Vicon intra-system comparisons. In addition, the intra-system 95%*LA* were similar to the 95%*SDD*.

The *RMS* values were smaller than the larger *MCID* values for all comparisons.

We have a successful screening criteria result for the LCMAS-2 (Markers) to Vicon (Markers) evaluation and when comparing each of these systems to

the Vicon (Rotation) data. This outcome indicates the marker based data is a surrogate measure for the rotation based data for this metric.

ROM - 1st Component - Knee Angle

For this metric all three types of comparisons had excellent inter- and intra-system correlation. All three types of comparisons had inter- and intra-system *SDD* values smaller than the *MCID* value.

The marker based angle comparison for LCMAS-2 (Markers) and Vicon (Markers) met our screening criteria. The Bland-Altman plots showed a bias, $\bar{d}$, of less than 25 degrees for inter-system comparisons, less than 7.3 degrees for LCMAS-2 (Markers) intra-system comparisons, and less than 2.4 degrees for Vicon (Markers) intra-system comparisons. In addition, the intra-system 95%*LA* were similar to the 95%*SDD*.

The comparison for LCMAS-2 (Markers) and Vicon (Rotation) met our screening criteria. The Bland-Altman plots showed a bias, $\bar{d}$, of less than 23 degrees for inter-system comparisons, less than 7.3 degrees for LCMAS-2 intra-system comparisons, and less than 2.6 degrees for Vicon intra-system comparisons. In addition, the intra-system 95%*LA* were similar to the 95%*SDD*.

The *RMS* values were smaller than the *MCID* values for all comparisons.

We have a successful screening criteria result for the LCMAS-2 (Markers) to Vicon (Markers) evaluation and when comparing each of these systems to the Vicon (Rotation) data. This outcome indicates the marker based data is a surrogate measure for the rotation based data for this metric. Again, we do acknowledge that for this metric the *MCID* value is rather large. This comparison indicates that maneuvers scored with large differences between groups such as the deep squat in a Functional Movement Screen (FMS) may be an appropriate use of our system while the accuracy for more sensitive comparisons requires more

exploration.

10.2.3.2 Secondary Variables DLS - LCMAS-2 Compared to Vicon

This section covers the secondary metrics summarized in Table 10.3 and detailed in Table 10.5.

ROM - 2nd Component - COM relative to BOS - Position

This metric met our screening criteria. The LCMAS-2 to Vicon comparisons had excellent inter-system correlation for Day 1 and adequate correlation for Day 2. In the intra-system comparisons, LCMAS-2 had excellent correlation for all comparisons and Vicon had adequate correlation for between repetitions Day 1 and between days, and excellent correlation for between repetitions Day 2. All comparisons had inter- and intra-system SDD values less than the $MCID$ value.

The Bland-Altman plots showed a bias, $\bar{d}$, of less than 1.2 cm for inter-system comparisons, less than 0.4 cm for LCMAS-2 intra-system comparisons, and less than 0.6 cm for Vicon intra-system comparisons. In addition, the intra-system 95% LA were similar to the 95% SDD .

The RMS values were smaller than the $MCID$ values for all comparisons.

We have a successful screening criteria result for the LCMAS-2 to Vicon evaluation. This outcome indicates our system can use this metric in evaluating maneuvers.

10.2.4 Single Leg Squat

10.2.4.1 Secondary Variables SLS - LCMAS-2 Compared to Vicon

This section covers the secondary metrics summarized in Table 10.6 and detailed in Table 10.7.

Max - 1st Component - Hip Angle

For this metric all three types of comparisons had excellent inter- and intra-system correlation. All three types of comparisons had inter- and intra-system *SDD* values less than the *MCID* value, with the exception of LCMAS-2 (Marker) to Vicon (Markers) inter-system comparison Day 1.

The marker based angle comparison for LCMAS-2 (Markers) and Vicon (Markers) did not meet our screening criteria.

The comparison for LCMAS-2 (Markers) and Vicon (Rotation) met our screening criteria. The Bland-Altman plots showed a bias, $\bar{d}$, of less than 4.2 degrees for inter-system comparisons, less than 5.2 degrees for LCMAS-2 intra-system comparisons, and less than 2 degrees for Vicon intra-system comparisons. In addition, the intra-system 95%*LA* were similar to the 95%*SDD*.

The *RMS* values were smaller than the *MCID* values for all comparisons.

We have a successful screening criteria result for the LCMAS-2 (Markers) to Vicon (Rotation) evaluation. This outcome indicates our system can use this metric in evaluating maneuvers.

Min - 1st Component - Knee Angle

For this metric all three types of comparisons had excellent inter- and intra-system correlation. All three types of comparisons had inter- and intra-system *SDD* values smaller than the larger *MCID* value. Intra-system comparisons

had *SDD* values less than the smaller *MCID* value for Vicon (Markers) between repetitions Day 1 and Day 2, and Vicon (Rotation) between repetitions Day 1 and Day 2. Inter-system comparisons had *SDD* values less than the smaller *MCID* value for Vicon (Markers) to Vicon (Rotation).

The marker based angle comparison for LCMAS-2 (Markers) and Vicon (Markers) met our screening criteria. The Bland-Altman plots showed a bias, $\bar{d}$, of less than 2.1 degrees for inter-system comparisons, less than 7.5 degrees for LCMAS-2 (Markers) intra-system comparisons, and less than 3.3 degrees for Vicon (Markers) intra-system comparisons. In addition, the intra-system 95%*LA* were similar to the 95%*SDD*.

The comparison for LCMAS-2 (Markers) and Vicon (Rotation) met our screening criteria. The Bland-Altman plots showed a bias, $\bar{d}$, of less than 5.5 degrees for inter-system comparisons, less than 7.5 degrees for LCMAS-2 intra-system comparisons, and less than 3.3 degrees for Vicon intra-system comparisons. In addition, the intra-system 95%*LA* were similar to the 95%*SDD*.

The *RMS* values were less than the smaller *MCID* values for all comparisons.

We have a successful screening criteria result for the LCMAS-2 (Markers) to Vicon (Markers) evaluation and when comparing each of these systems to the Vicon (Rotation) data. This outcome indicates the marker based data is a surrogate measure for the rotation based data for this metric.

ROM - 1st Component - Knee Angle

For this metric all three types of comparisons had excellent inter- and intra-system correlation. All three types of comparisons had inter- and intra-system *SDD* values smaller than the *MCID* value.

The marker based angle comparison for LCMAS-2 (Markers) and Vicon (Markers) met our screening criteria. The Bland-Altman plots showed a bias, $\bar{d}$, of less

than 16 degrees for inter-system comparisons, less than 10 degrees for LCMAS-2 (Markers) intra-system comparisons, and less than 3 degrees for Vicon (Markers) intra-system comparisons. In addition, the intra-system 95%*LA* were similar to the 95%*SDD*.

The comparison for LCMAS-2 (Markers) and Vicon (Rotation) met our screening criteria. The Bland-Altman plots showed a bias, $\bar{d}$, of less than 15 degrees for inter-system comparisons, less than 10 degrees for LCMAS-2 intra-system comparisons, and less than 3 degrees for Vicon intra-system comparisons. In addition, the intra-system 95%*LA* were similar to the 95%*SDD*.

The *RMS* values were smaller than the *MCID* values for all comparisons.

We have a successful screening criteria result for the LCMAS-2 (Markers) to Vicon (Markers) evaluation and when comparing each of these systems to the Vicon (Rotation) data. This outcome indicates the marker based data is a surrogate measure for the rotation based data for this metric. Again we do acknowledge, that for this metric the *MCID* value is rather large. This comparison indicates that maneuvers scored with large differences between groups such as the deep squat in a Functional Movement Screen (FMS) may be an appropriate use of our system while the accuracy for more sensitive comparisons needs more exploration.

Min - 2nd Component - Knee Angle

For this metric all three types of intra-system comparisons had excellent intra-system correlation. All three types of intra-system comparisons also had *SDD* values less than the smaller *MCID* value.

The marker based angle comparison for LCMAS-2 (Markers) and Vicon (Markers) met our screening criteria. This comparison had excellent inter-system correlation for both Day 1 and Day 2 and *SDD* values less than the smaller *MCID* value. The Bland-Altman plots showed a bias, $\bar{d}$, of less than 3.6 degrees for

inter-system comparisons, less than 0.8 degrees for LCMAS-2 (Markers) intra-system comparisons, and less than 0.3 degrees for Vicon (Markers) intra-system comparisons. In addition, the intra-system 95%*LA* were similar to the 95%*SDD*.

The comparison for LCMAS-2 (Markers) and Vicon (Rotation) met our screening criteria. This comparison had adequate inter-system correlation for both Day 1 and Day 2 and an *SDD* values less than the smaller *MCID* value for Day 2 and less than the larger *MCID* value for Day 1. The Bland-Altman plots showed a bias, $\bar{d}$, of less than 6.4 degrees for inter-system comparisons, less than 0.8 degrees for LCMAS-2 intra-system comparisons, and less than 0.2 degrees for Vicon intra-system comparisons. In addition, the intra-system 95%*LA* were similar to the 95%*SDD*.

Interestingly, Vicon (Markers) compared to Vicon (Rotation) did not meet our screening criteria. The inter-system correlation was poor for both days and *SDD* values were above the *MCID* value.

The *RMS* values were less than the smaller *MCID* value for all comparisons, with the exception of Vicon (Marker) to Vicon (Rotation) inter-system comparison where the *RMS* values were greater than the larger *MCID* value.

We have a successful screening criteria result for the LCMAS-2 (Markers) to Vicon (Markers) and LCMAS-2 (Markers) to Vicon (Rotation) evaluation. This outcome indicates our system can use this metric in evaluating maneuvers. However, caution should be used because of the lack of agreement between the Vicon (Markers) to Vicon (Rotation) data. A prospective study to determine thresholds for this metric with the low-cost system would be prudent.

Max - 2nd Component - Knee Angle

For this metric the marker based angle comparison for LCMAS-2 (Markers) and Vicon (Markers) met our screening criteria. This comparison had excellent

inter-system correlation for both Day 1 and Day 2. All intra-system comparisons had excellent correlation, with the exception of LCMAS-2 (Marker) between repetitions Day 1 which was adequately correlated. For all comparisons the *SDD* values were less than the smaller *MCID* value. The Bland-Altman plots showed a bias, $\bar{d}$, of less than 5.1 degrees for inter-system comparisons, less than 0.9 degrees for LCMAS-2 (Markers) intra-system comparisons, and less than 0.5 degrees for Vicon (Markers) intra-system comparisons. In addition, the intra-system 95%*LA* were similar to the 95%*SDD*.

The comparisons for LCMAS-2 (Markers) and Vicon (Markers) to Vicon (Rotation) did not meet our screening criteria. These comparisons had adequate inter-system correlations for both Day 1 and Day 2. The intra-system correlation for LCMAS-2 (Markers) was discussed above and the intra-system correlation for both Vicon systems was excellent. However, both sets of inter-system *SDD* values were greater than the larger *MCID* value on both days. All intra-system *SDD* values were less than the smaller *MCID* value, with the exception of the Vicon (Rotation) *SDD* value which was between the two *MCID* values.

The *RMS* values were less than the smaller *MCID* value for all comparisons, with the exception of Vicon (Marker) to Vicon (Rotation) inter-system comparison where the *RMS* values were less than the larger *MCID* value.

We have a successful screening criteria result for the LCMAS-2 (Markers) to Vicon (Markers) but not with either of the Vicon (Rotation) evaluations. This outcome indicates our system can possibly use this metric in evaluating maneuvers. However, a prospective study to determine thresholds and a normative database for this metric with the low-cost system is necessary.

Max - 2nd Component - Knee Moment

For this metric the comparison for the LCMAS-2 and Vicon systems in all three coordinate systems (joint (JCS), proximal (PCS), and distal (DCS)) had excellent inter- and intra-system correlation and *SDD* values smaller than the *MCID* value. This was the only metric reported that passed our screening criteria but did not have full data sets. We captured about two-thirds of the LCMAS-2 data and all of the Vicon data.

The comparison in the JCS met our screening criteria. The Bland-Altman plots showed a bias, $\bar{d}$, of less than 5.9 Nm for inter-system comparisons, less than 7.4 Nm for LCMAS-2 intra-system comparisons, and less than 0.9 Nm for Vicon intra-system comparisons. In addition, the intra-system 95%*LA* were similar to the 95%*SDD*.

The comparison in the PCS met our screening criteria. The Bland-Altman plots showed a bias, $\bar{d}$, of less than 3.5 Nm for inter-system comparisons, less than 3.9 Nm for LCMAS-2 intra-system comparisons, and less than 0.9 Nm for Vicon intra-system comparisons. In addition, the intra-system 95%*LA* were similar to the 95%*SDD*.

The comparison in the DCS met our screening criteria. The Bland-Altman plots showed a bias, $\bar{d}$, of less than 7.1 Nm for inter-system comparisons, less than 7.4 Nm for LCMAS-2 intra-system comparisons, and less than 0.9 Nm for Vicon intra-system comparisons. In addition, the intra-system 95%*LA* were similar to the 95%*SDD*.

The *RMS* values were less than the *MCID* value for all intra-system between repetition comparisons and Vicon intra-system between days comparisons. For the LCMAS-2 intra-system between days comparisons, only the PCS had an *RMS* value less than the *MCID* value. For inter-system comparisons all *RMS* values were greater than the *MCID* value.

With the *RMS* analysis, at this point in time the PCS seems to be the best for reporting this metric. All three coordinate systems passed the *ICC* and *SDD* based screening criteria, but caution should be used prior to using this metric in evaluating maneuvers until appropriate system improvements can be implemented to address the lack of agreement seen in the *RMS* values.

10.2.5 Conclusions

For each system we were able to assess the within-day and between-day repeatability for the full repetition time profiles as well as the peak value of each metric for the DVJ, DLS, and SLS maneuvers. These intra-system reliability measures are also known as test-retest reliability and help us evaluate the “consistency of a test or measure” [121]. Additionally, we were able to compare the reliability of LCMAS-2 to the industry gold standard Vicon system. Inter-system evaluations help us quantify the agreement between two methods of clinical measurement [11]. We also determined: 1) which marker based angles are good surrogate measures for the corresponding rotation based angle measurements; and 2) the PCS is the best to report moment data.

For all the maneuvers studied, our LCMAS-2 system has repeatable measures and *SDD* smaller than the *MCID* values from the scientific literature for some of the metrics (3 for DVJ, 5 for DLS, and 6 for SLS) between at-risk and normal populations. This outcome enables the use of the LCMAS-2 system as a screening tool for ACL injury risk and rehabilitation. To expand the number of metrics and the clinical relevance of this screening tool we propose continued system improvements and a prospective study to establish a normative database and identification of abnormal movement thresholds.

CHAPTER 11

Clinical Utility

11.1 Introduction

In the clinical setting, a tool to assess anterior cruciate ligament (ACL) injury risk and rehabilitation needs to be easy to implement, and simple to interpret. These requirements will facilitate a tool to be incorporated into clinical practice and impactful on patient health. We are motivated to create an algorithm to interpret a patient’s kinematic data captured with one of our LCMAS and provide the patient and practitioner with a simple assessment score. This score would quantify the level of ACL injury risk or level of rehabilitation due to the patient’s movement pattern. Once the level of injury risk is identified, interventions can be implemented and progress can be monitored quantitatively.

As we discussed in Chapter 1, a possible cause of non-contact ACL injury is a combination of deficiencies resulting in kinematic and kinetic abnormalities which can be visualized during screening maneuvers. Other researchers have attempted to create clinically friendly ACL injury risk screening assessment using the drop vertical jump (DVJ) [85]. However, when implemented by another research team, results were inconclusive [43]. This attempt at a clinically friendly assessment relied on validated 2-D surrogate measures [84] for the 3-D metrics identified in a prospective study [50].

Our aim is that with a 3-D measurement tool, there is potential to create a working algorithm for a clinically friendly injury risk and rehabilitation screening

tool.

In order to gain a sense of what our current low-cost systems are capable of assessing prior to performing a prospective study, we construct and implement a simple literature value based algorithm. We apply this algorithm with the DVJ, double leg squat (DLS), and single leg squat (SLS) data from Vicon, LCMAS-Single, and LCMAS-2 used in our test-retest reliability study.

We hypothesize that we can use a simple literature value based algorithm to create a straight-forward, quantitative, ACL injury risk score and assess the test-retest reliability for this score for our LCMAS-Single and LCMAS-2 compared to the gold standard Vicon system.

11.2 Methods

We created an algorithm based on literature values and five values from three kinematic components.

The algorithm was constructed with using simple linear relationships and weighting. The first component is peak knee flexion. According to Crossley, exceeding 60 degrees of knee flexion is considered an element of good performance on the SLS maneuver [29]. The second component is peak knee abduction angle. Here we used knee valgus motion and tibial length from Myer's tool development [85] to define the risk angle at 6 degrees. The third metric is peak hip adduction angle. We use the difference between a poor and good rating for a SLS, according to Hollman [52]. We note that McConnell [75] identified the first 20 degrees of knee flexion to be the most critical for proper movement. So, we also look at the angle of knee flexion when the peak values of knee abduction angle and peak hip adduction angle occur. If these peaks occur at less than 20 degrees of knee flexion, the risk contribution of the component is amplified indicating more injury risk. Next, we use a simple linear scale to assess a level of risk for each of the three

components. Finally, we weight these components into a single compiled score based on approximations of Myer's tool [85].

A simple visualization of this algorithm is presented in Figure 11.1, where the R values are the risk contribution of each metric and the w is the weighting factor. The output *OverallScore* is an easy to interpret value from 0 to 10, where 0-4 is Poor, 4-7 is Fair, and 7-10 is Good.

The needed algorithm input metrics were obtained from the study detailed in Chapter 8. We use data captured in the LCMAS-Single for the DVJ, and in the LCMAS-2 and Vicon for the DVJ, DLS, and SLS. To establish *MCID* values for our algorithm we calculate the point contribution of each metric at its individual *MCID* value without the additional penalty for the peak occurring in less than 20 degrees of flexion. The low *MCID* value is 0.72 points and the high *MCID* value is 2.64 points.

Finally, we perform the test-retest reliability calculations of the low-cost systems relative to the gold standard Vicon system using the data analysis and statistical methods outlined in Chapter 8.2.2.

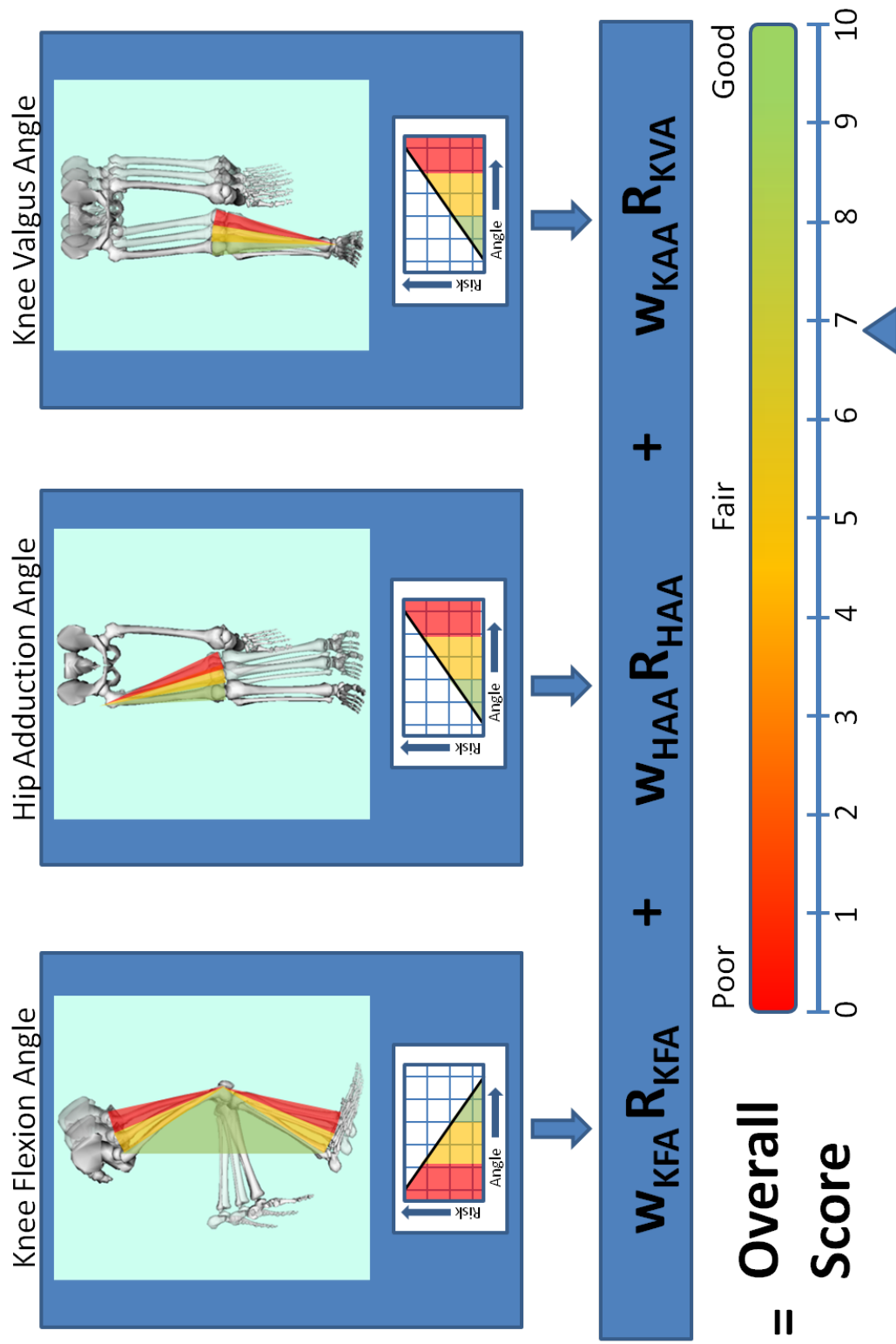


Figure 11.1: Simple literature based ACL injury risk assessment algorithm.

11.3 Results

Numerical results for the overall risk score evaluation are summarized in Table 11.1 and detailed in Tables 11.2 to 11.4. We remind the reader that interpretations of these two types of tables were presented in Chapter 9.1.4.

The tables consist of four different types of comparisons. First, we have comparisons between a version of LCMAS-Single models and the Vicon model risk score. Second, are comparisons between the LCMAS-Single or LCMAS-2 marker based angle risk score and the corresponding Vicon marker based angle risk score. The next type of comparison is LCMAS-Single or LCMAS-2 marker based angle risk score to the corresponding Vicon model or JCS based angle risk score. Finally, we examine the Vicon marker based angle risk score to the corresponding Vicon model or JCS based angle risk score.

For the DVJ, numerical results for the risk score comparisons of the LCMAS-Single and LCMAS-2 are presented in Table 11.2. In the LCMAS-Single only two model versions (Vicon Static - IK and Vicon Static - 6DOF) had values for all metrics in the risk score calculation and thus results to report. Next, numerical results for the risk score comparisons of the DLS for LCMAS-2 are presented in Table 11.3. Finally, numerical results for the risk score comparisons of the SLS for LCMAS-2 are presented in Table 11.4.

Table 11.1: Summary of ICC and SDD for Risk Score in all systems. Note: Inter-system circles represent Day 1 and Day 2; intra-system circles represent Between Repetitions (Day 1, Day 2), and Between Days.

Metric	Maneuver	Inter-System Comparison	Intra-System Comparisons										to	Model																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																												
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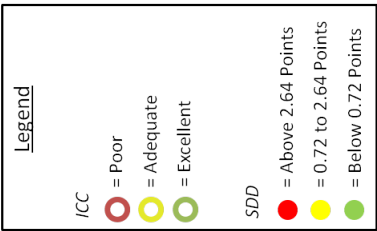


Table 11.2: *Summary Risk Score - DVJ - LCMAS-Single for JCS based angles.*

JCS to JCS	Risk Score	Comparison System	Inter-System: Vicon		Intra-System: Between Reps				Intra-System: Between Days	
			LCMAS-Single (Vicon Static, IK)		LCMAS-Single (Vicon Static, IK)		Vicon		LCMAS-Single (Vicon Static, IK)	
			Day 1	Day 2	Day 1	Day 2	Day 1	Day 2		Vicon
		ICC	0.073	0.219	0.487	0.781	0.892	0.838	0.511	0.970
		n	12	12	11	12	12	12	12	12
		SEM	1.39	1.17	1.38	0.61	0.38	0.51	1.21	0.28
		SDD	3.85	3.26	3.82	1.69	1.04	1.41	3.36	0.79
		SDD lower bound	-2.87	-1.54	-3.30	-2.03	-0.83	-1.36	-2.73	-0.91
		SDD upper bound	4.83	4.98	4.34	1.35	1.25	1.46	3.98	0.67
		$\bar{d}$	0.98	1.72	0.52	-0.34	0.21	0.05	0.62	-0.12
		$\bar{d}$ lower bound	-0.27	0.67	-0.80	-0.86	-0.12	-0.42	-0.43	-0.37
		$\bar{d}$ upper bound	2.23	2.78	1.84	0.19	0.53	0.53	1.68	0.14
		LA lower bound	-2.87	-1.54	-3.34	-1.96	-0.79	-1.41	-2.64	-0.90
		LA upper bound	4.83	4.98	4.38	1.28	1.21	1.52	3.89	0.67

JCS to JCS	Risk Score	Comparison System	Inter-System: Vicon		Intra-System: Between Reps				Intra-System: Between Days	
			LCMAS-Single (Vicon Static, 6DOF)		LCMAS-Single (Vicon Static, 6DOF)		Vicon		LCMAS-Single (Vicon Static, 6DOF)	
			Day 1	Day 2	Day 1	Day 2	Day 1	Day 2		Vicon
		ICC	0.253	0.573	0.780	0.886	0.892	0.838	0.824	0.970
		n	12	12	11	12	12	12	12	12
		SEM	1.38	1.10	0.93	0.70	0.38	0.51	0.92	0.28
		SDD	3.82	3.06	2.59	1.93	1.04	1.41	2.56	0.79
		SDD lower bound	-3.41	-2.43	-1.96	-1.90	-0.83	-1.36	-2.46	-0.91
		SDD upper bound	4.24	3.69	3.22	1.95	1.25	1.46	2.65	0.67
		$\bar{d}$	0.42	0.63	0.63	0.02	0.21	0.05	0.10	-0.12
		$\bar{d}$ lower bound	-0.82	-0.36	-0.18	-0.63	-0.12	-0.42	-0.77	-0.37
		$\bar{d}$ upper bound	1.66	1.62	1.45	0.68	0.53	0.53	0.96	0.14
		LA lower bound	-3.41	-2.43	-1.75	-1.99	-0.79	-1.41	-2.57	-0.90
		LA upper bound	4.24	3.69	3.02	2.04	1.21	1.52	2.76	0.67

Table 11.2: (cont.) *Evaluation Risk Score - DVJ - LCMAS-Single for marker based angles.*

Markers to Markers	Risk Score	Comparison System	Inter-System: Vicon (Markers)		Intra-System: Between Reps				Intra-System: Between Days	
			LCMAS-Single (Markers)		LCMAS-Single (Markers)		Vicon (Markers)		LCMAS-Single (Markers)	
			Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2
ICC		Statistic	-0.135	0.616	0.899	0.737	0.709	0.606	0.852	0.370
n			8	7	5	7	12	12	6	12
SEM			0.99	0.68	0.38	0.46	0.44	0.63	0.62	0.79
SDD			2.75	1.90	1.04	1.28	1.21	1.76	1.72	2.20
SDD lower bound			-3.60	-2.37	-0.61	-1.45	-1.07	-2.15	-1.57	-2.81
SDD upper bound			1.91	1.42	1.48	1.10	1.36	1.36	1.87	1.59
$\bar{d}$			-0.85	-0.48	0.43	-0.17	0.14	-0.39	0.15	-0.61
$\bar{d}$ lower bound			-2.02	-1.37	0.01	-0.80	-0.26	-0.93	-0.84	-1.23
$\bar{d}$ upper bound			0.33	0.42	0.86	0.46	0.54	0.14	1.14	0.02
LA lower bound			-3.60	-2.37	-0.24	-1.50	-1.09	-2.04	-1.70	-2.54
LA upper bound			1.91	1.42	1.10	1.16	1.38	1.26	2.00	1.33

Markers to ICS	Risk Score	Comparison System	Inter-System: Vicon LCMAS-Single (Markers)		Intra-System: Between Reps				Intra-System: Between Days	
			LCMAS-Single (Markers)		LCMAS-Single (Markers)		Vicon (Markers)		LCMAS-Single (Markers)	
			Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2
ICC		Statistic	0.051	0.341	0.899	0.737	0.892	0.838	0.852	0.970
n			8	7	5	7	12	12	6	12
SEM			1.27	1.02	0.38	0.46	0.38	0.51	0.62	0.28
SDD			3.53	2.83	1.04	1.28	1.04	1.41	1.72	0.79
SDD lower bound			-3.34	-2.56	-0.61	-1.45	-0.83	-1.36	-1.57	-0.91
SDD upper bound			3.72	3.09	1.48	1.10	1.25	1.46	1.87	0.67
$\bar{d}$			0.19	0.27	0.43	-0.17	0.21	0.05	0.15	-0.12
$\bar{d}$ lower bound			-1.31	-1.07	0.01	-0.80	-0.12	-0.42	-0.84	-0.37
$\bar{d}$ upper bound			1.70	1.60	0.86	0.46	0.53	0.53	1.14	0.14
LA lower bound			-3.34	-2.56	-0.24	-1.50	-0.79	-1.41	-1.70	-0.90
LA upper bound			3.72	3.09	1.10	1.16	1.21	1.52	2.00	0.67

Table 11.2: (cont.) *Evaluation Risk Score - DVJ - LCMAS-2 for marker based angles.*

Markers to Markers	Risk Score	Comparison System	Inter-System: Vicon (Markers)		Intra-System: Between Reps				Intra-System: Between Days	
			LCMAS-2 (Markers)		LCMAS-2 (Markers)		Vicon (Markers)		LCMAS-2 (Markers)	Vicon (Markers)
			Day 1	Day 2	Day 1	Day 2	Day 1	Day 2		
ICC		Statistic	0.811	0.107	0.409	0.640	0.709	0.606	-0.355	0.370
n			12	12	12	12	12	12	12	12
SEM			0.40	1.00	0.70	0.76	0.44	0.63	1.00	0.79
SDD			1.10	2.76	1.93	2.11	1.21	1.76	2.78	2.20
SDD lower bound			-0.14	-1.84	-1.79	-2.01	-1.07	-2.15	-3.43	-2.81
SDD upper bound			2.06	3.68	2.07	2.21	1.36	1.36	2.13	1.59
$\bar{d}$			0.96	0.92	0.14	0.10	0.14	-0.39	-0.65	-0.61
$\bar{d}$ lower bound			0.60	0.03	-0.50	-0.61	-0.26	-0.93	-1.49	-1.23
$\bar{d}$ upper bound			1.32	1.82	0.79	0.81	0.54	0.14	0.19	0.02
LA lower bound			-0.14	-1.84	-1.85	-2.09	-1.09	-2.04	-3.23	-2.54
LA upper bound			2.06	3.68	2.14	2.29	1.38	1.26	1.94	1.33

Markers to ICS	Risk Score	Comparison System	Inter-System: Vicon		Intra-System: Between Reps				Intra-System: Between Days	
			LCMAS-2 (Markers)		LCMAS-2 (Markers)		Vicon (Markers)		LCMAS-2 (Markers)	Vicon (Markers)
			Day 1	Day 2	Day 1	Day 2	Day 1	Day 2		
ICC		Statistic	-0.329	-1.279	0.409	0.640	0.892	0.838	-0.355	0.970
n			12	12	12	12	12	12	12	12
SEM			0.95	1.39	0.70	0.76	0.38	0.51	1.00	0.28
SDD			2.65	3.86	1.93	2.11	1.04	1.41	2.78	0.79
SDD lower bound			-1.10	-2.84	-1.79	-2.01	-0.83	-1.36	-3.43	-0.91
SDD upper bound			4.19	4.87	2.07	2.21	1.25	1.46	2.13	0.67
$\bar{d}$			1.55	1.02	0.14	0.10	0.21	0.05	-0.65	-0.12
$\bar{d}$ lower bound			0.69	-0.23	-0.50	-0.61	-0.12	-0.42	-1.49	-0.37
$\bar{d}$ upper bound			2.41	2.27	0.79	0.81	0.53	0.53	0.19	0.14
LA lower bound			-1.10	-2.84	-1.85	-2.09	-0.79	-1.41	-3.23	-0.90
LA upper bound			4.19	4.87	2.14	2.29	1.21	1.52	1.94	0.67

Table 11.2: (cont.) *Evaluation Risk Score - DVJ - Vicon.*

Markers to JCS	Risk Score	Comparison System	Inter-System: Vicon		Intra-System: Between Reps				Intra-System: Between Days	
			Vicon (Markers)		Vicon (Markers)		Day 1	Day 2	Vicon (Markers)	Vicon
			Day 1	Day 2	Day 1	Day 2				
ICC		Statistic	-1.650	0.441	0.709	0.606	0.892	0.838	0.370	0.970
n			12	12	12	12	12	12	12	12
SEM			1.14	0.94	0.44	0.63	0.38	0.51	0.79	0.28
SDD			3.17	2.60	1.21	1.76	1.04	1.41	2.20	0.79
SDD lower bound			-2.58	-2.50	-1.07	-2.15	-0.83	-1.36	-2.81	-0.91
SDD upper bound			3.76	2.70	1.36	1.36	1.25	1.46	1.59	0.67
$\bar{d}$			0.59	0.10	0.14	-0.39	0.21	0.05	-0.61	-0.12
$\bar{d}$ lower bound			-0.44	-0.75	-0.26	-0.93	-0.12	-0.42	-1.23	-0.37
$\bar{d}$ upper bound			1.61	0.94	0.54	0.14	0.53	0.53	0.02	0.14
LA lower bound			-2.58	-2.50	-1.09	-2.04	-0.79	-1.41	-2.54	-0.90
LA upper bound			3.76	2.70	1.38	1.26	1.21	1.52	1.33	0.67

Table 11.3: *Evaluation Risk Score - DLS - LCMAS-2 for marker based angles.*

Markers to Markers	Risk Score	Comparison System	Inter-System: Vicon (Markers)		Intra-System: Between Reps				Intra-System: Between Days	
			LCMAS-2 (Markers)		LCMAS-2 (Markers)		Vicon (Markers)		LCMAS-2 (Markers)	
			Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2
to Markers	Risk Score	ICC	0.038	0.121	0.161	0.025	0.952	0.991	0.379	0.960
		n	12	12	12	12	12	12	12	12
		SEM	0.63	0.71	0.03	0.09	0.20	0.10	0.03	0.27
		SDD	1.75	1.97	0.10	0.25	0.56	0.27	0.10	0.74
		SDD lower bound	-0.28	-0.51	-0.10	-0.27	-0.62	-0.24	-0.11	-0.74
		SDD upper bound	3.23	3.42	0.09	0.22	0.49	0.30	0.08	0.75
		$\bar{d}$	1.47	1.45	-0.01	-0.02	-0.06	0.03	-0.02	0.00
		$\bar{d}$ lower bound	0.91	0.81	-0.04	-0.11	-0.25	-0.06	-0.05	-0.25
		$\bar{d}$ upper bound	2.04	2.09	0.03	0.06	0.12	0.12	0.01	0.26
		LA lower bound	-0.28	-0.51	-0.11	-0.28	-0.63	-0.25	-0.11	-0.77
		LA upper bound	3.23	3.42	0.09	0.23	0.50	0.31	0.08	0.78

Markers to ICS	Risk Score	Comparison System	Inter-System: Vicon		Intra-System: Between Reps				Intra-System: Between Days	
			LCMAS-2 (Markers)		LCMAS-2 (Markers)		Vicon		LCMAS-2 (Markers)	
			Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2
to ICS	Risk Score	ICC	-0.031	0.035	0.161	0.025	0.970	0.989	0.379	0.987
		n	12	12	12	12	12	12	12	12
		SEM	0.79	0.75	0.03	0.09	0.19	0.11	0.03	0.18
		SDD	2.20	2.08	0.10	0.25	0.53	0.31	0.10	0.49
		SDD lower bound	0.14	0.15	-0.10	-0.27	-0.60	-0.29	-0.11	-0.40
		SDD upper bound	4.54	4.31	0.09	0.22	0.45	0.34	0.08	0.58
		$\bar{d}$	2.34	2.23	-0.01	-0.02	-0.07	0.03	-0.02	0.09
		$\bar{d}$ lower bound	1.63	1.56	-0.04	-0.11	-0.24	-0.08	-0.05	-0.06
		$\bar{d}$ upper bound	3.05	2.91	0.03	0.06	0.10	0.13	0.01	0.25
		LA lower bound	0.14	0.15	-0.11	-0.28	-0.60	-0.30	-0.11	-0.39
		LA upper bound	4.54	4.31	0.09	0.23	0.46	0.35	0.08	0.57

Table 11.3: (cont.) *Evaluation Risk Score - DLS - Vicon.*

Markers to JCS	Risk Score	Comparison System	Inter-System: Vicon		Intra-System: Between Reps				Intra-System: Between Days	
			Vicon (Markers)		Vicon (Markers)		Day 1	Day 2	Vicon (Markers)	Vicon
			Day 1	Day 2	Day 1	Day 2				
		ICC	0.452	0.324	0.952	0.991	0.970	0.989	0.960	0.987
		n	12	12	12	12	12	12	12	12
		SEM	0.85	0.95	0.20	0.10	0.19	0.11	0.27	0.18
		SDD	2.37	2.62	0.56	0.27	0.53	0.31	0.74	0.49
		SDD lower bound	-1.50	-1.84	-0.62	-0.24	-0.60	-0.29	-0.74	-0.40
		SDD upper bound	3.23	3.40	0.49	0.30	0.45	0.34	0.75	0.58
		$\bar{d}$	0.87	0.78	-0.06	0.03	-0.07	0.03	0.00	0.09
		$\bar{d}$ lower bound	0.10	-0.07	-0.25	-0.06	-0.24	-0.08	-0.25	-0.06
		$\bar{d}$ upper bound	1.63	1.63	0.12	0.12	0.10	0.13	0.26	0.25
		LA lower bound	-1.50	-1.84	-0.63	-0.25	-0.60	-0.30	-0.77	-0.39
		LA upper bound	3.23	3.40	0.50	0.31	0.46	0.35	0.78	0.57

Table 11.4: *Evaluation Risk Score - SLS - LCMAS-2 for marker based angles.*

Markers to Markers	Risk Score	Comparison System	Inter-System: Vicon (Markers)		Intra-System: Between Reps				Intra-System: Between Days	
			LCMAS-2 (Markers)		LCMAS-2 (Markers)		Vicon (Markers)		LCMAS-2 (Markers)	Vicon (Markers)
			Day 1	Day 2	Day 1	Day 2	Day 1	Day 2		
ICC		Statistic	-0.047	0.025	0.281	0.981	0.897	0.982	0.527	0.959
n			12	12	12	12	12	12	12	12
SEM			1.08	1.14	0.22	0.02	0.50	0.22	0.17	0.43
SDD			2.98	3.15	0.62	0.05	1.37	0.61	0.48	1.21
SDD lower bound			-3.81	-4.14	-0.49	-0.04	-1.24	-0.56	-0.63	-1.20
SDD upper bound			2.16	2.17	0.75	0.06	1.51	0.66	0.33	1.21
$\bar{d}$			-0.83	-0.99	0.13	0.01	0.14	0.05	-0.15	0.01
$\bar{d}$ lower bound			-1.79	-2.01	-0.06	0.00	-0.32	-0.15	-0.28	-0.40
$\bar{d}$ upper bound			0.14	0.04	0.32	0.03	0.59	0.26	-0.02	0.42
LA lower bound			-3.81	-4.14	-0.46	-0.03	-1.27	-0.58	-0.55	-1.25
LA upper bound			2.16	2.17	0.72	0.06	1.54	0.68	0.25	1.27

Markers to ICS	Risk Score	Comparison System	Inter-System: Vicon		Intra-System: Between Reps				Intra-System: Between Days	
			LCMAS-2 (Markers)		LCMAS-2 (Markers)		Vicon		LCMAS-2 (Markers)	Vicon
			Day 1	Day 2	Day 1	Day 2	Day 1	Day 2		
ICC		Statistic	-0.169	0.010	0.281	0.981	0.950	0.986	0.527	0.993
n			12	12	12	12	12	12	12	12
SEM			1.80	1.76	0.22	0.02	0.56	0.30	0.17	0.29
SDD			4.98	4.89	0.62	0.05	1.55	0.84	0.48	0.81
SDD lower bound			-6.72	-6.84	-0.49	-0.04	-1.51	-0.96	-0.63	-0.74
SDD upper bound			3.25	2.94	0.75	0.06	1.59	0.71	0.33	0.87
$\bar{d}$			-1.74	-1.95	0.13	0.01	0.04	-0.12	-0.15	0.06
$\bar{d}$ lower bound			-3.35	-3.54	-0.06	0.00	-0.49	-0.40	-0.28	-0.20
$\bar{d}$ upper bound			-0.12	-0.37	0.32	0.03	0.56	0.15	-0.02	0.33
LA lower bound			-6.72	-6.84	-0.46	-0.03	-1.58	-0.96	-0.55	-0.77
LA upper bound			3.25	2.94	0.72	0.06	1.66	0.71	0.25	0.90

Table 11.4: (cont.) *Evaluation Risk Score - SLS - Vicon.*

Markers to JCS	Risk Score	Comparison System	Inter-System: Vicon		Intra-System: Between Reps				Intra-System: Between Days	
			Vicon (Markers)		Vicon (Markers)		Vicon		Vicon (Markers)	
			Day 1	Day 2	Day 1	Day 2	Day 1	Day 2		
		ICC	0.872	0.913	0.897	0.982	0.950	0.986	0.959	0.993
		n	12	12	12	12	12	12	12	12
		SEM	0.96	0.84	0.50	0.22	0.56	0.30	0.43	0.29
		SDD	2.66	2.34	1.37	0.61	1.55	0.84	1.21	0.81
		SDD lower bound	-3.57	-3.30	-1.24	-0.56	-1.51	-0.96	-1.20	-0.74
		SDD upper bound	1.75	1.37	1.51	0.66	1.59	0.71	1.21	0.87
		$\bar{d}$	-0.91	-0.97	0.14	0.05	0.04	-0.12	0.01	0.06
		$\bar{d}$ lower bound	-1.77	-1.72	-0.32	-0.15	-0.49	-0.40	-0.40	-0.20
		$\bar{d}$ upper bound	-0.05	-0.21	0.59	0.26	0.56	0.15	0.42	0.33
		LA lower bound	-3.57	-3.30	-1.27	-0.58	-1.58	-0.96	-1.25	-0.77
		LA upper bound	1.75	1.37	1.54	0.68	1.66	0.71	1.27	0.90

11.4 Discussion

In order to avoid repetition when discussing the intra-system results, for each maneuver we will first analyze the intra-system results and then evaluate the inter-system results.

11.4.1 Drop Vertical Jump

Intra-System - DVJ

For the LCMAS-Single (Vicon Static - IK) intra-system comparisons, between repetitions Day 1 had adequate correlation, between repetitions Day 2 had excellent correlation, and between days had adequate correlation. The *SDD* for between repetitions Day 1 and between days was greater than the larger *MCID*, while the *SDD* for between repetitions Day 2 was less than the larger *MCID*. This system does not pass the intra-system portion of our screening criteria and improvements to the system and/or the algorithm are necessary for potential use of this combination as a clinical tool.

With the LCMAS-Single (Vicon Static - 6DOF) all intra-system comparisons had excellent correlation. The *SDD* for all comparisons was less than the larger *MCID*. This system does pass the intra-system portion of our screening criteria and we look to the inter-system comparisons to evaluate the potential use of this system with the algorithm as a clinical tool.

In the LCMAS-Single (Markers) intra-system comparisons, between repetitions Day 1 had excellent correlation, between repetitions Day 2 had adequate correlation, and between days had excellent correlation. The *SDD* for all comparisons was less than the larger *MCID*. This system also passes the intra-system portion of our screening criteria and we look to the inter-system comparisons to evaluate the potential use of this system with the algorithm as a clinical tool.

For the LCMAS-2 (Markers) intra-system comparisons, between repetitions Day 1 had adequate correlation, between repetitions Day 2 had adequate correlation, and between days had poor correlation. The *SDD* for between repetitions Day 1 and Day 2 was less than the larger *MCID*, while the *SDD* for between days was greater than the larger *MCID*. This system does not pass the intra-system portion of our screening criteria and improvements to the system and/or the algorithm are necessary for potential use of this combination as a clinical tool.

With Vicon (Markers) intra-system comparisons, between repetitions Day 1 had adequate correlation, between repetitions Day 2 had adequate correlation, and between days had poor correlation. The *SDD* for all comparisons was less than the larger *MCID*. This system does not pass the intra-system portion of our screening criteria and improvements to the algorithm are necessary for potential use of this combination of system and algorithm as a clinical tool.

Finally, for Vicon (Rotation) all intra-system comparisons had excellent correlation. The *SDD* for all comparisons was less than the larger *MCID*. This system does pass the intra-system portion of our screening criteria and since this system is our gold standard it indicates the viability of the risk score algorithm as a clinical tool.

Inter-System - DVJ

For the LCMAS-Single (Vicon Static - IK) to Vicon (Rotation) all inter-system comparisons had poor correlation. The *SDD* for all comparisons was greater than the larger *MCID*. The LCMAS-Single (Vicon Static - IK) does not pass our screening criteria for the DVJ and improvements to the system and/or the algorithm are necessary for potential use of this combination as a clinical tool.

In the LCMAS-Single (Vicon Static - 6DOF) to Vicon (Rotation) inter-system comparison, Day 1 had poor correlation and Day 2 had adequate correlation. The

SDD for all comparisons was greater than the larger *MCID*. The LCMAS-Single (Vicon Static - 6DOF) does not pass our screening criteria for the DVJ and improvements to the system and/or the algorithm are necessary for potential use of this combination as a clinical tool.

With the LCMAS-Single (Markers) to Vicon (Markers) inter-system comparison, Day 1 had poor correlation and Day 2 had adequate correlation. The *SDD* for Day 1 was greater than the larger *MCID*, while the *SDD* for Day 2 was less than the larger *MCID*. The LCMAS-Single (Markers) does not pass our screening criteria relative to Vicon (Markers) for the DVJ, however it does show promise with one valid day of inter-system comparison, a valid LCMAS-Single (Markers) intra-system comparison and an almost valid Vicon (Markers) intra-system comparison. Improvements to the LCMAS-Single (Markers) and/or the algorithm are necessary for potential use of this combination as a clinical tool.

For the LCMAS-Single (Markers) to Vicon (Rotation) all inter-system comparisons had poor correlation. The *SDD* for all comparisons was greater than the larger *MCID*. The LCMAS-Single (Markers) does not pass our screening criteria relative to Vicon (Rotation) for the DVJ and improvements to the system and/or the algorithm are necessary for potential use of this combination as a clinical tool.

In the LCMAS-2 (Markers) to Vicon (Markers) inter-system comparison, Day 1 had excellent correlation and Day 2 had poor correlation. The *SDD* for Day 1 was less than the larger *MCID*, while the *SDD* for Day 2 was greater than the larger *MCID*. The LCMAS-2 (Markers) does not pass our screening criteria relative to Vicon (Markers) for the DVJ, however it does show promise with one valid day of inter-system comparison, an almost valid intra-system comparisons. Improvements to the LCMAS-2 (Markers) and/or the algorithm are necessary for potential use of this combination as a clinical tool.

With the LCMAS-2 (Markers) to Vicon (Rotation) all inter-system comparisons had poor correlation. The *SDD* for all comparisons was greater than the

larger *MCID*. The LCMAS-2 (Markers) does not pass our screening criteria relative to Vicon (Rotation) for the DVJ and improvements to the system and/or the algorithm are necessary for potential use of this combination as a clinical tool.

Finally, in the Vicon (Markers) to Vicon (Rotation) inter-system comparison, Day 1 had poor correlation and Day 2 had adequate correlation. The *SDD* for Day 1 was greater than the larger *MCID*, while the *SDD* for Day 2 was less than the larger *MCID*. The Vicon (Markers) does not pass our screening criteria relative to Vicon (Rotation) for the DVJ, however it does show promise with one valid day of inter-system comparison, an almost valid Vicon (Markers) intra-system comparison, and a valid Vicon (Rotation) intra-system comparison. Improvements to the algorithm are necessary for potential use of the combination of Vicon (Markers) with an algorithm as a clinical tool.

11.4.2 Double Leg Squat

Intra-System - DLS

For the LCMAS-2 (Markers) all intra-system comparisons had poor correlation. The *SDD* for all comparisons was less than the smaller *MCID*. This system does not pass the intra-system portion of our screening criteria and improvements to the system and/or the algorithm are necessary for potential use of this combination as a clinical tool.

With Vicon (Markers) all intra-system comparisons had excellent correlation. The *SDD* for between repetitions Day 1 and Day 2 was less than the smaller *MCID*, while the *SDD* for between days was less than the larger *MCID*. This system does pass the intra-system portion of our screening criteria and we look to the inter-system comparisons to evaluate the potential use of this system with the algorithm as a clinical tool.

Finally, for Vicon (Rotation) all intra-system comparisons had excellent

correlation. The *SDD* for all comparisons was less than the smaller *MCID*. This system does pass the intra-system portion of our screening criteria and since this system is our gold standard it indicates the viability of the risk score algorithm as a clinical tool.

Inter-System - DLS

For the LCMAS-2 (Markers) to Vicon (Markers) inter-system comparison, all inter-system comparisons had poor correlation. The *SDD* for all comparisons was less than the larger *MCID*. The LCMAS-2 (Markers) does not pass our screening criteria relative to Vicon (Markers) for the DLS, however it does show promise with valid *SDD* values for the inter- and intra-system comparisons. Improvements to the LCMAS-2 (Markers) and/or the algorithm are necessary for potential use of this combination as a clinical tool.

With the LCMAS-2 (Markers) to Vicon (Rotation) inter-system comparison, all inter-system comparisons had poor correlation. The *SDD* for all comparisons was less than the larger *MCID*. The LCMAS-2 (Markers) does not pass our screening criteria relative to Vicon (Rotation) for the DLS, however it does show promise with valid *SDD* values for the inter- and intra-system comparisons. Improvements to the LCMAS-2 (Markers) and/or the algorithm are necessary for potential use of this combination as a clinical tool.

Finally, in the Vicon (Markers) to Vicon (Rotation) inter-system comparison, Day 1 had adequate correlation and Day 2 had poor correlation. The *SDD* for all comparisons was less than the larger *MCID*. The Vicon (Markers) does not pass our screening criteria relative to Vicon (Rotation) for the DLS, however it does show promise with a valid Day 1 and an almost valid Day 2 inter-system comparison, a valid Vicon (Markers) intra-system comparison, and a valid Vicon (Rotation) intra-system comparison. Improvements to the algorithm are necessary for potential use of the combination of Vicon (Markers) with an algorithm as a

clinical tool.

11.4.3 Single Leg Squat

Intra-System - SLS

For the LCMAS-2 (Markers) intra-system comparisons, between repetitions Day 1 had poor correlation, between repetitions Day 2 had excellent correlation, and between days had adequate correlation. The *SDD* for all comparisons was less than the larger *MCID*. This system does not pass the intra-system portion of our screening criteria and improvements to the system and/or the algorithm are necessary for potential use of this combination as a clinical tool.

With Vicon (Markers) all intra-system comparisons had excellent correlation. The *SDD* for between repetitions Day 1 and between days was less than the larger *MCID*, while the *SDD* for between repetitions Day 2 was less than the smaller *MCID*. This system does pass the intra-system portion of our screening criteria and we look to the inter-system comparisons to evaluate the potential use of this system with the algorithm as a clinical tool.

Finally, in Vicon (Rotation) all intra-system comparisons had excellent correlation. The *SDD* for all comparisons was less than the larger *MCID*. This system does pass the intra-system portion of our screening criteria and since this system is our gold standard it indicates the viability of the risk score algorithm as a clinical tool.

Inter-System - SLS

For the LCMAS-2 (Markers) to Vicon (Markers) all inter-system comparisons had poor correlation. The *SDD* for all comparisons was greater than the larger *MCID*. The LCMAS-2 (Markers) does not pass our screening criteria relative to Vicon (Markers) for the SLS. Improvements to the LCMAS-2 (Markers) and/or

the algorithm are necessary for potential use of this combination as a clinical tool.

With the LCMAS-2 (Markers) to Vicon (Rotation) all inter-system comparisons had poor correlation. The *SDD* for all comparisons was greater than the larger *MCID*. The LCMAS-2 (Markers) does not pass our screening criteria relative to Vicon (Rotation) for the SLS. Improvements to the LCMAS-2 (Markers) and/or the algorithm are necessary for potential use of this combination as a clinical tool.

Finally, in the Vicon (Markers) to Vicon (Rotation) all inter-system comparisons had excellent correlation. The *SDD* for Day 1 was greater than the larger *MCID*, while the *SDD* for Day 2 was less than the larger *MCID*. The Vicon (Markers) does not pass our screening criteria relative to Vicon (Rotation) for the SLS, however it does show promise with an almost valid Day 1 and a valid Day 2 inter-system comparison, a valid Vicon (Markers) intra-system comparison, and a valid Vicon (Rotation) intra-system comparison. Improvements to the algorithm are necessary for potential use of the combination of Vicon (Markers) with an algorithm as a clinical tool.

11.5 Conclusion

We were able to use a simple literature value based algorithm to create a straightforward, quantitative, ACL injury risk score and assess the test-retest reliability for this score for our LCMAS-Single and LCMAS-2 compared to the gold standard Vicon system.

Despite our low-cost systems' ability to successfully detect individual metrics, no low-cost system with the current version of the algorithm passed our screening criteria. However, we did see potential for our envisioned clinical utility with either system improvement, algorithm improvements, or both. These algorithm improvements could include using different metrics and tailoring the risk scale

and weighting factor of each metric based on statistical evaluation to maximize the agreement between a LCMAS and Vicon *OverallScore*. The present form of LCMAS-Single and LCMAS-2 can be implemented in the clinical setting for detection of the individual metrics as detailed in Chapters [9](#) and [10](#).

Each maneuver was assessed using the same risk score algorithm for all systems. Going forward with algorithm development, we will explore tailoring a separate algorithm to each type of maneuver. We may also consider consolidating these separate algorithms from each type of maneuver into a master overall score for a clinical injury risk and rehabilitation assessment tool.

CHAPTER 12

Conclusions

12.1 Current Studies

Throughout this work we have made the case for the necessity of a low-cost quantitative clinical tool for identifying at risk individuals before injury occurs. We have identified limitations in current screening tools and created different versions of low-cost tools that we hope will address the accessibility and accuracy shortcomings of currently available systems.

In an effort to evaluate the system improvements to the LCMAS-Single, we scrutinized marker detection in a static posture, relative to the gold standard Vicon system and saw substantial gains.

Next, we laid out a detailed test-retest reliability study to assess the performance of our low-cost systems relative to the gold standard Vicon system for detecting kinematic and kinetic metrics associated with knee injury risk. This methodology can be applied to comparing any new system to the corresponding industry gold standard system.

In the LCMAS-Single test-retest reliability assessments we successfully detected 6 different metrics for the drop vertical jump (DVJ) maneuver, with repeatable measures and *SDD* smaller than the *MCID* values from the scientific literature for some of the metrics between at-risk and normal populations, enabling use of the system as a screening tool for ACL injury risk and rehabilitation. For LCMAS-Single using markers based angles relative to Vicon markers based angles,

we identified two metrics: Initial Contact (IC) 2nd component knee angle, and Maximum (Max) 2nd component knee angle. With the LCMAS-Single using the Vicon Static reference posture and IK model relative to the Vicon industry gold standard, we identified four metrics: Max 1st component hip angle, IC 2nd component hip angle, Minimum (Min) 1st knee angle, and Range of Motion (ROM) 1st component center of mass (COM) position. Finally, for the LCMAS-Single using the Vicon Static reference posture and 6DOF model relative to the Vicon industry gold standard, we identified three metrics: Max 1st component hip angle, Min 1st knee angle, and ROM 1st component COM position. The results of this study are summarized in Table 9.1 on page 153. To expand the number of metrics and the clinical relevance of this screening tool we propose continued system improvements and a prospective study to establish a normative database and identification of abnormal movement thresholds.

In the LCMAS-2 test-retest reliability assessments, we also successfully detected several metrics for the DVJ, double leg squat (DLS), and single leg squat (SLS) maneuvers. For all the maneuvers studied, our LCMAS-2 system has repeatable measures and *SDD* smaller than the *MCID* values from the scientific literature for some of the metrics between at-risk and normal populations. In the DVJ, we identified three metrics: Max 1st component hip angle, Min 1st knee angle, and ROM 1st knee angle (summarized in Table 10.1 on page 195). For the DLS, we identified five metrics: Max 1st component hip angle, IC 2nd component hip angle, Min 1st knee angle, ROM 1st knee angle, and ROM 2nd component COM relative to base of support (BOS) position (summarized in Table 10.3 on page 203). Finally, in the SLS we identified six metrics: Max 1st component hip angle, Min 1st knee angle, ROM 1st knee angle, Min 2nd component knee angle, Max 2nd component knee angle, and Min 2nd component knee moment (summarized in Table 10.6 on page 214). This outcome enables the use of the LCMAS-2 system as a screening tool for ACL injury risk and rehabilitation. To expand

the number of metrics and the clinical relevance of this screening tool we again propose continued system improvements and a prospective study to establish a normative database and identification of abnormal movement thresholds.

To demonstrate our envisioned clinical utility, we used a simple literature value based algorithm to create a straight-forward, quantitative, ACL injury risk score and assessed the test-retest reliability for this score for our LCMAS-Single and LCMAS-2 compared to the gold standard Vicon system. Despite our low-cost systems' ability to successfully detect individual metrics, no low-cost system with the current version of the algorithm passed our screening criteria, summarized in Table 11.1 on page 251. However, we did see potential for our envisioned clinical utility with either system improvement, algorithm improvements, or both. The present form of LCMAS-Single and LCMAS-2 can be implemented in the clinical setting for detection of the individual metrics detailed in the previous paragraphs.

We have demonstrated the potential for a clinically-relevant, accurate, low-cost movement assessment tool that can revolutionize orthopaedic medicine by shifting the focus from reactionary to preventative.

12.2 Future Potential

Future potential areas of exploration include applications in clinical practice, physical and occupational therapy (e.g. fall prevention [127]), ergonomics (e.g. 3D Static Strength Prediction Program (3DSSPP) [22]), and sports, and expanding research with OpenSim modeling (e.g. Kar included an ACL component into a model used with drop-landings [59, 60]) and FEA (e.g. Kiapour has developed an ACL strain model used with drop-landings [63, 64]).

It is also interesting to consider increasing the scope of metrics to include other variables such as joint power and incorporating electromyographic (EMG) and inertial sensors.

APPENDIX A

Numerical Results: Test-Retest Reliability

This appendix contains numerical results for metrics that did not meet our screening criteria that were listed in summary tables.

A.1 LCMAS-Single - DVJ

Primary and secondary variables summarized in Table 9.1, from the LCMAS-Single DVJ trials are presented in Tables A.1 and A.2, respectively.

A.2 LCMAS-2 - DVJ

Primary and secondary variables summarized in Table 10.1, from the LCMAS-2 DVJ trials are presented in Tables A.3 and A.4, respectively.

A.3 LCMAS-2 - DLS

Primary and secondary variables summarized in Table 10.3, from the LCMAS-2 DLS trials that are presented in Tables A.5 and A.6, respectively.

A.4 LCMAS-2 - SLS

Secondary and primary variables summarized in Table 10.6, from the LCMAS-2 SLS trials that are presented in Tables A.7 and A.8, respectively.

Table A.1: *Primary Variables - DVJ - LCMAS-Single - ROM - 1st Component - Hip Angle.*

Component Parameter	ROM 1st Hip Angle Marker	Comparison System	Inter-System: Vicon (Markers)		Intra-System: Between Repts				Intra-System: Between Days		MCID
			LCMAS-Single (Markers)		LCMAS-Single (Markers)		Vicon (Markers)		LCMAS-Single (Markers)		
			Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
ICC		Statistic	0.810	0.767	0.900	0.673	0.973	0.965	0.756	0.968	
n			11	10	7	8	12	12	9	12	
SEM			17.79	12.40	14.49	16.26	3.73	3.40	21.17	5.15	
SDD			49.30	34.37	40.17	45.08	10.33	9.43	58.67	14.27	31.6 degrees
SDD lower bound			-52.04	-28.75	-47.44	-58.92	-10.76	-7.83	-49.22	-10.15	
SDD upper bound			46.55	39.98	32.90	31.24	9.90	11.04	68.12	18.40	
$\bar{d}$			-2.74	5.61	-7.27	-13.84	-0.43	1.61	9.45	4.12	
$\bar{d}$ lower bound			-19.64	-6.93	-26.41	-30.26	-3.92	-1.40	-13.71	0.14	
$\bar{d}$ upper bound			14.15	18.15	11.87	2.58	3.05	4.62	32.61	8.11	
LA lower bound			-52.04	-28.75	-47.84	-52.33	-11.19	-7.68	-49.60	-8.17	
LA upper bound			46.55	39.98	33.30	24.65	10.32	10.90	68.50	16.41	
RMS (individual)			20.41		11.40		4.61				
Fraction (individual)			0.67		0.63		1.00				
RMS (mean)			21.49						16.45	8.52	
Fraction (mean)			0.88						0.75	1.00	

Component Parameter	ROM 1st Hip Angle	Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID
			LCMAS-Single (Markers)		LCMAS-Single (Markers)		Vicon		LCMAS-Single (Markers)		
			Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
ICC		Statistic	0.649	0.708	0.900	0.673	0.973	0.948	0.756	0.953	
n			11	10	7	8	12	12	9	12	
SEM			21.88	12.70	14.49	16.26	2.97	3.16	21.17	4.89	
SDD			60.66	35.21	40.17	45.08	8.24	8.76	58.67	13.55	31.6 degrees
SDD lower bound			-69.24	-37.62	-47.44	-58.92	-8.65	-7.31	-49.22	-9.92	
SDD upper bound			52.08	32.80	32.90	31.24	7.83	10.22	68.12	17.18	
$\bar{d}$			-8.58	-2.41	-7.27	-13.84	-0.41	1.45	9.45	3.63	
$\bar{d}$ lower bound			-29.37	-15.26	-26.41	-30.26	-3.19	-1.35	-13.71	-0.28	
$\bar{d}$ upper bound			12.21	10.44	11.87	2.58	2.37	4.26	32.61	7.53	
LA lower bound			-69.24	-37.62	-47.84	-52.33	-8.98	-7.20	-49.60	-8.42	
LA upper bound			52.08	32.80	33.30	24.65	8.16	10.11	68.50	15.67	
RMS (individual)			19.45		11.40		3.82				
Fraction (individual)			0.67		0.63		1.00				
RMS (mean)			20.92						16.45	6.31	
Fraction (mean)			0.88						0.75	1.00	

Table A.1: (cont.) *Primary Variables - DVJ - LCMAS-Single - ROM - 1st Component - Hip Angle.*

Component Parameter	ROM 1st Hip Angle	Comparison System	Inter-System: Vicon		Intra-System: Between Reps				Intra-System: Between Days		MCID
			Vicon (Markers)		Vicon (Markers)		Day 1	Day 2	Vicon (Markers)	Vicon	
			Day 1	Day 2	Day 1	Day 2					
ICC			0.915	0.929	0.973	0.965	0.973	0.948	0.968	0.953	
n			12	12	12	12	12	12	12	12	
SEM			8.08	5.98	3.73	3.40	2.97	3.16	5.15	4.89	
SDD			22.40	16.56	10.33	9.43	8.24	8.76	14.27	13.55	
SDD lower bound			-30.20	-23.87	-10.76	-7.83	-8.65	-7.31	-10.15	-9.92	31.6
SDD upper bound			14.60	9.26	9.90	11.04	7.83	10.22	18.40	17.18	degrees
$\bar{d}$			-7.80	-7.30	-0.43	1.61	-0.41	1.45	4.12	3.63	
$\bar{d}$ lower bound			-15.06	-12.67	-3.92	-1.40	-3.19	-1.35	0.14	-0.28	
$\bar{d}$ upper bound			-0.54	-1.94	3.05	4.62	2.37	4.26	8.11	7.53	
LA lower bound			-30.20	-23.87	-11.19	-7.68	-8.98	-7.20	-8.17	-8.42	
LA upper bound			14.60	9.26	10.32	10.90	8.16	10.11	16.41	15.67	
RMS (individual)			10.52		4.61		3.82				
Fraction (individual)			1.00		1.00		1.00				
RMS (mean)			10.46						8.52	6.31	
Fraction (mean)			1.00						1.00	1.00	

Table A.1: (cont.) *Primary Variables - DVJ - LCMAS-Single - ROM - 1st Component - Knee Angle.*

Component Parameter	ROM 1st	Knee Angle JCS	Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID
				LCMAS-Single (Vicon Static, IK)		LCMAS-Single (Vicon Static, IK)		Vicon		LCMAS-Single (Vicon Static, IK)		
				Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
ICC			ICC	0.866	0.738	0.117	0.204	0.952	0.831	0.852	0.897	
n			n	12	12	12	12	12	12	12	12	
SEM			SEM	7.13	8.90	19.01	14.08	3.44	6.15	6.55	6.75	
SDD			SDD	19.75	24.68	52.70	39.04	9.55	17.05	18.16	18.72	
SDD lower bound			SDD lower bound	-15.15	-25.39	-41.50	-39.91	-9.66	-16.18	-17.61	-12.84	51.4
SDD upper bound			SDD upper bound	24.36	23.96	63.90	38.16	9.43	17.92	18.72	24.60	degrees
$\bar{d}$			$\bar{d}$	4.60	-0.72	11.20	-0.87	-0.11	0.87	0.56	5.88	
$\bar{d}$ lower bound			$\bar{d}$ lower bound	-1.80	-8.72	-5.02	-14.08	-3.34	-4.87	-5.58	0.88	
$\bar{d}$ upper bound			$\bar{d}$ upper bound	11.01	7.28	27.42	12.33	3.12	6.62	6.70	10.88	
LA lower bound			LA lower bound	-15.15	-25.39	-38.84	-41.61	-10.08	-16.85	-18.38	-9.53	
LA upper bound			LA upper bound	24.36	23.96	61.24	39.86	9.86	18.59	19.49	21.29	
RMS (individual)			RMS (individual)	11.67		10.20		4.79				
Fraction (individual)			Fraction (individual)	1.00		1.00		1.00		10.13	5.40	
RMS (mean)			RMS (mean)	10.74						1.00	1.00	
Fraction (mean)			Fraction (mean)	1.00								

Component Parameter	ROM 1st	Knee Angle JCS	Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID
				LCMAS-Single (Vicon Static, 6DOF)		LCMAS-Single (Vicon Static, 6DOF)		Vicon		LCMAS-Single (Vicon Static, 6DOF)		
				Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
ICC			ICC	0.648	0.475	0.336	0.750	0.952	0.831	0.891	0.897	
n			n	12	12	12	12	12	12	12	12	
SEM			SEM	12.55	15.33	18.63	11.59	3.44	6.15	8.99	6.75	
SDD			SDD	34.79	42.49	51.65	32.11	9.55	17.05	24.91	18.72	
SDD lower bound			SDD lower bound	-23.70	-32.00	-41.98	-34.95	-9.66	-16.18	-19.64	-12.84	51.4
SDD upper bound			SDD upper bound	45.88	52.97	61.32	29.28	9.43	17.92	30.18	24.60	degrees
$\bar{d}$			$\bar{d}$	11.09	10.49	9.67	-2.84	-0.11	0.87	5.27	5.88	
$\bar{d}$ lower bound			$\bar{d}$ lower bound	-0.18	-3.29	-6.60	-13.55	-3.34	-4.87	-2.40	0.88	
$\bar{d}$ upper bound			$\bar{d}$ upper bound	22.37	24.26	25.94	7.87	3.12	6.62	12.95	10.88	
LA lower bound			LA lower bound	-23.70	-32.00	-40.51	-35.87	-10.08	-16.85	-18.40	-9.53	
LA upper bound			LA upper bound	45.88	52.97	59.85	30.20	9.86	18.59	28.95	21.29	
RMS (individual)			RMS (individual)	16.68		11.10		4.79				
Fraction (individual)			Fraction (individual)	1.00		1.00		1.00				
RMS (mean)			RMS (mean)	15.88						13.78	5.40	
Fraction (mean)			Fraction (mean)	1.00						1.00	1.00	

Table A.1: (cont.) *Primary Variables - DVJ - LCMAS-Single - ROM - 1st Component - Knee Angle.*

Component Parameter		Comparison System	Inter-System: Vicon (Markers)		Intra-System: Between Repts				Intra-System: Between Days		MCID
			LCMAS-Single (Markers)		LCMAS-Single (Markers)		Vicon (Markers)		LCMAS-Single (Markers)	Vicon (Markers)	
ROM 1st	Knee Angle Marker	Statistic	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
		ICC	0.093	0.873			0.952	0.825	0.791	0.892	
		n	10	7			12	12	7	12	
		SEM	15.54	7.85			3.34	6.25	11.67	6.76	
		SDD	43.06	21.76			9.26	17.34	32.36	18.74	
		SDD lower bound	-20.66	-11.51			-9.56	-16.32	-43.61	-13.45	51.4 degrees
		SDD upper bound	65.46	32.01			8.96	18.36	21.10	24.03	
		$\bar{d}$	22.40	10.25			-0.30	1.02	-11.26	5.29	
		$\bar{d}$ lower bound	6.68	-0.02			-3.43	-4.81	-23.32	0.01	
		$\bar{d}$ upper bound	38.12	20.52			2.83	6.85	0.80	10.58	
		LA lower bound	-20.66	-11.51			-9.95	-16.97	-36.82	-11.01	
		LA upper bound	65.46	32.01			9.35	19.01	14.30	21.60	
		RMS (individual)	10.68				4.74				
		Fraction (individual)	0.61				1.00		8.04	6.18	
		RMS (mean)	10.55						0.58	1.00	
		Fraction (mean)	0.71								

Component Parameter		Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID
			LCMAS-Single (Markers)		LCMAS-Single (Markers)		Vicon		LCMAS-Single (Markers)	Vicon	
ROM 1st	Knee Angle	Statistic	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
		ICC	0.134	0.856			0.952	0.831	0.791	0.897	
		n	10	7			12	12	7	12	
		SEM	15.56	8.32			3.44	6.15	11.67	6.75	
		SDD	43.14	23.07			9.55	17.05	32.36	18.72	
		SDD lower bound	-19.09	-11.41			-9.66	-16.18	-43.61	-12.84	51.4 degrees
		SDD upper bound	67.19	34.73			9.43	17.92	21.10	24.60	
		$\bar{d}$	24.05	11.66			-0.11	0.87	-11.26	5.88	
		$\bar{d}$ lower bound	8.30	0.78			-3.34	-4.87	-23.32	0.88	
		$\bar{d}$ upper bound	39.80	22.55			3.12	6.62	0.80	10.88	
		LA lower bound	-19.09	-11.41			-10.08	-16.85	-36.82	-9.53	
		LA upper bound	67.19	34.73			9.86	18.59	14.30	21.29	
		RMS (individual)	12.43				4.79				
		Fraction (individual)	0.61				1.00		8.04	5.40	
		RMS (mean)	12.69						0.58	1.00	
		Fraction (mean)	0.71								

Table A.1: (cont.) *Primary Variables - DVJ - LCMAS-Single - ROM - 1st Component - Knee Angle.*

Component Parameter	Comparison System	Inter-System: Vicon		Intra-System: Between Reps		Intra-System: Between Days		MCID	
		Vicon (Markers)		Vicon		Vicon (Markers)			Vicon
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2		
ROM 1st	ICC	0.998	0.998	0.952	0.825	0.952	0.831	0.892	0.897
Knee Angle	n	12	12	12	12	12	12	12	12
	SEM	1.05	1.05	3.34	6.25	3.44	6.15	6.76	6.75
	SDD	2.92	2.91	9.26	17.34	9.55	17.05	18.74	18.72
	SDD lower bound	-1.51	-2.09	-9.56	-16.32	-9.66	-16.18	-13.45	-12.84
	SDD upper bound	4.34	3.74	8.96	18.36	9.43	17.92	24.03	24.60
	$\bar{d}$	1.41	0.83	-0.30	1.02	-0.11	0.87	5.29	5.88
	$\bar{d}$ lower bound	0.47	-0.12	-3.43	-4.81	-3.34	-4.87	0.01	0.88
	$\bar{d}$ upper bound	2.36	1.77	2.83	6.85	3.12	6.62	10.58	10.88
	LA lower bound	-1.51	-2.09	-9.95	-16.97	-10.08	-16.85	-11.01	-9.53
	LA upper bound	4.34	3.74	9.35	19.01	9.86	18.59	21.60	21.29
	RMS (individual)	3.89		4.74		4.79			
	Fraction (individual)	1.00		1.00		1.00			
	RMS (mean)	3.88						6.18	5.40
	Fraction (mean)	1.00						1.00	1.00

Table A.1: (cont.) Primary Variables - DVJ - LCMAS-Single - Min - 2nd Component - Knee Angle.

Component Parameter	Comparison System	Inter-System: Vicon (Markers)		Intra-System: Between Repts				Intra-System: Between Days		MCID
		LCMAS-Single (Markers)		LCMAS-Single (Markers)		Vicon (Markers)		LCMAS-Single (Markers)	Vicon (Markers)	
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2			
Min 2nd Knee Angle Marker	ICC	0.457	0.803	0.881	0.597	0.759	0.615	0.748	0.496	
	n	10	10	9	7	12	12	9	12	
	SEM	2.90	1.40	1.31	1.37	1.00	1.39	2.41	1.74	
	SDD	8.05	3.87	3.63	3.79	2.76	3.84	6.69	4.82	6.35 to
	SDD lower bound	-11.43	-5.23	-3.03	-3.47	-2.24	-4.59	-5.04	-6.03	7.6
	SDD upper bound	4.67	2.51	4.23	4.11	3.28	3.09	8.35	3.61	degrees
	$\bar{d}$	-3.38	-1.36	0.60	0.32	0.52	-0.75	1.65	-1.21	
	$\bar{d}$ lower bound	-6.32	-2.77	-0.83	-1.58	-0.35	-1.95	-0.78	-2.63	
	$\bar{d}$ upper bound	-0.44	0.05	2.03	2.23	1.39	0.45	4.09	0.21	
	LA lower bound	-11.43	-5.23	-3.04	-3.72	-2.17	-4.46	-4.55	-5.59	
	LA upper bound	4.67	2.51	4.24	4.36	3.20	2.95	7.86	3.17	
	RMS (individual)	1.55		2.39		2.20				
	Fraction (individual)	0.72		0.67		1.00		2.12	1.91	
	RMS (mean)	1.54						0.75	1.00	
	Fraction (mean)	0.83								

Component Parameter	Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID
		LCMAS-Single (Markers)		LCMAS-Single (Markers)		Vicon		LCMAS-Single (Markers)	Vicon	
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2			
Min 2nd Knee Angle	ICC	-0.314	0.218	0.881	0.597	0.897	0.914	0.748	0.883	
	n	10	10	9	7	12	12	9	12	
	SEM	4.03	3.40	1.31	1.37	0.83	1.18	2.41	1.53	
	SDD	11.17	9.42	3.63	3.79	2.31	3.27	6.69	4.24	6.35 to
	SDD lower bound	-12.90	-10.19	-3.03	-3.47	-1.59	-3.67	-5.04	-4.57	7.6
	SDD upper bound	9.45	8.65	4.23	4.11	3.03	2.86	8.35	3.92	degrees
	$\bar{d}$	-1.73	-0.77	0.60	0.32	0.72	-0.40	1.65	-0.32	
	$\bar{d}$ lower bound	-5.81	-4.21	-0.83	-1.58	0.10	-1.48	-0.78	-1.74	
	$\bar{d}$ upper bound	2.35	2.67	2.03	2.23	1.34	0.67	4.09	1.10	
	LA lower bound	-12.90	-10.19	-3.04	-3.72	-1.19	-3.72	-4.55	-4.71	
	LA upper bound	9.45	8.65	4.24	4.36	2.63	2.91	7.86	4.06	
	RMS (individual)	5.03		2.39		1.99				
	Fraction (individual)	0.72		0.67		1.00		2.12	2.70	
	RMS (mean)	4.57						0.75	1.00	
	Fraction (mean)	0.83								

Table A.1: (cont.) *Primary Variables - DVJ - LCMAS-Single - Min - 2nd Component - Knee Angle.*

Component Parameter	Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID
		Vicon (Markers)		Vicon (Markers)		Vicon (Markers)		Vicon (Markers)		
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
Min 2nd Knee Angle	ICC	-1.199	0.404	0.759	0.615	0.897	0.914	0.496	0.883	
	n	12	12	12	12	12	12	12	12	
	SEM	2.67	2.78	1.00	1.39	0.83	1.18	1.74	1.53	
	SDD	7.41	7.70	2.76	3.84	2.31	3.27	4.82	4.24	6.35 to
	SDD lower bound	-6.20	-7.37	-2.24	-4.59	-1.59	-3.67	-6.03	-4.57	7.6
	SDD upper bound	8.62	8.02	3.28	3.09	3.03	2.86	3.61	3.92	degrees
	$\bar{d}$	1.21	0.32	0.52	-0.75	0.72	-0.40	-1.21	-0.32	
	$\bar{d}$ lower bound	-1.19	-2.17	-0.35	-1.95	0.10	-1.48	-2.63	-1.74	
	$\bar{d}$ upper bound	3.61	2.82	1.39	0.45	1.34	0.67	0.21	1.10	
	LA lower bound	-6.20	-7.37	-2.17	-4.46	-1.19	-3.72	-5.59	-4.71	
	LA upper bound	8.62	8.02	3.20	2.95	2.63	2.91	3.17	4.06	
	RMS (individual)	4.98		2.20		1.99				
	Fraction (individual)	1.00		1.00		1.00				
	RMS (mean)	4.77						1.91	2.70	
	Fraction (mean)	1.00						1.00	1.00	

Table A.1: (cont.) *Primary Variables - DVJ - LCMAS-Single - Min - 2nd Component - Knee Moment.*

Component Parameter			Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID
				LCMAS-Single (Vicon Static, 6DOF)		Vicon		LCMAS-Single (Vicon Static, 6DOF)		Vicon		
Min	2nd	Knee Moment JCS	Statistic	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
26.9 Nm			ICC	0.441	0.383			0.523	0.341	0.804	0.806	
			n	6	6			12	12	6	12	
			SEM	13.02	8.05			7.69	6.69	8.61	4.94	
			SDD	36.08	22.33			21.31	18.53	23.85	13.70	
			SDD lower bound	-23.15	-8.38			-22.15	-22.33	-22.21	-16.39	
			SDD upper bound	49.01	36.27			20.46	14.73	25.50	11.01	
			$\bar{d}$	12.93	13.95			-0.84	-3.80	1.64	-2.69	
			$\bar{d}$ lower bound	-6.38	1.99			-8.03	-9.54	-12.22	-6.97	
			$\bar{d}$ upper bound	32.25	25.90			6.35	1.95	15.51	1.59	
			LA lower bound	-23.15	-8.38			-23.03	-21.52	-24.25	-15.90	
			LA upper bound	49.01	36.27			21.35	13.93	27.53	10.52	
			RMS (individual)	12.75				8.13				
			Fraction (individual)	0.43				1.00				
		RMS (mean)	12.12							11.75	6.50	
		Fraction (mean)	0.50							0.50	1.00	
Component Parameter			Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID
				LCMAS-Single (Kinect Static, IK)		Vicon		LCMAS-Single (Kinect Static, IK)		Vicon		
Min	2nd	Knee Moment JCS	Statistic	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
26.9 Nm			ICC	0.714	-0.024			0.523	0.341	-0.844	0.806	
			n	4	6			12	12	4	12	
			SEM	4.75	22.24			7.69	6.69	3.39	4.94	
			SDD	13.18	61.65			21.31	18.53	9.40	13.70	
			SDD lower bound	-18.39	-53.20			-22.15	-22.33	-7.85	-16.39	
			SDD upper bound	7.97	70.10			20.46	14.73	10.95	11.01	
			$\bar{d}$	-5.21	8.45			-0.84	-3.80	1.55	-2.69	
			$\bar{d}$ lower bound	-15.91	-24.56			-8.03	-9.54	-6.79	-6.97	
			$\bar{d}$ upper bound	5.49	41.46			6.35	1.95	9.89	1.59	
			LA lower bound	-18.39	-53.20			-23.03	-21.52	-8.73	-15.90	
			LA upper bound	7.97	70.10			21.35	13.93	11.82	10.52	
			RMS (individual)	12.67				8.13				
			Fraction (individual)	0.42				1.00				
		RMS (mean)	12.69							8.13	6.50	
		Fraction (mean)	0.50							0.50	1.00	

Table A.1: (cont.) *Primary Variables - DVJ - LCMAS-Single - Min - 2nd Component - Knee Moment.*

Component Parameter	Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID
		LCMAS-Single (Kinect Static, IK)		LCMAS-Single (Kinect Static, IK)		Vicon		LCMAS-Single (Kinect Static, IK)		
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
Min 2nd Knee Moment PCS	ICC	0.790	0.391	0.823	0.855	0.877	0.913	0.718	0.951	
	n	4	6	4	4	12	12	4	12	
	SEM	6.99	35.05	5.06	16.21	7.25	6.64	19.44	6.38	
	SDD	19.39	97.16	14.03	44.94	20.09	18.42	53.90	17.68	26.9
	SDD lower bound	-17.96	-72.44	-15.81	-50.50	-19.36	-18.10	-35.75	-15.87	Nm
	SDD upper bound	20.82	121.87	12.25	39.39	20.81	18.74	72.04	19.49	
	$\bar{d}$	1.43	24.72	-1.78	-5.55	0.73	0.32	18.14	1.81	
	$\bar{d}$ lower bound	-14.31	-27.30	-14.52	-46.43	-6.06	-5.91	-19.82	-4.05	
	$\bar{d}$ upper bound	17.17	76.74	10.96	35.32	7.51	6.55	56.11	7.68	
	LA lower bound	-17.96	-72.44	-17.47	-55.91	-20.20	-18.90	-28.62	-16.28	
	LA upper bound	20.82	121.87	13.91	44.80	21.65	19.55	64.91	19.90	
	RMS (individual)	23.65		15.22		8.30				
	Fraction (individual)	0.42		0.35		1.00				
	RMS (mean)	28.69						22.96	7.69	
	Fraction (mean)	0.50						0.50	1.00	

Table A.1: (cont.) *Primary Variables - DVJ - LCMAS-Single - Max - 2nd Component - Knee Moment.*

Component Parameter		Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID	
			LCMAS-Single (Vicon Static, IK)		LCMAS-Single (Vicon Static, IK)		Vicon		LCMAS-Single (Vicon Static, IK)			
Max 2nd	Knee Moment JCS	Statistic	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2		
		ICC	0.400	0.904			0.226	0.701	0.686	0.532	0.418	0.890
		n	8	8			6	6	12	12	8	12
		SEM	19.19	3.81			54.45	4.30	6.23	7.26	19.63	4.25
		SDD	53.19	10.55			150.92	11.93	17.25	20.12	54.42	11.79
		SDD lower bound	-73.47	-21.38			-119.73	-11.23	-19.19	-26.66	-44.53	-8.92
		SDD upper bound	32.92	-0.28			182.10	12.63	15.31	13.58	64.32	14.65
		$\bar{d}$	-20.28	-10.83			31.19	0.70	-1.94	-6.54	9.90	2.87
		$\bar{d}$ lower bound	-42.96	-15.33			-49.75	-6.25	-7.64	-11.79	-13.29	-0.64
		$\bar{d}$ upper bound	2.41	-6.33			112.12	7.65	3.76	-1.29	33.08	6.37
		LA lower bound	-73.47	-21.38			-119.97	-12.28	-19.52	-22.74	-44.46	-7.96
		LA upper bound	32.92	-0.28			182.34	13.68	15.64	9.67	64.26	13.69
		RMS (individual)	17.47				18.16		8.13			
		Fraction (individual)	0.54				0.46		1.00			
		RMS (mean)	14.79								11.08	6.50
		Fraction (mean)	0.67								0.67	1.00

Component Parameter		Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID
			LCMAS-Single (Vicon Static, 6DOF)		LCMAS-Single (Vicon Static, 6DOF)		Vicon		LCMAS-Single (Vicon Static, 6DOF)		
Max 2nd	Knee Moment JCS	Statistic	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
		ICC	0.640	0.787	0.343	0.633	0.686	0.532	0.679	0.890	
		n	6	6	5	6	12	12	6	12	
		SEM	12.90	4.34	35.38	7.98	6.23	7.26	12.44	4.25	
		SDD	35.76	12.04	98.06	22.13	17.25	20.12	34.49	11.79	
		SDD lower bound	-43.75	-14.53	-120.70	-29.14	-19.19	-26.66	-27.01	-8.92	
		SDD upper bound	27.77	9.55	75.43	15.11	15.31	13.58	41.96	14.65	
		$\bar{d}$	-7.99	-2.49	-22.64	-7.01	-1.94	-6.54	7.48	2.87	
		$\bar{d}$ lower bound	-27.14	-8.94	-84.58	-17.18	-7.64	-11.79	-10.84	-0.64	
		$\bar{d}$ upper bound	11.15	3.95	39.30	3.16	3.76	-1.29	25.79	6.37	
		LA lower bound	-43.75	-14.53	-120.41	-26.01	-19.52	-22.74	-26.72	-7.96	
		LA upper bound	27.77	9.55	75.14	11.98	15.64	9.67	41.68	13.69	
		RMS (individual)	12.75		13.67		8.13				
		Fraction (individual)	0.43		0.46		1.00				
		RMS (mean)	12.12						11.75	6.50	
		Fraction (mean)	0.50						0.50	1.00	

Table A.1: (cont.) *Primary Variables - DVJ - LCMAS-Single - Max - 2nd Component - Knee Moment.*

Component Parameter		Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID
			LCMAS-Single (Kinect Static, IK)		LCMAS-Single (Kinect Static, IK)		Vicon		LCMAS-Single (Kinect Static, IK)		
Max 2nd	Knee Moment JCS	Statistic	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
		ICC	0.882	0.102			0.733	-0.578	0.686	0.532	0.890
		n	4	6			4	4	12	12	12
		SEM	4.83	6.67			9.45	12.83	6.23	7.26	4.25
		SDD	13.37	18.48			26.18	35.56	17.25	20.12	11.79
		SDD lower bound	-24.72	-24.11			-17.37	-42.85	-19.19	-26.66	-8.92
		SDD upper bound	2.03	12.85			35.00	28.27	15.31	13.58	14.65
		$\bar{d}$	-11.35	-5.63			8.81	-7.29	-1.94	-6.54	2.87
		$\bar{d}$ lower bound	-22.20	-15.53			-9.63	-37.81	-7.64	-11.79	-0.64
		$\bar{d}$ upper bound	-0.49	4.26			27.26	23.24	3.76	-1.29	6.37
		LA lower bound	-24.72	-24.11			-13.91	-44.89	-19.52	-22.74	-7.96
		LA upper bound	2.03	12.85			31.54	30.31	15.64	9.67	13.69
		RMS (individual)	12.67				10.48		8.13		
		Fraction (individual)	0.42				0.35		1.00		
		RMS (mean)	12.69								6.50
		Fraction (mean)	0.50								1.00

Component Parameter		Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID
			LCMAS-Single (Vicon Static, 6DOF)		LCMAS-Single (Vicon Static, 6DOF)		Vicon		LCMAS-Single (Vicon Static, 6DOF)		
Max 2nd	Knee Moment PCS	Statistic	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
		ICC	0.434	0.398			0.550	0.696	0.622	0.412	0.697
		n	6	6			5	6	12	12	12
		SEM	18.73	8.48			27.46	8.08	5.71	7.71	4.91
		SDD	51.91	23.51			76.10	22.40	15.84	21.37	13.61
		SDD lower bound	-68.12	-31.55			-98.16	-29.73	-20.21	-23.12	-11.83
		SDD upper bound	35.69	15.48			54.04	15.08	11.47	19.62	15.39
		$\bar{d}$	-16.22	-8.04			-22.06	-7.33	-4.37	-1.75	1.78
		$\bar{d}$ lower bound	-44.01	-20.63			-66.42	-17.41	-8.88	-8.89	-2.67
		$\bar{d}$ upper bound	11.58	4.55			22.30	2.76	0.14	5.40	6.23
		LA lower bound	-68.12	-31.55			-92.08	-26.16	-18.29	-23.78	-11.96
		LA upper bound	35.69	15.48			47.96	11.51	9.55	20.28	15.52
		RMS (individual)	23.63				19.73		8.30		
		Fraction (individual)	0.43				0.46		1.00		
		RMS (mean)	22.77								7.69
		Fraction (mean)	0.50								1.00

Table A.1: (cont.) *Primary Variables - DVJ - LCMAS-Single - Max - 2nd Component - Knee Moment.*

Component Parameter	Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID
		LCMAS-Single (Kinect Static, IK)		LCMAS-Single (Kinect Static, IK)		Vicon		LCMAS-Single (Kinect Static, IK)		
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
Max 2nd Knee Moment DCS	ICC	0.700	0.363	-0.890	0.616	0.774	0.469	0.639	0.789	
	n	3	4	2	3	12	12	2	12	
	SEM	4.56	8.50	13.12	6.67	5.43	8.83	5.07	6.34	
	SDD	12.63	23.56	36.35	18.49	15.06	24.47	14.05	17.58	26.9
	SDD lower bound	-8.49	-26.85	-19.24	-20.62	-16.89	-28.10	-20.72	-17.39	Nm
	SDD upper bound	16.78	20.27	53.46	16.36	13.23	20.83	7.37	17.77	
	$\bar{d}$	4.15	-3.29	17.11	-2.13	-1.83	-3.63	-6.67	0.19	
	$\bar{d}$ lower bound	-11.87	-22.42	-73.83	-30.09	-6.78	-11.56	-39.88	-5.76	
	$\bar{d}$ upper bound	20.16	15.84	108.05	25.83	3.12	4.29	26.54	6.14	
	LA lower bound	-8.49	-26.85	-2.73	-24.19	-17.10	-28.08	-13.92	-18.16	
	LA upper bound	16.78	20.27	36.95	19.93	13.45	20.82	0.57	18.54	
	RMS (individual)	35.08		19.69		8.53				
	Fraction (individual)	0.27		0.20		1.00				
	RMS (mean)	34.21						27.72	9.54	
	Fraction (mean)	0.35						0.25	1.00	

Table A.2: *Secondary Variables - DVJ - LCMAS-Single - ROM - 2nd Component - COM Position.*

Component Parameter	Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID		
		LCMAS-Single (Vicon Static, 6DOF)		LCMAS-Single (Vicon Static, 6DOF)		Vicon		LCMAS-Single (Vicon Static, 6DOF)				
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2			
ROM 2nd	Position COM	ICC		0.616	0.924	-0.953	0.860	0.300	0.488	0.795	0.859	
		n		4	5	3	4	12	12	3	12	
		SEM		0.014	0.006	0.028	0.004	0.023	0.017	0.014	0.010	
		SDD		0.038	0.017	0.076	0.011	0.063	0.048	0.038	0.029	
		SDD lower bound		-0.048	-0.027	-0.109	-0.010	-0.051	-0.046	-0.050	-0.030	
		SDD upper bound		0.029	0.007	0.043	0.012	0.074	0.049	0.025	0.027	
		$\bar{d}$		-0.010	-0.010	-0.033	0.001	0.012	0.001	-0.013	-0.002	
		$\bar{d}$ lower bound		-0.040	-0.021	-0.096	-0.009	-0.008	-0.015	-0.056	-0.011	
		$\bar{d}$ upper bound		0.021	0.001	0.030	0.011	0.031	0.017	0.030	0.008	
		LA lower bound		-0.048	-0.027	-0.083	-0.011	-0.049	-0.048	-0.047	-0.032	
		LA upper bound		0.029	0.007	0.017	0.014	0.072	0.051	0.021	0.028	
		RMS (individual)		0.018		0.022		0.024				
		Fraction (individual)		0.361		0.417		1.000				
		RMS (mean)		0.017						0.022	0.027	
		Fraction (mean)		0.500						0.500	1.000	

Table A.2: (cont.) Secondary Variables - DVJ - LCMAS-Single - ROM - 2nd Component - COM relative to BOS Position.

Component Parameter ROM 2nd Position COM relative to BOS	Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID
		LCMAS-Single (Vicon Static, 6DOF)		LCMAS-Single (Vicon Static, 6DOF)		Vicon		LCMAS-Single (Vicon Static, 6DOF)		
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
ICC	Statistic	0.863	0.888	-0.138	0.436	0.046	0.427	0.650	0.302	
n		4	6	3	5	12	12	4	12	
SEM		0.016	0.009	0.020	0.018	0.025	0.021	0.028	0.019	
SDD		0.045	0.024	0.055	0.050	0.070	0.059	0.077	0.052	
SDD lower bound		-0.051	-0.040	-0.065	-0.045	-0.063	-0.081	-0.110	-0.067	0.0404
SDD upper bound		0.040	0.008	0.045	0.056	0.077	0.037	0.044	0.037	m
$\bar{d}$		-0.005	-0.016	-0.010	0.005	0.007	-0.022	-0.033	-0.015	
$\bar{d}$ lower bound		-0.042	-0.029	-0.090	-0.029	-0.016	-0.035	-0.072	-0.030	
$\bar{d}$ upper bound		0.031	-0.003	0.070	0.040	0.031	-0.008	0.005	0.000	
LA lower bound		-0.051	-0.040	-0.073	-0.050	-0.064	-0.064	-0.080	-0.060	
LA upper bound		0.040	0.008	0.053	0.060	0.079	0.021	0.014	0.030	
RMS (individual)		0.018		0.024		0.020				
Fraction (individual)		0.361		0.417		1.000				
RMS (mean)		0.019						0.038	0.015	
Fraction (mean)		0.500						0.500	1.000	

Table A.2: (cont.) Secondary Variables - DVJ - LCMAS-Single - MKF - 2nd Component - Hip Angle.

Component Parameter	Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID
		LCMAS-Single (Vicon Static, IK)		LCMAS-Single (Vicon Static, IK)		Vicon		LCMAS-Single (Vicon Static, IK)		
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
MKF 2nd Hip Angle JCS	ICC	0.977	0.974	0.863	0.928	0.944	0.979	0.974	0.973	
	n	12	12	12	12	12	12	12	12	
	SEM	2.16	2.28	3.89	2.88	2.35	1.42	2.38	2.22	
	SDD	5.98	6.31	10.79	7.98	6.50	3.94	6.59	6.14	6.3
	SDD lower bound	-9.70	-9.14	-9.65	-5.20	-7.02	-3.45	-6.92	-7.36	degrees
	SDD upper bound	2.27	3.48	11.94	10.76	5.99	4.42	6.25	4.92	
	$\bar{d}$	-3.71	-2.83	1.15	2.78	-0.51	0.49	-0.34	-1.22	
	$\bar{d}$ lower bound	-5.65	-4.88	-2.43	0.81	-2.69	-0.81	-2.55	-3.13	
	$\bar{d}$ upper bound	-1.77	-0.79	4.72	4.76	1.66	1.78	1.88	0.70	
	LA lower bound	-9.70	-9.14	-9.88	-3.30	-7.22	-3.50	-7.18	-7.13	
	LA upper bound	2.27	3.48	12.17	8.87	6.20	4.48	6.51	4.69	
	RMS (individual)	3.71		3.84		2.08				
	Fraction (individual)	1.00		1.00		1.00		3.80	2.63	
RMS (mean)	3.32						1.00	1.00		
Fraction (mean)	1.00									

Component Parameter	Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID
		LCMAS-Single (Vicon Static, 6DOF)		LCMAS-Single (Vicon Static, 6DOF)		Vicon		LCMAS-Single (Vicon Static, 6DOF)		
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
MKF 2nd Hip Angle JCS	ICC	0.911	0.943	0.843	0.901	0.944	0.979	0.941	0.973	
	n	12	12	12	12	12	12	12	12	
	SEM	3.63	3.18	3.26	3.21	2.35	1.42	2.99	2.22	
	SDD	10.07	8.81	9.05	8.90	6.50	3.94	8.29	6.14	6.3
	SDD lower bound	-11.68	-10.03	-7.75	-6.81	-7.02	-3.45	-9.10	-7.36	degrees
	SDD upper bound	8.45	7.60	10.35	11.00	5.99	4.42	7.47	4.92	
	$\bar{d}$	-1.62	-1.22	1.30	2.10	-0.51	0.49	-0.82	-1.22	
	$\bar{d}$ lower bound	-4.88	-4.07	-1.64	-0.58	-2.69	-0.81	-3.57	-3.13	
	$\bar{d}$ upper bound	1.65	1.64	4.24	4.77	1.66	1.78	1.94	0.70	
	LA lower bound	-11.68	-10.03	-7.76	-6.16	-7.22	-3.50	-9.31	-7.13	
	LA upper bound	8.45	7.60	10.37	10.35	6.20	4.48	7.68	4.69	
	RMS (individual)	4.09		4.35		2.08				
	Fraction (individual)	1.00		1.00		1.00		4.52	2.63	
RMS (mean)	3.51						1.00	1.00		
Fraction (mean)	1.00									

Table A.2: (cont.) Secondary Variables - DVJ - LCMAS-Single - MKF - 2nd Component - Hip Angle.

Component Parameter MKF 2nd Hip Angle Marker	Comparison System Statistic	Inter-System: Vicon (Markers)		Intra-System: Between Reps				Intra-System: Between Days		MCID
		LCMAS-Single (Markers)		LCMAS-Single (Markers)		Vicon (Markers)		LCMAS-Single (Markers)	Vicon (Markers)	
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2			
ICC		0.637	0.814	0.641	0.833	0.901	0.970	0.797	0.940	
n		12	10	9	8	12	12	10	12	
SEM		5.19	3.91	2.99	3.02	2.23	1.31	3.96	2.42	
SDD		14.39	10.85	8.29	8.36	6.19	3.62	10.98	6.72	6.3
SDD lower bound		-18.76	-15.10	-7.51	-5.04	-6.44	-3.17	-11.72	-7.58	degrees
SDD upper bound		10.01	6.60	9.08	11.68	5.94	4.07	10.24	5.86	
$\bar{d}$		-4.38	-4.25	0.79	3.32	-0.25	0.45	-0.74	-0.86	
$\bar{d}$ lower bound		-9.04	-8.21	-2.60	0.93	-2.34	-0.74	-4.93	-3.06	
$\bar{d}$ upper bound		0.28	-0.29	4.18	5.72	1.84	1.64	3.45	1.34	
LA lower bound		-18.76	-15.10	-7.86	-2.29	-6.69	-3.22	-12.22	-7.65	
LA upper bound		10.01	6.60	9.43	8.93	6.20	4.12	10.73	5.94	
RMS (individual)		4.10		3.49		1.97				
Fraction (individual)		0.78		0.71		1.00		4.41	2.67	
RMS (mean)		4.03						0.83	1.00	
Fraction (mean)		0.92								

Component Parameter MKF 2nd Hip Angle	Comparison System Statistic	Inter-System: Vicon		Intra-System: Between Reps				Intra-System: Between Days		MCID
		LCMAS-Single (Markers)		LCMAS-Single (Markers)		Vicon		LCMAS-Single (Markers)	Vicon	
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2			
ICC		0.525	0.727	0.641	0.833	0.944	0.979	0.797	0.973	
n		12	10	9	8	12	12	10	12	
SEM		6.91	5.52	2.99	3.02	2.35	1.42	3.96	2.22	
SDD		19.17	15.31	8.29	8.36	6.50	3.94	10.98	6.14	6.3
SDD lower bound		-23.51	-19.38	-7.51	-5.04	-7.02	-3.45	-11.72	-7.36	degrees
SDD upper bound		14.82	11.25	9.08	11.68	5.99	4.42	10.24	4.92	
$\bar{d}$		-4.34	-4.07	0.79	3.32	-0.51	0.49	-0.74	-1.22	
$\bar{d}$ lower bound		-10.56	-9.66	-2.60	0.93	-2.69	-0.81	-4.93	-3.13	
$\bar{d}$ upper bound		1.87	1.52	4.18	5.72	1.66	1.78	3.45	0.70	
LA lower bound		-23.51	-19.38	-7.86	-2.29	-7.22	-3.50	-12.22	-7.13	
LA upper bound		14.82	11.25	9.43	8.93	6.20	4.48	10.73	4.69	
RMS (individual)		5.85		3.49		2.08				
Fraction (individual)		0.78		0.71		1.00		4.41	2.63	
RMS (mean)		5.77						0.83	1.00	
Fraction (mean)		0.92								

Table A.2: (cont.) Secondary Variables - DVJ - LCMAS-Single - MKF - 2nd Component - Hip Angle.

Component Parameter	Comparison System	Inter-System: Vicon		Intra-System: Between Reps				Intra-System: Between Days		MCID
		Vicon (Markers)		Vicon (Markers)		Vicon		Vicon (Markers)	Vicon	
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2			
MKF 2nd Hip Angle	ICC	0.940	0.951	0.901	0.970	0.944	0.979	0.940	0.973	
	n	12	12	12	12	12	12	12	12	
	SEM	2.82	2.68	2.23	1.31	2.35	1.42	2.42	2.22	
	SDD	7.83	7.42	6.19	3.62	6.50	3.94	6.72	6.14	
	SDD lower bound	-7.79	-7.02	-6.44	-3.17	-7.02	-3.45	-7.58	-7.36	6.3
	SDD upper bound	7.86	7.81	5.94	4.07	5.99	4.42	5.86	4.92	degrees
	$\bar{d}$	0.04	0.39	-0.25	0.45	-0.51	0.49	-0.86	-1.22	
	$\bar{d}$ lower bound	-2.50	-2.01	-2.34	-0.74	-2.69	-0.81	-3.06	-3.13	
	$\bar{d}$ upper bound	2.57	2.80	1.84	1.64	1.66	1.78	1.34	0.70	
	LA lower bound	-7.79	-7.02	-6.69	-3.22	-7.22	-3.50	-7.65	-7.13	
	LA upper bound	7.86	7.81	6.20	4.12	6.20	4.48	5.94	4.69	
	RMS (individual)	3.63		1.97		2.08				
	Fraction (individual)	1.00		1.00		1.00				
	RMS (mean)	3.62						2.67	2.63	
	Fraction (mean)	1.00						1.00	1.00	

Table A.2: (cont.) Secondary Variables - DVJ - LCMAS-Single - ROM - 2nd Component - Knee Angle.

Component Parameter	ROM 2nd Knee Angle Marker	Comparison System	Inter-System: Vicon (Markers)		Intra-System: Between Repts				Intra-System: Between Days		MCID
			LCMAS-Single (Markers)		LCMAS-Single (Markers)		Vicon (Markers)		LCMAS-Single (Markers)		
			Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	(Markers)	(Markers)	
ICC		ICC	0.630	0.847	0.311	0.804	0.896	0.881	0.299	0.944	
n		n	10	10	9	7	12	12	9	12	
SEM		SEM	2.45	1.98	2.35	1.63	1.53	1.63	2.76	1.51	
SDD		SDD	6.80	5.48	6.52	4.52	4.23	4.51	7.66	4.19	8.0
SDD lower bound		SDD lower bound	-4.31	-4.60	-5.65	-5.41	-4.08	-4.70	-9.12	-3.03	degrees
SDD upper bound		SDD upper bound	9.28	6.36	7.39	3.63	4.38	4.32	6.19	5.35	
$\bar{d}$		$\bar{d}$	2.49	0.88	0.87	-0.89	0.15	-0.19	-1.46	1.16	
$\bar{d}$ lower bound		$\bar{d}$ lower bound	0.01	-1.12	-1.75	-3.01	-1.28	-1.71	-4.42	-0.03	
$\bar{d}$ upper bound		$\bar{d}$ upper bound	4.97	2.88	3.49	1.24	1.58	1.33	1.49	2.35	
LA lower bound		LA lower bound	-4.31	-4.60	-5.80	-5.39	-4.26	-4.88	-8.99	-2.51	
LA upper bound		LA upper bound	9.28	6.36	7.54	3.62	4.56	4.50	6.07	4.84	
RMS (individual)		RMS (individual)	1.55		2.39		2.20				
Fraction (individual)		Fraction (individual)	0.72		0.67		1.00		2.12	1.91	
RMS (mean)		RMS (mean)	1.54						0.75	1.00	
Fraction (mean)		Fraction (mean)	0.83								

Component Parameter	ROM 2nd Knee Angle	Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID
			LCMAS-Single (Markers)		LCMAS-Single (Markers)		Vicon		LCMAS-Single (Markers)		
			Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	(Markers)	(Markers)	
ICC		ICC	0.047	0.721	0.311	0.804	0.912	0.971	0.299	0.961	
n		n	10	10	9	7	12	12	9	12	
SEM		SEM	3.27	3.06	2.35	1.63	1.90	1.01	2.76	1.67	
SDD		SDD	9.06	8.48	6.52	4.52	5.26	2.79	7.66	4.62	8.0
SDD lower bound		SDD lower bound	-5.64	-4.60	-5.65	-5.41	-5.89	-2.86	-9.12	-4.46	degrees
SDD upper bound		SDD upper bound	12.47	12.37	7.39	3.63	4.63	2.73	6.19	4.77	
$\bar{d}$		$\bar{d}$	3.41	3.88	0.87	-0.89	-0.63	-0.07	-1.46	0.15	
$\bar{d}$ lower bound		$\bar{d}$ lower bound	0.11	0.79	-1.75	-3.01	-2.36	-1.01	-4.42	-1.41	
$\bar{d}$ upper bound		$\bar{d}$ upper bound	6.72	6.98	3.49	1.24	1.10	0.88	1.49	1.71	
LA lower bound		LA lower bound	-5.64	-4.60	-5.80	-5.39	-5.97	-2.98	-8.99	-4.66	
LA upper bound		LA upper bound	12.47	12.37	7.54	3.62	4.71	2.85	6.07	4.97	
RMS (individual)		RMS (individual)	5.03		2.39		1.99				
Fraction (individual)		Fraction (individual)	0.72		0.67		1.00		2.12	2.70	
RMS (mean)		RMS (mean)	4.57						0.75	1.00	
Fraction (mean)		Fraction (mean)	0.83								

Table A.2: (cont.) *Secondary Variable - DVJ - LCMAS-Singles - ROM - 2nd Component - Knee Angle.*

Component Parameter		Comparison System	Inter-System: Vicon		Intra-System: Between Reps				Intra-System: Between Days		MCID
			Vicon (Markers)		Vicon (Markers)		Vicon (Markers)		Vicon (Markers)		
ROM 2nd Knee Angle	Statistic	ICC	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
	n		0.858	0.882	0.896	0.881	0.912	0.971	0.944	0.961	
			12	12	12	12	12	12	12	12	
	SEM		2.70	2.47	1.53	1.63	1.90	1.01	1.51	1.67	
	SDD		7.47	6.85	4.23	4.51	5.26	2.79	4.19	4.62	
	SDD lower bound		-5.44	-3.81	-4.08	-4.70	-5.89	-2.86	-3.03	-4.46	8.0 degrees
	SDD upper bound		9.51	9.90	4.38	4.32	4.63	2.73	5.35	4.77	
	$\bar{d}$		2.04	3.05	0.15	-0.19	-0.63	-0.07	1.16	0.15	
	$\bar{d}$ lower bound		-0.38	0.82	-1.28	-1.71	-2.36	-1.01	-0.03	-1.41	
	$\bar{d}$ upper bound		4.46	5.27	1.58	1.33	1.10	0.88	2.35	1.71	
	LA lower bound		-5.44	-3.81	-4.26	-4.88	-5.97	-2.98	-2.51	-4.66	
	LA upper bound		9.51	9.90	4.56	4.50	4.71	2.85	4.84	4.97	
	RMS (individual)		4.98		2.20		1.99				
	Fraction (individual)		1.00		1.00		1.00				
	RMS (mean)		4.77						1.91	2.70	
	Fraction (mean)		1.00						1.00	1.00	

Table A.2: (cont.) Secondary Variables - DVJ - LCMAS-Single - MKF - 2nd Component - Knee Angle.

Component Parameter	Comparison System	Statistic	Inter-System: Vicon (Markers)		Intra-System: Between Reps				Intra-System: Between Days		MCID
			LCMAS-Single (Markers)		LCMAS-Single (Markers)		Vicon (Markers)		LCMAS-Single (Markers)		
			Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
MKF 2nd	Knee Angle	ICC	0.965	0.919	0.827	0.934	0.847	0.944	0.954	0.971	4.5 to 5.1 degrees
		n	10	10	9	7	12	12	9	12	
		SEM	1.54	2.11	2.49	1.53	2.66	1.36	1.83	1.48	
		SDD	4.28	5.85	6.89	4.24	7.38	3.78	5.07	4.10	
		SDD lower bound	-3.62	-5.22	-5.74	-4.69	-6.25	-3.03	-4.95	-3.90	
		SDD upper bound	4.95	6.48	8.04	3.79	8.50	4.53	5.19	4.30	
		$\bar{d}$	0.66	0.63	1.15	-0.45	1.12	0.75	0.12	0.20	
		$\bar{d}$ lower bound	-0.90	-1.51	-1.56	-2.57	-1.26	-0.43	-1.99	-1.18	
		$\bar{d}$ upper bound	2.23	2.76	3.86	1.66	3.51	1.93	2.22	1.58	
		LA lower bound	-3.62	-5.22	-5.76	-4.93	-6.23	-2.90	-5.25	-4.07	
		LA upper bound	4.95	6.48	8.06	4.03	8.47	4.39	5.49	4.47	
		RMS (individual)	1.55		2.39		2.20				
		Fraction (individual)	0.72		0.67		1.00		2.12	1.91	
		RMS (mean)	1.54						0.75	1.00	
		Fraction (mean)	0.83								

Component Parameter	Comparison System	Statistic	Inter-System: Vicon		Intra-System: Between Reps				Intra-System: Between Days		MCID
			LCMAS-Single (Markers)		LCMAS-Single (Markers)		Vicon		LCMAS-Single (Markers)		
			Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
MKF 2nd	Knee Angle	ICC	0.775	0.857	0.827	0.934	0.981	0.971	0.954	0.978	4.5 to 5.1 degrees
		n	10	10	9	7	12	12	9	12	
		SEM	4.39	4.35	2.49	1.53	1.42	1.80	1.83	2.20	
		SDD	12.17	12.07	6.89	4.24	3.92	5.00	5.07	6.10	
		SDD lower bound	-11.46	-11.62	-5.74	-4.69	-3.38	-4.37	-4.95	-4.80	
		SDD upper bound	12.89	12.53	8.04	3.79	4.47	5.63	5.19	7.39	
		$\bar{d}$	0.71	0.46	1.15	-0.45	0.54	0.63	0.12	1.29	
		$\bar{d}$ lower bound	-3.73	-3.95	-1.56	-2.57	-0.73	-1.01	-1.99	-0.59	
		$\bar{d}$ upper bound	5.16	4.86	3.86	1.66	1.82	2.27	2.22	3.17	
		LA lower bound	-11.46	-11.62	-5.76	-4.93	-3.40	-4.43	-5.25	-4.50	
		LA upper bound	12.89	12.53	8.06	4.03	4.49	5.69	5.49	7.08	
		RMS (individual)	5.03		2.39		1.99				
		Fraction (individual)	0.72		0.67		1.00		2.12	2.70	
		RMS (mean)	4.57						0.75	1.00	
		Fraction (mean)	0.83								

Table A.2: (cont.) *Secondary Variables - DVJ - LCMAS-Single - MKF - 2nd Component - Knee Angle.*

Component Parameter		Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID
			Vicon (Markers)		Vicon (Markers)		Vicon (Markers)		Vicon (Markers)		
			Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
MKF 2nd	Knee Angle	ICC	0.834	0.775	0.847	0.944	0.981	0.971	0.971	0.978	
		n	12	12	12	12	12	12	12	12	
		SEM	4.55	5.37	2.66	1.36	1.42	1.80	1.48	2.20	
		SDD	12.61	14.90	7.38	3.78	3.92	5.00	4.10	6.10	
		SDD lower bound	-11.40	-14.78	-6.25	-3.03	-3.38	-4.37	-3.90	-4.80	4.5 to
		SDD upper bound	13.82	15.01	8.50	4.53	4.47	5.63	4.30	7.39	5.1
		$\bar{d}$	1.21	0.12	1.12	0.75	0.54	0.63	0.20	1.29	degrees
		$\bar{d}$ lower bound	-2.88	-4.71	-1.26	-0.43	-0.73	-1.01	-1.18	-0.59	
		$\bar{d}$ upper bound	5.30	4.95	3.51	1.93	1.82	2.27	1.58	3.17	
		LA lower bound	-11.40	-14.78	-6.23	-2.90	-3.40	-4.43	-4.07	-4.50	
		LA upper bound	13.82	15.01	8.47	4.39	4.49	5.69	4.47	7.08	
		RMS (individual)	4.98		2.20		1.99				
		Fraction (individual)	1.00		1.00		1.00				
		RMS (mean)	4.77						1.91	2.70	
		Fraction (mean)	1.00						1.00	1.00	

Table A.3: *Primary Variables - DVJ - LCMAS-2 - ROM - 1st Component - Hip Angle.*

Component Parameter	ROM 1st Hip Angle Marker	Comparison System	Inter-System: Vicon (Markers)		Intra-System: Between Repts				Intra-System: Between Days		MCID
			LCMAS-2 (Markers)		LCMAS-2 (Markers)		Vicon (Markers)		LCMAS-2 (Markers)		
			Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
ICC			0.919	0.949	0.977	0.444	0.973	0.965	0.755	0.968	
n			12	12	12	12	12	12	12	12	
SEM			10.23	5.03	4.80	11.07	3.73	3.40	14.40	5.15	
SDD			28.37	13.94	13.31	30.69	10.33	9.43	39.92	14.28	31.6
SDD lower bound			-54.17	-44.70	-12.55	-37.56	-10.76	-7.83	-40.75	-10.15	degrees
SDD upper bound			2.56	-16.82	14.07	23.82	9.90	11.04	39.09	18.40	
$\bar{d}$			-25.81	-30.76	0.76	-6.87	-0.43	1.61	-0.83	4.12	
$\bar{d}$ lower bound			-35.00	-35.28	-3.72	-16.20	-3.92	-1.40	-14.34	0.14	
$\bar{d}$ upper bound			-16.61	-26.24	5.24	2.47	3.05	4.62	12.67	8.11	
LA lower bound			-54.17	-44.70	-13.05	-35.67	-11.18	-7.68	-42.49	-8.17	
LA upper bound			2.56	-16.82	14.58	21.94	10.32	10.90	40.83	16.42	
RMS (individual)			18.68		6.94		4.64				
Fraction (individual)			1.00		1.00		1.00				
RMS (mean)			18.01						14.67	8.51	
Fraction (mean)			1.00						1.00	1.00	

Component Parameter	ROM 1st Hip Angle	Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID
			LCMAS-2 (Markers)		LCMAS-2 (Markers)		Vicon		LCMAS-2 (Markers)		
			Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
ICC			0.767	0.948	0.977	0.444	0.973	0.948	0.755	0.953	
n			12	12	12	12	12	12	12	12	
SEM			15.11	4.41	4.80	11.07	2.97	3.16	14.40	4.89	
SDD			41.88	12.21	13.31	30.69	8.24	8.76	39.92	13.55	31.6
SDD lower bound			-75.49	-50.28	-12.55	-37.56	-8.65	-7.31	-40.75	-9.92	degrees
SDD upper bound			8.27	-25.85	14.07	23.82	7.83	10.22	39.09	17.17	
$\bar{d}$			-33.61	-38.07	0.76	-6.87	-0.41	1.45	-0.83	3.63	
$\bar{d}$ lower bound			-47.18	-42.02	-3.72	-16.20	-3.19	-1.35	-14.34	-0.28	
$\bar{d}$ upper bound			-20.03	-34.11	5.24	2.47	2.37	4.26	12.67	7.53	
LA lower bound			-75.49	-50.28	-13.05	-35.67	-8.98	-7.20	-42.49	-8.42	
LA upper bound			8.27	-25.85	14.58	21.94	8.16	10.11	40.83	15.67	
RMS (individual)			23.69		6.94		3.83				
Fraction (individual)			1.00		1.00		1.00				
RMS (mean)			23.14						14.67	6.31	
Fraction (mean)			1.00						1.00	1.00	

Table A.3: (cont.) *Primary Variables - DVJ - LCMAS-2 - ROM - 1st Component - Hip Angle.*

Component Parameter	Comparison System	Inter-System: Vicon		Intra-System: Between Reps		Intra-System: Between Days		MCID			
		Vicon (Markers)		Vicon (Markers)		Vicon (Markers)					
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2				
ROM 1st	Hip Angle	ICC	0.915	0.929	0.973	0.965	0.973	0.948	0.968	0.953	
		n	12	12	12	12	12	12	12	12	
		SEM	8.08	5.98	3.73	3.40	2.97	3.16	5.15	4.89	
		SDD	22.41	16.56	10.33	9.43	8.24	8.76	14.28	13.55	
		SDD lower bound	-30.21	-23.87	-10.76	-7.83	-8.65	-7.31	-10.15	-9.92	31.6
		SDD upper bound	14.60	9.26	9.90	11.04	7.83	10.22	18.40	17.17	degrees
		$\bar{d}$	-7.80	-7.30	-0.43	1.61	-0.41	1.45	4.12	3.63	
		$\bar{d}$ lower bound	-15.07	-12.67	-3.92	-1.40	-3.19	-1.35	0.14	-0.28	
		$\bar{d}$ upper bound	-0.54	-1.94	3.05	4.62	2.37	4.26	8.11	7.53	
		LA lower bound	-30.21	-23.87	-11.18	-7.68	-8.98	-7.20	-8.17	-8.42	
		LA upper bound	14.60	9.26	10.32	10.90	8.16	10.11	16.42	15.67	
		RMS (individual)	10.51		4.64		3.83				
		Fraction (individual)	1.00		1.00		1.00				
		RMS (mean)	10.46						8.51	6.31	
		Fraction (mean)	1.00						1.00	1.00	

Table A.3: (cont.) *Primary Variables - DVJ - LCMAS-2 - IC - 2nd Component - Hip Angle.*

Component Parameter IC 2nd Hip Angle Marker	Comparison System Statistic	Inter-System: Vicon (Markers)		Intra-System: Between Reps				Intra-System: Between Days		MCID
		LCMAS-2 (Markers)		LCMAS-2 (Markers)		Vicon (Markers)		LCMAS-2 (Markers)		
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
ICC	ICC	0.602	0.604	0.938	0.987	0.920	0.911	0.990	0.924	
n	n	12	12	12	12	12	12	12	12	
SEM	SEM	9.13	9.39	4.25	1.85	1.48	1.79	2.28	2.01	
SDD	SDD	25.31	26.02	11.77	5.13	4.11	4.96	6.31	5.56	9.41 to
SDD lower bound	SDD lower bound	-27.16	-26.40	-11.32	-5.80	-5.69	-3.71	-5.43	-6.15	11.14
SDD upper bound	SDD upper bound	23.46	25.64	12.22	4.45	2.53	6.22	7.18	4.97	degrees
$\bar{d}$	$\bar{d}$	-1.85	-0.38	0.45	-0.68	-1.58	1.25	0.88	-0.59	
$\bar{d}$ lower bound	$\bar{d}$ lower bound	-10.05	-8.81	-3.53	-2.35	-2.49	-0.20	-1.18	-2.43	
$\bar{d}$ upper bound	$\bar{d}$ upper bound	6.35	8.06	4.42	1.00	-0.67	2.71	2.93	1.25	
LA lower bound	LA lower bound	-27.16	-26.40	-11.81	-5.85	-4.40	-3.25	-5.46	-6.27	
LA upper bound	LA upper bound	23.46	25.64	12.71	4.50	1.23	5.76	7.21	5.09	
RMS (individual)	RMS (individual)	12.74		3.81		1.96				
Fraction (individual)	Fraction (individual)	1.00		1.00		1.00				
RMS (mean)	RMS (mean)	12.62						3.50	2.67	
Fraction (mean)	Fraction (mean)	1.00						1.00	1.00	

Component Parameter IC 2nd Hip Angle	Comparison System Statistic	Inter-System: Vicon		Intra-System: Between Reps				Intra-System: Between Days		MCID
		LCMAS-2 (Markers)		LCMAS-2 (Markers)		Vicon		LCMAS-2 (Markers)		
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
ICC	ICC	0.852	0.841	0.938	0.987	0.964	0.945	0.990	0.977	
n	n	12	12	12	12	12	12	12	12	
SEM	SEM	6.62	6.88	4.25	1.85	1.63	1.99	2.28	1.78	
SDD	SDD	18.35	19.07	11.77	5.13	4.52	5.52	6.31	4.93	9.41 to
SDD lower bound	SDD lower bound	-20.31	-18.52	-11.32	-5.80	-6.33	-4.09	-5.43	-6.58	11.14
SDD upper bound	SDD upper bound	16.39	19.63	12.22	4.45	2.71	6.95	7.18	3.29	degrees
$\bar{d}$	$\bar{d}$	-1.96	0.56	0.45	-0.68	-1.81	1.43	0.88	-1.64	
$\bar{d}$ lower bound	$\bar{d}$ lower bound	-7.91	-5.63	-3.53	-2.35	-2.76	-0.18	-1.18	-2.91	
$\bar{d}$ upper bound	$\bar{d}$ upper bound	3.99	6.74	4.42	1.00	-0.86	3.04	2.93	-0.37	
LA lower bound	LA lower bound	-20.31	-18.52	-11.81	-5.85	-4.74	-3.54	-5.46	-5.55	
LA upper bound	LA upper bound	16.39	19.63	12.71	4.50	1.12	6.40	7.21	2.27	
RMS (individual)	RMS (individual)	9.40		3.81		2.08				
Fraction (individual)	Fraction (individual)	1.00		1.00		1.00				
RMS (mean)	RMS (mean)	9.22						3.50	2.63	
Fraction (mean)	Fraction (mean)	1.00						1.00	1.00	

Table A.3: (cont.) *Primary Variables - DVJ - LCMAS-2 - IC - 2nd Component - Hip Angle.*

Component Parameter IC 2nd Hip Angle	Comparison System	Inter-System: Vicon		Intra-System: Between Reps				Intra-System: Between Days		MCID
		Vicon (Markers)		Vicon (Markers)		Vicon (Markers)		Vicon (Markers)		
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
ICC	Statistic	0.897	0.916	0.920	0.911	0.964	0.945	0.924	0.977	
n		12	12	12	12	12	12	12	12	
SEM		3.02	2.74	1.48	1.79	1.63	1.99	2.01	1.78	
SDD		8.36	7.60	4.11	4.96	4.52	5.52	5.56	4.93	9.41 to
SDD lower bound		-8.48	-6.66	-5.69	-3.71	-6.33	-4.09	-6.15	-6.58	11.14
SDD upper bound		8.25	8.53	2.53	6.22	2.71	6.95	4.97	3.29	degrees
$\bar{d}$		-0.11	0.94	-1.58	1.25	-1.81	1.43	-0.59	-1.64	
$\bar{d}$ lower bound		-2.82	-1.53	-2.49	-0.20	-2.76	-0.18	-2.43	-2.91	
$\bar{d}$ upper bound		2.60	3.40	-0.67	2.71	-0.86	3.04	1.25	-0.37	
LA lower bound		-8.48	-6.66	-4.40	-3.25	-4.74	-3.54	-6.27	-5.55	
LA upper bound		8.25	8.53	1.23	5.76	1.12	6.40	5.09	2.27	
RMS (individual)		3.63		1.96		2.08				
Fraction (individual)		1.00		1.00		1.00				
RMS (mean)		3.62						2.67	2.63	
Fraction (mean)		1.00						1.00	1.00	

Table A.3: (cont.) *Primary Variables - DVJ - LCMAS-2 - IC - 2nd Component - Knee Angle.*

Component Parameter		Comparison System	Inter-System: Vicon (Markers)		Intra-System: Between Repts				Intra-System: Between Days		MCID
			LCMAS-2 (Markers)	Day 1	Day 2	LCMAS-2 (Markers)	Day 1	Day 2	LCMAS-2 (Markers)	Vicon (Markers)	
IC 2nd	Knee Angle Marker	Statistic									
		ICC	0.666	0.758		0.452	0.833	0.929	0.876	0.948	
		n	12	12		12	12	12	12	12	
		SEM	2.79	2.74		4.16	2.36	0.79	1.02	2.50	0.95
		SDD	7.72	7.60		11.52	6.55	2.19	2.82	6.92	2.63
		SDD lower bound	-6.83	-6.38		-13.36	-6.98	-2.20	-1.74	-6.93	-2.97
		SDD upper bound	8.62	8.82		9.68	6.11	2.18	3.89	6.91	2.29
		$\bar{d}$	0.90	1.22		-1.84	-0.43	-0.01	1.07	-0.01	-0.34
		$\bar{d}$ lower bound	-1.61	-1.24		-5.55	-2.63	-0.75	0.44	-2.36	-1.20
		$\bar{d}$ upper bound	3.40	3.68		1.86	1.77	0.73	1.71	2.33	0.52
		LA lower bound	-6.83	-6.38		-13.27	-7.21	-2.30	-0.88	-7.24	-2.99
		LA upper bound	8.62	8.82		9.59	6.35	2.27	3.03	7.21	2.32
		RMS (individual)	4.54		2.95		2.21				
		Fraction (individual)	1.00		1.00		1.00				
		RMS (mean)	4.24						2.99	1.91	
		Fraction (mean)	1.00						1.00	1.00	
Component Parameter		Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID
			LCMAS-2 (Markers)	Day 1	Day 2	LCMAS-2 (Markers)	Day 1	Day 2	LCMAS-2 (Markers)	Vicon	
IC 2nd	Knee Angle	Statistic									
		ICC	0.396	0.450		0.452	0.833	0.935	0.910	0.974	
		n	12	12		12	12	12	12	12	
		SEM	4.07	4.30		4.16	2.36	1.19	1.47	2.50	1.07
		SDD	11.29	11.93		11.52	6.55	3.29	4.07	6.92	2.95
		SDD lower bound	-9.92	-10.59		-13.36	-6.98	-2.67	-2.96	-6.93	-2.94
		SDD upper bound	12.66	13.27		9.68	6.11	3.92	5.18	6.91	2.97
		$\bar{d}$	1.37	1.34		-1.84	-0.43	0.62	1.11	-0.01	0.02
		$\bar{d}$ lower bound	-2.29	-2.53		-5.55	-2.63	-0.41	-0.05	-2.36	-0.98
		$\bar{d}$ upper bound	5.03	5.20		1.86	1.77	1.66	2.27	2.33	1.02
		LA lower bound	-9.92	-10.59		-13.27	-7.21	-2.57	-2.48	-7.24	-3.07
		LA upper bound	12.66	13.27		9.59	6.35	3.82	4.70	7.21	3.10
		RMS (individual)	6.46		2.95		1.99				
		Fraction (individual)	1.00		1.00		1.00				
		RMS (mean)	6.09						2.99	2.69	
		Fraction (mean)	1.00						1.00	1.00	

Table A.3: (cont.) *Primary Variables - DVJ - LCMAS-2 - IC - 2nd Component - Knee Angle.*

Component Parameter IC 2nd Knee Angle	Comparison System	Inter-System: Vicon		Intra-System: Between Reps				Intra-System: Between Days		MCID
		Vicon (Markers)		Vicon (Markers)		Vicon (Markers)		Vicon (Markers)		
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2			
ICC	Statistic	0.387	0.371	0.929	0.876	0.935	0.910	0.948	0.974	
n		12	12	12	12	12	12	12	12	
SEM		3.40	3.53	0.79	1.02	1.19	1.47	0.95	1.07	
SDD		9.42	9.79	2.19	2.82	3.29	4.07	2.63	2.95	
SDD lower bound		-8.94	-9.67	-2.20	-1.74	-2.67	-2.96	-2.97	-2.94	6.17 to
SDD upper bound		9.89	9.91	2.18	3.89	3.92	5.18	2.29	2.97	8.4
$\bar{d}$		0.47	0.12	-0.01	1.07	0.62	1.11	-0.34	0.02	degrees
$\bar{d}$ lower bound		-2.58	-3.06	-0.75	0.44	-0.41	-0.05	-1.20	-0.98	
$\bar{d}$ upper bound		3.53	3.29	0.73	1.71	1.66	2.27	0.52	1.02	
LA lower bound		-8.94	-9.67	-2.30	-0.88	-2.57	-2.48	-2.99	-3.07	
LA upper bound		9.89	9.91	2.27	3.03	3.82	4.70	2.32	3.10	
RMS (individual)		4.98		2.21		1.99				
Fraction (individual)		1.00		1.00		1.00				
RMS (mean)		4.77						1.91	2.69	
Fraction (mean)		1.00						1.00	1.00	

Table A.3: (cont.) Primary Variables - DVJ - LCMAS-2 - Min - 2nd Component - Knee Angle.

Component Parameter	Min 2nd	Knee Angle Marker	Comparison System	Inter-System: Vicon (Markers)		Intra-System: Between Reps				Intra-System: Between Days		MCID	
				Statistic	LCMAS-2 (Markers)	LCMAS-2 (Markers)		Vicon (Markers)		LCMAS-2 (Markers)	Vicon (Markers)		
						Day 1	Day 2	Day 1	Day 2				
Knee Angle	Min 2nd	Knee Angle Marker	ICC		0.836	0.208	0.329	0.710	0.759	0.615	0.266	0.496	6.35 to 7.6 degrees
			n		12	12	12	12	12	12	12	12	
			SEM		1.06	2.41	2.29	1.65	1.00	1.39	2.38	1.74	
			SDD		2.93	6.69	6.36	4.58	2.76	3.84	6.59	4.82	
			SDD lower bound		-0.16	-4.20	-7.00	-4.27	-2.24	-4.59	-8.08	-6.03	
			SDD upper bound		5.70	9.18	5.72	4.89	3.28	3.09	5.10	3.61	
			$\bar{d}$		2.77	2.49	-0.64	0.31	0.52	-0.75	-1.49	-1.21	
			$\bar{d}$ lower bound		1.82	0.32	-2.75	-1.23	-0.35	-1.95	-3.49	-2.63	
			$\bar{d}$ upper bound		3.72	4.66	1.47	1.85	1.39	0.45	0.51	0.21	
			LA lower bound		-0.16	-4.20	-7.15	-4.43	-2.17	-4.46	-7.66	-5.59	
			LA upper bound		5.70	9.18	5.87	5.05	3.20	2.95	4.67	3.17	
			RMS (individual)		4.54		2.95		2.21				
			Fraction (individual)		1.00		1.00		1.00		2.99	1.91	
			RMS (mean)		4.24						1.00	1.00	
			Fraction (mean)		1.00								
Knee Angle	Min 2nd	Knee Angle	ICC		-0.300	-0.414	0.329	0.710	0.897	0.914	0.266	0.883	6.35 to 7.6 degrees
			n		12	12	12	12	12	12	12	12	
			SEM		2.46	3.79	2.29	1.65	0.83	1.18	2.38	1.53	
			SDD		6.83	10.50	6.36	4.58	2.31	3.27	6.59	4.24	
			SDD lower bound		-2.84	-7.69	-7.00	-4.27	-1.59	-3.67	-8.08	-4.57	
			SDD upper bound		10.81	13.31	5.72	4.89	3.03	2.86	5.10	3.92	
			$\bar{d}$		3.98	2.81	-0.64	0.31	0.72	-0.40	-1.49	-0.32	
			$\bar{d}$ lower bound		1.77	-0.59	-2.75	-1.23	0.10	-1.48	-3.49	-1.74	
			$\bar{d}$ upper bound		6.19	6.22	1.47	1.85	1.34	0.67	0.51	1.10	
			LA lower bound		-2.84	-7.69	-7.15	-4.43	-1.19	-3.72	-7.66	-4.71	
			LA upper bound		10.81	13.31	5.87	5.05	2.63	2.91	4.67	4.06	
			RMS (individual)		6.46		2.95		1.99				
			Fraction (individual)		1.00		1.00		1.00		2.99	2.69	
			RMS (mean)		6.09						1.00	1.00	
			Fraction (mean)		1.00								

Table A.3: (cont.) *Primary Variables - DVJ - LCMAS-2 - Min - 2nd Component - Knee Angle.*

Component Parameter Min 2nd Knee Angle	Comparison System	Inter-System: Vicon				Intra-System: Between Reps				Intra-System: Between Days		MCID
		Vicon (Markers)		Vicon		Vicon (Markers)		Vicon				
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2			
ICC		-1.199	0.404	0.759	0.615	0.897	0.914	0.496	0.883			
n		12	12	12	12	12	12	12	12			
SEM		2.67	2.78	1.00	1.39	0.83	1.18	1.74	1.53			
SDD		7.41	7.70	2.76	3.84	2.31	3.27	4.82	4.24			
SDD lower bound		-6.20	-7.37	-2.24	-4.59	-1.59	-3.67	-6.03	-4.57	6.35 to		
SDD upper bound		8.62	8.02	3.28	3.09	3.03	2.86	3.61	3.92	7.6		
$\bar{d}$		1.21	0.32	0.52	-0.75	0.72	-0.40	-1.21	-0.32	degrees		
$\bar{d}$ lower bound		-1.19	-2.17	-0.35	-1.95	0.10	-1.48	-2.63	-1.74			
$\bar{d}$ upper bound		3.61	2.82	1.39	0.45	1.34	0.67	0.21	1.10			
LA lower bound		-6.20	-7.37	-2.17	-4.46	-1.19	-3.72	-5.59	-4.71			
LA upper bound		8.62	8.02	3.20	2.95	2.63	2.91	3.17	4.06			
RMS (individual)		4.98		2.21		1.99						
Fraction (individual)		1.00		1.00		1.00						
RMS (mean)		4.77						1.91	2.69			
Fraction (mean)		1.00						1.00	1.00			

Table A.3: (cont.) *Primary Variables - DVJ - LCMAS-2 - Max - 2nd Component - Knee Angle.*

Component Parameter		Comparison System	Inter-System: Vicon (Markers)		Intra-System: Between Repts				Intra-System: Between Days		MCID	
			LCMAS-2 (Markers)		LCMAS-2 (Markers)		Vicon (Markers)		LCMAS-2 (Markers)			Vicon (Markers)
Max 2nd	Knee Angle Marker	Statistic	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2		
		ICC	0.710	0.930	12	12	0.250	0.966	0.882	0.910	0.692	0.968
		n	12	12	12	12	12	12	12	12	12	12
		SEM	2.94	1.75	3.96	0.92	1.89	1.24	3.02	1.19	3.31	6.2 to 8.72 degrees
		SDD	8.15	4.85	10.97	2.56	5.23	3.45	8.37	3.31	3.36	
		SDD lower bound	-4.71	-2.07	-8.55	-2.54	-4.56	-4.39	-9.07	-3.36	-0.05	
		SDD upper bound	11.59	7.64	13.40	2.58	5.89	2.50	7.67	3.26	-1.17	
		$\bar{d}$	3.44	2.79	2.43	0.02	0.67	-0.95	-0.70	-0.05	1.07	
		$\bar{d}$ lower bound	0.80	1.21	-0.92	-0.85	-1.05	-1.93	-3.50	-1.17	-3.51	
		$\bar{d}$ upper bound	6.08	4.36	5.77	0.89	2.38	0.04	2.09	1.07	3.41	
		LA lower bound	-4.71	-2.07	-7.90	-2.66	-4.62	-3.98	-9.32	-3.51		
		LA upper bound	11.59	7.64	12.75	2.69	5.95	2.09	7.92	3.41		
		RMS (individual)	4.54		2.95		2.21					
		Fraction (individual)	1.00		1.00		1.00					
		RMS (mean)	4.24									
		Fraction (mean)	1.00									
Component Parameter		Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID	
			LCMAS-2 (Markers)		LCMAS-2 (Markers)		Vicon		LCMAS-2 (Markers)			Vicon
Max 2nd	Knee Angle	Statistic	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2		
		ICC	0.440	0.852	12	12	0.250	0.966	0.948	0.968	0.692	0.950
		n	12	12	12	12	12	12	12	12	12	12
		SEM	4.40	3.25	3.96	0.92	1.55	1.28	3.02	2.15	2.15	6.2 to 8.72 degrees
		SDD	12.19	9.02	10.97	2.56	4.30	3.54	8.37	5.95	5.95	
		SDD lower bound	-5.50	-2.86	-8.55	-2.54	-4.21	-4.01	-9.07	-6.12	-6.12	
		SDD upper bound	18.88	15.18	13.40	2.58	4.39	3.06	7.67	5.78	5.78	
		$\bar{d}$	6.69	6.16	2.43	0.02	0.09	-0.47	-0.70	-0.17	-0.17	
		$\bar{d}$ lower bound	2.74	3.23	-0.92	-0.85	-1.37	-1.63	-3.50	-2.18	-2.18	
		$\bar{d}$ upper bound	10.64	9.08	5.77	0.89	1.54	0.68	2.09	1.84	1.84	
		LA lower bound	-5.50	-2.86	-7.90	-2.66	-4.40	-4.04	-9.32	-6.37	-6.37	
		LA upper bound	18.88	15.18	12.75	2.69	4.58	3.09	7.92	6.03	6.03	
		RMS (individual)	6.46		2.95		1.99					
		Fraction (individual)	1.00		1.00		1.00					
		RMS (mean)	6.09									
		Fraction (mean)	1.00									

Table A.3: (cont.) *Primary Variables - DVJ - LCMAS-2 - Max - 2nd Component - Knee Angle.*

Component Parameter	Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID
		Vicon (Markers)		Vicon (Markers)		Vicon (Markers)		Vicon (Markers)		
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
Max 2nd Knee Angle	ICC	0.750	0.660	0.882	0.910	0.948	0.968	0.968	0.950	
	n	12	12	12	12	12	12	12	12	
	SEM	3.75	4.29	1.89	1.24	1.55	1.28	1.19	2.15	
	SDD	10.39	11.88	5.23	3.45	4.30	3.54	3.31	5.95	6.2 to
	SDD lower bound	-7.14	-8.51	-4.56	-4.39	-4.21	-4.01	-3.36	-6.12	8.72
	SDD upper bound	13.64	15.25	5.89	2.50	4.39	3.06	3.26	5.78	degrees
	$\bar{d}$	3.25	3.37	0.67	-0.95	0.09	-0.47	-0.05	-0.17	
	$\bar{d}$ lower bound	-0.12	-0.48	-1.05	-1.93	-1.37	-1.63	-1.17	-2.18	
	$\bar{d}$ upper bound	6.62	7.22	2.38	0.04	1.54	0.68	1.07	1.84	
	LA lower bound	-7.14	-8.51	-4.62	-3.98	-4.40	-4.04	-3.51	-6.37	
	LA upper bound	13.64	15.25	5.95	2.09	4.58	3.09	3.41	6.03	
	RMS (individual)	4.98		2.21		1.99				
	Fraction (individual)	1.00		1.00		1.00				
	RMS (mean)	4.77						1.91	2.69	
	Fraction (mean)	1.00						1.00	1.00	

Table A.3: (cont.) *Primary Variables - DVJ - LCMAS-2 - Min - 2nd Component - Knee Moment.*

Component Parameter	Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID
		LCMAS-2 (Model)		LCMAS-2 (Model)		Vicon		LCMAS-2 (Model)		
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
Min 2nd Knee Moment PCS	ICC	0.957	0.833	0.677	0.830	0.877	0.913	0.571	0.951	
	n	7	7	4	4	12	12	5	12	
	SEM	6.47	10.78	9.80	10.55	7.25	6.64	15.31	6.38	
	SDD	17.93	29.87	27.15	29.23	20.09	18.42	42.44	17.68	
	SDD lower bound	-9.71	-15.72	-25.43	-25.29	-19.36	-18.10	-25.59	-15.87	26.9
	SDD upper bound	26.16	44.02	28.88	33.18	20.82	18.74	59.30	19.49	Nm
	$\bar{d}$	8.23	14.15	1.72	3.95	0.73	0.32	16.85	1.81	
	$\bar{d}$ lower bound	-0.24	0.05	-23.54	-22.48	-6.06	-5.91	-2.02	-4.05	
	$\bar{d}$ upper bound	16.69	28.24	26.98	30.37	7.51	6.55	35.73	7.68	
	LA lower bound	-9.71	-15.72	-29.39	-28.61	-20.20	-18.90	-12.94	-16.28	
	LA upper bound	26.16	44.02	32.83	36.50	21.66	19.55	46.65	19.90	
	RMS (individual)	30.17		23.82		8.34				
	Fraction (individual)	0.38		0.25		1.00				
	RMS (mean)	28.85						18.95	7.68	
	Fraction (mean)	0.58						0.42	1.00	

Table A.4: *Secondary Variables - DVJ - LCMAS-2 - ROM - 1st Component - COM Position.*

Component Parameter		Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID
			LCMAS-2 (Model)		LCMAS-2 (Model)		Vicon		LCMAS-2 (Model)		
ROM 1st	Position COM	Statistic	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
		ICC	0.904	0.905	0.598	0.813	0.776	0.478	0.225	0.777	
		n	12	12	12	12	12	12	12	12	
		SEM	0.004	0.004	0.009	0.006	0.005	0.008	0.010	0.005	
		SDD	0.010	0.012	0.024	0.016	0.014	0.023	0.028	0.015	
		SDD lower bound	-0.015	-0.011	-0.022	-0.016	-0.014	-0.019	-0.022	-0.015	
		SDD upper bound	0.006	0.014	0.027	0.016	0.014	0.027	0.034	0.015	
		$\bar{d}$	-0.005	0.002	0.002	0.000	0.000	0.004	0.006	0.000	
		$\bar{d}$ lower bound	-0.008	-0.002	-0.006	-0.005	-0.005	-0.004	-0.003	-0.005	
		$\bar{d}$ upper bound	-0.001	0.006	0.010	0.005	0.005	0.011	0.014	0.005	
		LA lower bound	-0.015	-0.011	-0.023	-0.016	-0.015	-0.019	-0.021	-0.016	
		LA upper bound	0.006	0.014	0.027	0.017	0.015	0.027	0.033	0.015	
		RMS (individual)	0.005		0.020		0.019				
		Fraction (individual)	1.000		1.000		1.000				
		RMS (mean)	0.003						0.024	0.023	
		Fraction (mean)	1.000						1.000	1.000	

Table A.4: (cont.) Secondary Variables - DVJ - LCMAS-2 - MKF - 2nd Component - Hip Angle.

Component Parameter		Comparison System	Inter-System: Vicon (Markers)		Intra-System: Between Repts				Intra-System: Between Days		MCID
			LCMAS-2 (Markers)		LCMAS-2 (Markers)		Vicon (Markers)		LCMAS-2 (Markers)		
MKF 2nd	Hip Angle Marker	Statistic	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
		ICC	0.622	0.609	0.962	0.985	0.901	0.970	0.995	0.940	6.3 degrees
		n	12	12	12	12	12	12	12	12	
		SEM	9.95	10.61	3.58	2.28	2.23	1.31	1.78	2.43	
		SDD	27.57	29.42	9.92	6.31	6.19	3.62	4.94	6.72	
		SDD lower bound	-28.66	-30.28	-8.78	-4.91	-6.44	-3.17	-5.57	-7.58	
		SDD upper bound	26.49	28.56	11.05	7.70	5.94	4.07	4.30	5.86	
		$\bar{d}$	-1.08	-0.86	1.14	1.39	-0.25	0.45	-0.63	-0.86	
		$\bar{d}$ lower bound	-10.02	-10.40	-2.14	-0.53	-2.34	-0.74	-2.25	-3.06	
		$\bar{d}$ upper bound	7.85	8.68	4.41	3.32	1.84	1.64	0.98	1.34	
		LA lower bound	-28.66	-30.28	-8.96	-4.54	-6.70	-3.22	-5.63	-7.66	
		LA upper bound	26.49	28.56	11.23	7.33	6.19	4.12	4.36	5.94	
		RMS (individual)	12.74		3.81		1.96				
		Fraction (individual)	1.00		1.00		1.00				
		RMS (mean)	12.62						3.50	2.67	
		Fraction (mean)	1.00						1.00	1.00	

Component Parameter		Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID
			LCMAS-2 (Markers)		LCMAS-2 (Markers)		Vicon		LCMAS-2 (Markers)		
MKF 2nd	Hip Angle	Statistic	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
		ICC	0.838	0.815	0.962	0.985	0.944	0.979	0.995	0.973	6.3 degrees
		n	12	12	12	12	12	12	12	12	
		SEM	7.53	8.26	3.58	2.28	2.35	1.42	1.78	2.22	
		SDD	20.89	22.89	9.92	6.31	6.50	3.94	4.94	6.15	
		SDD lower bound	-21.93	-23.35	-8.78	-4.91	-7.02	-3.45	-5.57	-7.36	
		SDD upper bound	19.84	22.42	11.05	7.70	5.99	4.42	4.30	4.93	
		$\bar{d}$	-1.05	-0.47	1.14	1.39	-0.52	0.49	-0.63	-1.22	
		$\bar{d}$ lower bound	-7.82	-7.89	-2.14	-0.53	-2.69	-0.81	-2.25	-3.14	
		$\bar{d}$ upper bound	5.72	6.95	4.41	3.32	1.66	1.78	0.98	0.70	
		LA lower bound	-21.93	-23.35	-8.96	-4.54	-7.23	-3.50	-5.63	-7.13	
		LA upper bound	19.84	22.42	11.23	7.33	6.20	4.48	4.36	4.70	
		RMS (individual)	9.40		3.81		2.08				
		Fraction (individual)	1.00		1.00		1.00				
		RMS (mean)	9.22						3.50	2.63	
		Fraction (mean)	1.00						1.00	1.00	

Table A.4: (cont.) *Secondary Variables - DVJ - LCMAS-2 - MKF - 2nd Component - Hip Angle.*

Component Parameter	Comparison System	Inter-System: Vicon		Intra-System: Between Reps				Intra-System: Between Days		MCID
		Vicon (Markers)		Vicon (Markers)		Vicon (Markers)		Vicon (Markers)		
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
MKF 2nd Hip Angle	ICC	0.940	0.951	0.901	0.970	0.944	0.979	0.940	0.973	6.3 degrees
	n	12	12	12	12	12	12	12	12	
	SEM	2.82	2.68	2.23	1.31	2.35	1.42	2.43	2.22	
	SDD	7.83	7.42	6.19	3.62	6.50	3.94	6.72	6.15	
	SDD lower bound	-7.79	-7.02	-6.44	-3.17	-7.02	-3.45	-7.58	-7.36	
	SDD upper bound	7.86	7.81	5.94	4.07	5.99	4.42	5.86	4.93	
	$\bar{d}$	0.03	0.39	-0.25	0.45	-0.52	0.49	-0.86	-1.22	
	$\bar{d}$ lower bound	-2.50	-2.01	-2.34	-0.74	-2.69	-0.81	-3.06	-3.14	
	$\bar{d}$ upper bound	2.57	2.80	1.84	1.64	1.66	1.78	1.34	0.70	
	LA lower bound	-7.79	-7.02	-6.70	-3.22	-7.23	-3.50	-7.66	-7.13	
	LA upper bound	7.86	7.81	6.19	4.12	6.20	4.48	5.94	4.70	
	RMS (individual)	3.63		1.96		2.08				
	Fraction (individual)	1.00		1.00		1.00				
	RMS (mean)	3.62						2.67	2.63	
	Fraction (mean)	1.00						1.00	1.00	

Table A.4: (cont.) *Secondary Variables - DVJ - LCMAS-2 - ROM - 2nd Component - Knee Angle.*

Component Parameter	ROM 2nd	Knee Angle Marker	Comparison System	Inter-System: Vicon (Markers)		Intra-System: Between Repts				Intra-System: Between Days		MCID	
				Statistic	LCMAS-2 (Markers)	LCMAS-2 (Markers)		Vicon (Markers)		LCMAS-2 (Markers)	Vicon (Markers)		
						Day 1	Day 2	Day 1	Day 2				
ROM 2nd	Knee Angle	Marker	ICC		0.781	0.809	0.288	0.774	0.896	0.881	0.765	0.944	8.0 degrees
			n		12	12	12	12	12	12	12	12	
			SEM		2.64	2.69	5.21	1.90	1.53	1.63	2.79	1.51	
			SDD		7.31	7.45	14.44	5.26	4.23	4.51	7.75	4.19	
			SDD lower bound		-6.64	-7.15	-11.37	-5.55	-4.08	-4.70	-6.95	-3.03	
			SDD upper bound		7.98	7.75	17.51	4.97	4.38	4.32	8.54	5.35	
			$\bar{d}$		0.67	0.30	3.07	-0.29	0.15	-0.19	0.79	1.16	
			$\bar{d}$ lower bound		-1.70	-2.12	-1.38	-2.06	-1.28	-1.71	-1.78	-0.03	
			$\bar{d}$ upper bound		3.04	2.71	7.51	1.48	1.58	1.33	3.36	2.35	
			LA lower bound		-6.64	-7.15	-10.65	-5.75	-4.26	-4.88	-7.14	-2.51	
			LA upper bound		7.98	7.75	16.78	5.17	4.56	4.50	8.72	4.84	
			RMS (individual)		4.54		2.95		2.21				
			Fraction (individual)		1.00		1.00		1.00		2.99	1.91	
			RMS (mean)		4.24						1.00	1.00	
			Fraction (mean)		1.00								
ROM 2nd	Knee Angle	Marker	ICC		0.435	0.819	0.288	0.774	0.912	0.971	0.765	0.961	8.0 degrees
			n		12	12	12	12	12	12	12	12	
			SEM		4.45	3.05	5.21	1.90	1.90	1.01	2.79	1.67	
			SDD		12.34	8.45	14.44	5.26	5.26	2.79	7.75	4.62	
			SDD lower bound		-9.63	-5.10	-11.37	-5.55	-5.89	-2.86	-6.95	-4.46	
			SDD upper bound		15.05	11.79	17.51	4.97	4.63	2.73	8.54	4.77	
			$\bar{d}$		2.71	3.34	3.07	-0.29	-0.63	-0.07	0.79	0.15	
			$\bar{d}$ lower bound		-1.29	0.61	-1.38	-2.06	-2.36	-1.01	-1.78	-1.41	
			$\bar{d}$ upper bound		6.71	6.08	7.51	1.48	1.10	0.88	3.36	1.71	
			LA lower bound		-9.63	-5.10	-10.65	-5.75	-5.97	-2.98	-7.14	-4.66	
			LA upper bound		15.05	11.79	16.78	5.17	4.71	2.85	8.72	4.97	
			RMS (individual)		6.46		2.95		1.99				
			Fraction (individual)		1.00		1.00		1.00		2.99	2.69	
			RMS (mean)		6.09						1.00	1.00	
			Fraction (mean)		1.00								

Table A.4: (cont.) *Secondary Variables - DVJ - LCMAS-2 - ROM - 2nd Component - Knee Angle.*

Component Parameter	Comparison System	Inter-System: Vicon		Intra-System: Between Reps				Intra-System: Between Days		MCID
		Vicon (Markers)		Vicon		Day 1	Day 2	Vicon (Markers)	Vicon	
		Day 1	Day 2	Day 1	Day 2					
ROM 2nd Knee Angle	ICC	0.858	0.882	0.896	0.881	0.912	0.971	0.944	0.961	
	n	12	12	12	12	12	12	12	12	
	SEM	2.70	2.47	1.53	1.63	1.90	1.01	1.51	1.67	
	SDD	7.47	6.85	4.23	4.51	5.26	2.79	4.19	4.62	
	SDD lower bound	-5.44	-3.81	-4.08	-4.70	-5.89	-2.86	-3.03	-4.46	8.0 degrees
	SDD upper bound	9.51	9.90	4.38	4.32	4.63	2.73	5.35	4.77	
	$\bar{d}$	2.04	3.05	0.15	-0.19	-0.63	-0.07	1.16	0.15	
	$\bar{d}$ lower bound	-0.38	0.82	-1.28	-1.71	-2.36	-1.01	-0.03	-1.41	
	$\bar{d}$ upper bound	4.46	5.27	1.58	1.33	1.10	0.88	2.35	1.71	
	LA lower bound	-5.44	-3.81	-4.26	-4.88	-5.97	-2.98	-2.51	-4.66	
	LA upper bound	9.51	9.90	4.56	4.50	4.71	2.85	4.84	4.97	
	RMS (individual)	4.98		2.21		1.99				
	Fraction (individual)	1.00		1.00		1.00				
	RMS (mean)	4.77						1.91	2.69	
	Fraction (mean)	1.00						1.00	1.00	

Table A.4: (cont.) *Secondary Variables - DVJ - LCMAS-2 - MKF - 2nd Component - Knee Angle.*

Component Parameter	Comparison System	Inter-System: Vicon (Markers)		Intra-System: Between Repts				Intra-System: Between Days		MCID	
		Statistic	LCMAS-2 (Markers)	LCMAS-2 (Markers)		Vicon (Markers)		LCMAS-2 (Markers)	Vicon (Markers)		
				Day 1	Day 2	Day 1	Day 2				
MKF 2nd Knee Angle Marker	ICC		0.539	0.695	0.106	0.854	0.847	0.944	0.814	0.971	4.5 to 5.1 degrees
	n		12	12	12	12	12	12	12	12	
	SEM		4.05	3.29	3.71	1.55	2.66	1.36	1.75	1.48	
	SDD		11.21	9.13	10.29	4.30	7.38	3.78	4.84	4.10	
	SDD lower bound		-10.80	-8.86	-10.12	-4.51	-6.26	-3.03	-4.78	-3.90	
	SDD upper bound		11.63	9.40	10.46	4.10	8.50	4.53	4.90	4.30	
	$\bar{d}$		0.41	0.27	0.17	-0.20	1.12	0.75	0.06	0.20	
	$\bar{d}$ lower bound		-3.22	-2.69	-3.31	-1.65	-1.27	-0.43	-1.58	-1.18	
	$\bar{d}$ upper bound		4.05	3.23	3.65	1.25	3.50	1.93	1.70	1.58	
	LA lower bound		-10.80	-8.86	-10.57	-4.68	-6.24	-2.90	-5.00	-4.07	
	LA upper bound		11.63	9.40	10.92	4.27	8.48	4.39	5.11	4.47	
	RMS (individual)		4.54		2.95		2.21				
	Fraction (individual)		1.00		1.00		1.00		2.99	1.91	
	RMS (mean)		4.24						1.00	1.00	
	Fraction (mean)		1.00								

Component Parameter	Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID	
		Statistic	LCMAS-2 (Markers)	LCMAS-2 (Markers)		Vicon		LCMAS-2 (Markers)	Vicon		
				Day 1	Day 2	Day 1	Day 2				
MKF 2nd Knee Angle	ICC		0.168	0.458	0.106	0.854	0.981	0.971	0.814	0.978	4.5 to 5.1 degrees
	n		12	12	12	12	12	12	12	12	
	SEM		7.09	6.84	3.71	1.55	1.42	1.80	1.75	2.20	
	SDD		19.64	18.96	10.29	4.30	3.92	5.00	4.84	6.10	
	SDD lower bound		-18.01	-18.57	-10.12	-4.51	-3.37	-4.37	-4.78	-4.80	
	SDD upper bound		21.27	19.35	10.46	4.10	4.48	5.63	4.90	7.39	
	$\bar{d}$		1.63	0.39	0.17	-0.20	0.55	0.63	0.06	1.29	
	$\bar{d}$ lower bound		-4.74	-5.76	-3.31	-1.65	-0.73	-1.01	-1.58	-0.58	
	$\bar{d}$ upper bound		7.99	6.54	3.65	1.25	1.83	2.27	1.70	3.17	
	LA lower bound		-18.01	-18.57	-10.57	-4.68	-3.39	-4.43	-5.00	-4.50	
	LA upper bound		21.27	19.35	10.92	4.27	4.49	5.69	5.11	7.09	
	RMS (individual)		6.46		2.95		1.99				
	Fraction (individual)		1.00		1.00		1.00		2.99	2.69	
	RMS (mean)		6.09						1.00	1.00	
	Fraction (mean)		1.00								

Table A.4: (cont.) *Secondary Variables - DVJ - LCMAS-2 - MKF - 2nd Component - Knee Angle.*

Component Parameter	Comparison System	Inter-System: Vicon		Intra-System: Between Reps				Intra-System: Between Days		MCID	
		Vicon (Markers)		Vicon (Markers)		Vicon (Markers)		Vicon (Markers)			
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2		
MKF 2nd	Knee Angle	ICC	0.834	0.775	0.847	0.944	0.981	0.971	0.971	0.978	
		n	12	12	12	12	12	12	12	12	
		SEM	4.55	5.37	2.66	1.36	1.42	1.80	1.48	2.20	
		SDD	12.61	14.90	7.38	3.78	3.92	5.00	4.10	6.10	4.5 to
		SDD lower bound	-11.40	-14.78	-6.26	-3.03	-3.37	-4.37	-3.90	-4.80	5.1
		SDD upper bound	13.83	15.01	8.50	4.53	4.48	5.63	4.30	7.39	degrees
		$\bar{d}$	1.21	0.12	1.12	0.75	0.55	0.63	0.20	1.29	
		$\bar{d}$ lower bound	-2.88	-4.71	-1.27	-0.43	-0.73	-1.01	-1.18	-0.58	
		$\bar{d}$ upper bound	5.30	4.95	3.50	1.93	1.83	2.27	1.58	3.17	
		LA lower bound	-11.40	-14.78	-6.24	-2.90	-3.39	-4.43	-4.07	-4.50	
		LA upper bound	13.83	15.01	8.48	4.39	4.49	5.69	4.47	7.09	
		RMS (individual)	4.98		2.21		1.99				
		Fraction (individual)	1.00		1.00		1.00				
		RMS (mean)	4.77						1.91	2.69	
		Fraction (mean)	1.00						1.00	1.00	

Table A.5: *Primary Variables - DLS - LCMAS-2 - ROM - 1st Component - Hip Angle.*

Component Parameter		Comparison System	Inter-System: Vicon (Markers)		Intra-System: Between Repts				Intra-System: Between Days		MCID
			LCMAS-2 (Markers)		LCMAS-2 (Markers)		Vicon (Markers)		LCMAS-2 (Markers)	Vicon (Markers)	
ROM 1st	Hip Angle Marker	Statistic	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
		ICC	0.896	0.869	0.898	0.892	0.878	0.869	0.933	0.966	
		n	12	12	12	12	12	12	12	12	
		SEM	15.79	14.75	12.31	10.23	10.62	10.61	12.99	7.77	
		SDD	43.77	40.88	34.12	28.36	29.45	29.41	36.02	21.53	31.6
		SDD lower bound	-59.96	-65.56	-28.14	-21.04	-30.41	-23.69	-41.32	-18.35	degrees
		SDD upper bound	27.58	16.20	40.10	35.68	28.48	35.13	30.71	24.72	
		$\bar{d}$	-16.19	-24.68	5.98	7.32	-0.97	5.72	-5.30	3.18	
		$\bar{d}$ lower bound	-30.38	-37.93	-4.87	-0.96	-10.92	-3.49	-16.98	-3.79	
		$\bar{d}$ upper bound	-2.00	-11.43	16.83	15.60	8.98	14.93	6.37	10.16	
		LA lower bound	-59.96	-65.56	-27.49	-18.23	-31.66	-22.68	-41.32	-18.34	
		LA upper bound	27.58	16.20	39.45	32.87	29.72	34.12	30.72	24.71	
		RMS (individual)	15.12		8.59		7.21				
		Fraction (individual)	1.00		1.00		1.00		10.23	7.27	
		RMS (mean)	14.53						1.00	1.00	
		Fraction (mean)	1.00								

Component Parameter		Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID
			LCMAS-2 (Markers)		LCMAS-2 (Markers)		Vicon		LCMAS-2 (Markers)	Vicon	
ROM 1st	Hip Angle	Statistic	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
		ICC	0.885	0.850	0.898	0.892	0.970	0.983	0.933	0.985	
		n	12	12	12	12	12	12	12	12	
		SEM	15.24	14.17	12.31	10.23	4.11	2.90	12.99	4.02	
		SDD	42.24	39.26	34.12	28.36	11.41	8.04	36.02	11.14	31.6
		SDD lower bound	-74.17	-78.74	-28.14	-21.04	-12.15	-9.28	-41.32	-8.90	degrees
		SDD upper bound	10.30	-0.21	40.10	35.68	10.66	6.79	30.71	13.37	
		$\bar{d}$	-31.94	-39.47	5.98	7.32	-0.74	-1.24	-5.30	2.24	
		$\bar{d}$ lower bound	-45.63	-52.20	-4.87	-0.96	-4.57	-3.84	-16.98	-1.23	
		$\bar{d}$ upper bound	-18.24	-26.75	16.83	15.60	3.09	1.35	6.37	5.70	
		LA lower bound	-74.17	-78.74	-27.49	-18.23	-12.56	-9.24	-41.32	-8.46	
		LA upper bound	10.30	-0.21	39.45	32.87	11.07	6.76	30.72	12.93	
		RMS (individual)	14.47		8.59		4.85				
		Fraction (individual)	1.00		1.00		1.00		10.23	6.10	
		RMS (mean)	13.92						1.00	1.00	
		Fraction (mean)	1.00								

Table A.5: (cont.) *Primary Variables - DLS - LCMAS-2 - ROM - 1st Component - Hip Angle.*

Component Parameter	ROM 1st Hip Angle	Comparison System	Inter-System: Vicon		Intra-System: Between Reps				Intra-System: Between Days		MCID
			Vicon (Markers)		Vicon (Markers)		Vicon (Markers)		Vicon (Markers)		
			Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
		ICC	0.939	0.968	0.878	0.869	0.970	0.983	0.966	0.985	
		n	12	12	12	12	12	12	12	12	
		SEM	9.60	6.49	10.62	10.61	4.11	2.90	7.77	4.02	
		SDD	26.60	17.98	29.45	29.41	11.41	8.04	21.53	11.14	
		SDD lower bound	-42.34	-32.78	-30.41	-23.69	-12.15	-9.28	-18.35	-8.90	31.6 degrees
		SDD upper bound	10.86	3.19	28.48	35.13	10.66	6.79	24.72	13.37	
		$\bar{d}$	-15.74	-14.80	-0.97	5.72	-0.74	-1.24	3.18	2.24	
		$\bar{d}$ lower bound	-24.37	-20.62	-10.92	-3.49	-4.57	-3.84	-3.79	-1.23	
		$\bar{d}$ upper bound	-7.12	-8.97	8.98	14.93	3.09	1.35	10.16	5.70	
		LA lower bound	-42.34	-32.78	-31.66	-22.68	-12.56	-9.24	-18.34	-8.46	
		LA upper bound	10.86	3.19	29.72	34.12	11.07	6.76	24.71	12.93	
		RMS (individual)	11.42		7.21		4.85				
		Fraction (individual)	1.00		1.00		1.00				
		RMS (mean)	11.12						7.27	6.10	
		Fraction (mean)	1.00						1.00	1.00	

Table A.5: (cont.) *Primary Variables - DLS - LCMAS-2 - IC - 2nd Component - Knee Angle.*

Component Parameter		Comparison System	Inter-System: Vicon (Markers)		Intra-System: Between Repts				Intra-System: Between Days		MCID	
			LCMAS-2 (Markers)		LCMAS-2 (Markers)		Vicon (Markers)		LCMAS-2 (Markers)	Vicon (Markers)		
IC 2nd	Knee Angle Marker	Statistic	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2		
Knee Angle		ICC	0.831	0.843	0.908	0.979	0.973	0.998	0.980	0.992		
		n	12	12	12	12	12	12	12	12	12	
		SEM	4.25	4.41	3.12	1.53	0.83	0.25	2.06	0.65		
		SDD	11.78	12.22	8.65	4.24	2.31	0.68	5.71	1.81		6.17 to
		SDD lower bound	-10.56	-11.47	-7.26	-3.56	-2.39	-0.69	-6.28	-1.89		8.4
		SDD upper bound	13.01	12.96	10.04	4.93	2.22	0.68	5.15	1.73		degrees
		$\bar{d}$	1.22	0.74	1.39	0.69	-0.08	0.00	-0.56	-0.08		
		$\bar{d}$ lower bound	-2.60	-3.22	-1.39	-0.68	-0.86	-0.24	-2.46	-0.69		
		$\bar{d}$ upper bound	5.04	4.70	4.17	2.05	0.69	0.23	1.34	0.53		
		LA lower bound	-10.56	-11.47	-7.18	-3.52	-2.49	-0.72	-6.42	-1.96		
		LA upper bound	13.01	12.96	9.97	4.89	2.32	0.71	5.29	1.80		
		RMS (individual)	4.22		1.89		1.35					
		Fraction (individual)	1.00		1.00		1.00					
		RMS (mean)	4.09						3.35	1.24		
		Fraction (mean)	1.00						1.00	1.00		
Component Parameter		Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID	
			LCMAS-2 (Markers)		LCMAS-2 (Markers)		Vicon		LCMAS-2 (Markers)	Vicon		
IC 2nd	Knee Angle	Statistic	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2		
Knee Angle		ICC	0.623	0.640	0.908	0.979	0.926	0.991	0.980	0.989		
		n	12	12	12	12	12	12	12	12	12	
		SEM	5.59	5.91	3.12	1.53	1.06	0.38	2.06	0.58		
		SDD	15.50	16.38	8.65	4.24	2.94	1.07	5.71	1.61		6.17 to
		SDD lower bound	-14.18	-15.76	-7.26	-3.56	-3.10	-1.16	-6.28	-1.48		8.4
		SDD upper bound	16.81	17.01	10.04	4.93	2.79	0.97	5.15	1.74		degrees
		$\bar{d}$	1.32	0.63	1.39	0.69	-0.15	-0.09	-0.56	0.13		
		$\bar{d}$ lower bound	-3.71	-4.69	-1.39	-0.68	-1.14	-0.45	-2.46	-0.41		
		$\bar{d}$ upper bound	6.34	5.94	4.17	2.05	0.84	0.26	1.34	0.67		
		LA lower bound	-14.18	-15.76	-7.18	-3.52	-3.21	-1.19	-6.42	-1.53		
		LA upper bound	16.81	17.01	9.97	4.89	2.91	1.01	5.29	1.79		
		RMS (individual)	8.65		1.89		1.56					
		Fraction (individual)	1.00		1.00		1.00					
		RMS (mean)	8.55						3.35	2.65		
		Fraction (mean)	1.00						1.00	1.00		

Table A.5: (cont.) *Primary Variables - DLS - LCMAS-2 - IC - 2nd Component - Knee Angle.*

Component Parameter	Comparison System	Inter-System: Vicon				Intra-System: Between Repts				Intra-System: Between Days		MCID
		Vicon (Markers)		Vicon		Vicon (Markers)		Vicon		Vicon (Markers)		
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
IC 2nd Knee Angle	Statistic	ICC	0.800	0.817	0.973	0.998	0.926	0.991	0.992	0.989		
	n		12	12	12	12	12	12	12	12		
	SEM		2.58	2.58	0.83	0.25	1.06	0.38	0.65	0.58		
	SDD		7.14	7.16	2.31	0.68	2.94	1.07	1.81	1.61	6.17 to	
	SDD lower bound		-7.04	-7.27	-2.39	-0.69	-3.10	-1.16	-1.89	-1.48	8.4	
	SDD upper bound		7.23	7.04	2.22	0.68	2.79	0.97	1.73	1.74	degrees	
	$\bar{d}$		0.09	-0.12	-0.08	0.00	-0.15	-0.09	-0.08	0.13		
	$\bar{d}$ lower bound		-2.22	-2.44	-0.86	-0.24	-1.14	-0.45	-0.69	-0.41		
	$\bar{d}$ upper bound		2.41	2.20	0.69	0.23	0.84	0.26	0.53	0.67		
	LA lower bound		-7.04	-7.27	-2.49	-0.72	-3.21	-1.19	-1.96	-1.53		
	LA upper bound		7.23	7.04	2.32	0.71	2.91	1.01	1.80	1.79		
	RMS (individual)		5.49		1.35		1.56					
	Fraction (individual)		1.00		1.00		1.00					
	RMS (mean)		5.43						1.24	2.65		
	Fraction (mean)		1.00						1.00	1.00		

Table A.5: (cont.) Primary Variables - DLS - LCMAS-2 - Min - 2nd Component - Knee Angle.

Component Parameter	Comparison System	Inter-System: Vicon (Markers)		Intra-System: Between Reps				Intra-System: Between Days		MCID	
		Statistic	LCMAS-2 (Markers)	(Markers)		(Markers)		Vicon (Markers)			
				Day 1	Day 2	Day 1	Day 2				
Min 2nd Knee Angle Marker	ICC		-0.042	0.694	0.767	0.509	0.950	0.990	0.181	0.966	6.35 to 7.6 degrees
	n		12	12	12	12	12	12	12	12	
	SEM		2.40	1.55	1.85	1.92	0.46	0.23	2.26	0.56	
	SDD		6.64	4.29	5.12	5.33	1.29	0.64	6.27	1.56	
	SDD lower bound		-0.69	1.41	-4.87	-5.07	-1.51	-0.60	-6.48	-1.53	
	SDD upper bound		12.60	9.99	5.38	5.59	1.07	0.68	6.06	1.60	
	$\bar{d}$		5.95	5.70	0.26	0.26	-0.22	0.04	-0.21	0.04	
	$\bar{d}$ lower bound		3.80	4.31	-1.47	-1.53	-0.63	-0.17	-2.33	-0.49	
	$\bar{d}$ upper bound		8.10	7.09	1.98	2.06	0.19	0.26	1.91	0.57	
	LA lower bound		-0.69	1.41	-5.07	-5.28	-1.49	-0.62	-6.75	-1.60	
	LA upper bound		12.60	9.99	5.58	5.80	1.05	0.71	6.33	1.67	
	RMS (individual)		4.22		1.89		1.35				
	Fraction (individual)		1.00		1.00		1.00		3.35	1.24	
	RMS (mean)		4.09						1.00	1.00	
	Fraction (mean)		1.00								
Min 2nd Knee Angle	ICC		-1.331	-0.390	0.767	0.509	0.980	0.972	0.181	0.989	6.35 to 7.6 degrees
	n		12	12	12	12	12	12	12	12	
	SEM		3.18	2.61	1.85	1.92	0.39	0.44	2.26	0.39	
	SDD		8.82	7.23	5.12	5.33	1.07	1.21	6.27	1.09	
	SDD lower bound		-0.91	0.17	-4.87	-5.07	-1.22	-1.38	-6.48	-0.79	
	SDD upper bound		16.73	14.63	5.38	5.59	0.93	1.03	6.06	1.40	
	$\bar{d}$		7.91	7.40	0.26	0.26	-0.14	-0.18	-0.21	0.30	
	$\bar{d}$ lower bound		5.05	5.05	-1.47	-1.53	-0.49	-0.57	-2.33	-0.01	
	$\bar{d}$ upper bound		10.77	9.74	1.98	2.06	0.21	0.21	1.91	0.61	
	LA lower bound		-0.91	0.17	-5.07	-5.28	-1.22	-1.38	-6.75	-0.66	
	LA upper bound		16.73	14.63	5.58	5.80	0.94	1.03	6.33	1.26	
	RMS (individual)		8.65		1.89		1.56				
	Fraction (individual)		1.00		1.00		1.00		3.35	2.65	
	RMS (mean)		8.55						1.00	1.00	
	Fraction (mean)		1.00								

Table A.5: (cont.) *Primary Variables - DLS - LCMAS-2 - Min - 2nd Component - Knee Angle.*

Component Parameter		Comparison System	Inter-System: Vicon		Intra-System: Between Reps				Intra-System: Between Days		MCID
			Vicon		Vicon		Vicon		Vicon		
			Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	(Markers)	(Markers)	
Min	2nd	ICC	0.446	0.329	0.950	0.990	0.980	0.972	0.966	0.989	
		n	12	12	12	12	12	12	12	12	
		SEM	2.04	2.23	0.46	0.23	0.39	0.44	0.56	0.39	
		SDD	5.65	6.18	1.29	0.64	1.07	1.21	1.56	1.09	6.35 to
		SDD lower bound	-3.69	-4.48	-1.51	-0.60	-1.22	-1.38	-1.53	-0.79	7.6
		SDD upper bound	7.61	7.87	1.07	0.68	0.93	1.03	1.60	1.40	degrees
		$\bar{d}$	1.96	1.69	-0.22	0.04	-0.14	-0.18	0.04	0.30	
		$\bar{d}$ lower bound	0.13	-0.31	-0.63	-0.17	-0.49	-0.57	-0.49	-0.01	
		$\bar{d}$ upper bound	3.79	3.70	0.19	0.26	0.21	0.21	0.57	0.61	
		LA lower bound	-3.69	-4.48	-1.49	-0.62	-1.22	-1.38	-1.60	-0.66	
		LA upper bound	7.61	7.87	1.05	0.71	0.94	1.03	1.67	1.26	
		RMS (individual)	5.49		1.35		1.56				
		Fraction (individual)	1.00		1.00		1.00				
		RMS (mean)	5.43						1.24	2.65	
		Fraction (mean)	1.00						1.00	1.00	

Table A.5: (cont.) Primary Variables - DLS - LCMAS-2 - Max - 2nd Component - Knee Angle.

Component Parameter	Comparison System	Inter-System: Vicon (Markers)		Intra-System: Between Repts				Intra-System: Between Days		MCID
		Statistic	LCMAS-2 (Markers)	LCMAS-2 (Markers)		Vicon (Markers)		LCMAS-2 (Markers)	Vicon (Markers)	
				Day 1	Day 2	Day 1	Day 2			
Max 2nd Knee Angle Marker	ICC		0.905	0.935	0.911	0.676	0.939	0.837	0.618	0.933
	n		12	12	12	12	12	12	12	12
	SEM		1.68	1.49	1.24	2.96	0.91	1.30	3.53	1.30
	SDD		4.65	4.14	3.44	8.20	2.53	3.60	9.79	3.60
	SDD lower bound		0.59	-0.89	-2.65	-9.46	-2.52	-4.15	-12.49	-4.31
	SDD upper bound		9.90	7.40	4.23	6.93	2.54	3.05	7.08	2.88
	$\bar{d}$		5.25	3.26	0.79	-1.27	0.01	-0.55	-2.71	-0.71
	$\bar{d}$ lower bound		3.74	1.91	-0.25	-3.91	-0.85	-1.71	-5.49	-1.84
	$\bar{d}$ upper bound		6.76	4.60	1.83	1.38	0.87	0.62	0.08	0.41
	LA lower bound		0.59	-0.89	-2.41	-9.43	-2.63	-4.14	-11.30	-4.17
	LA upper bound		9.90	7.40	4.00	6.89	2.66	3.04	5.89	2.75
	RMS (individual)			4.22		1.89		1.35		
	Fraction (individual)			1.00		1.00		1.00		
	RMS (mean)			4.09					3.35	1.24
	Fraction (mean)			1.00					1.00	1.00
Max 2nd Knee Angle	ICC		0.694	0.822	0.911	0.676	0.995	0.962	0.618	0.930
	n		12	12	12	12	12	12	12	12
	SEM		4.81	3.68	1.24	2.96	0.63	1.54	3.53	3.08
	SDD		13.34	10.21	3.44	8.20	1.75	4.28	9.79	8.54
	SDD lower bound		-0.66	-0.12	-2.65	-9.46	-1.61	-5.38	-12.49	-8.66
	SDD upper bound		26.02	20.30	4.23	6.93	1.89	3.17	7.08	8.42
	$\bar{d}$		12.68	10.09	0.79	-1.27	0.14	-1.10	-2.71	-0.12
	$\bar{d}$ lower bound		8.35	6.78	-0.25	-3.91	-0.45	-2.35	-5.49	-3.01
	$\bar{d}$ upper bound		17.00	13.40	1.83	1.38	0.73	0.15	0.08	2.77
	LA lower bound		-0.66	-0.12	-2.41	-9.43	-1.67	-4.96	-11.30	-9.03
	LA upper bound		26.02	20.30	4.00	6.89	1.95	2.75	5.89	8.79
	RMS (individual)			8.65		1.89		1.56		
	Fraction (individual)			1.00		1.00		1.00		
	RMS (mean)			8.55					3.35	2.65
	Fraction (mean)			1.00					1.00	1.00

Table A.5: (cont.) *Primary Variables - DLS - LCMAS-2 - Max - 2nd Component - Knee Angle.*

Component Parameter	Comparison System	Inter-System: Vicon		Intra-System: Between Reps		Intra-System: Between Days		MCID	
		Vicon (Markers)		Vicon (Markers)		Vicon (Markers)			
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2		
Max 2nd Knee Angle	ICC	0.768	0.773	0.939	0.837	0.995	0.962	0.933	0.930
	n	12	12	12	12	12	12	12	12
	SEM	4.25	3.77	0.91	1.30	0.63	1.54	1.30	3.08
	SDD	11.79	10.46	2.53	3.60	1.75	4.28	3.60	8.54
	SDD lower bound	-4.36	-3.62	-2.52	-4.15	-1.61	-5.38	-4.31	-8.66
	SDD upper bound	19.22	17.30	2.54	3.05	1.89	3.17	2.88	8.42
	$\bar{d}$	7.43	6.84	0.01	-0.55	0.14	-1.10	-0.71	-0.12
	$\bar{d}$ lower bound	3.61	3.45	-0.85	-1.71	-0.45	-2.35	-1.84	-3.01
	$\bar{d}$ upper bound	11.25	10.23	0.87	0.62	0.73	0.15	0.41	2.77
	LA lower bound	-4.36	-3.62	-2.63	-4.14	-1.67	-4.96	-4.17	-9.03
	LA upper bound	19.22	17.30	2.66	3.04	1.95	2.75	2.75	8.79
	RMS (individual)	5.49		1.35		1.56			
	Fraction (individual)	1.00		1.00		1.00			
	RMS (mean)	5.43						1.24	2.65
	Fraction (mean)	1.00						1.00	1.00

Table A.5: (cont.) *Primary Variables - DLS - LCMAS-2 - Min - 2nd Component - Knee Moment.*

Component Parameter	Comparison System	Inter-System: Vicon		Intra-System: Between Reps				Intra-System: Between Days		MCID
		LCMAS-2 (Model)		LCMAS-2 (Model)		Vicon		LCMAS-2 (Model)		
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
Min 2nd Knee Moment PCS	ICC	0.872	0.799	0.965	0.866	0.988	0.941	0.981	0.961	
	n	4	3	2	2	12	12	3	12	
	SEM	15.22	25.77	3.38	6.68	2.51	5.28	9.77	6.32	
	SDD	42.20	71.43	9.36	18.53	6.95	14.65	27.09	17.52	26.9
	SDD lower bound	-35.17	-51.48	-7.41	-27.53	-5.47	-8.31	-24.31	-16.81	Nm
	SDD upper bound	49.22	91.39	11.31	9.53	8.43	20.98	29.87	18.22	
	$\bar{d}$	7.02	19.95	1.95	-9.00	1.48	6.34	2.78	0.70	
	$\bar{d}$ lower bound	-27.23	-70.59	-53.47	-45.64	-0.66	3.71	-38.41	-5.21	
	$\bar{d}$ upper bound	41.28	110.49	57.37	27.64	3.62	8.97	43.97	6.62	
	LA lower bound	-35.17	-51.48	-10.14	-17.00	-5.12	-1.78	-29.72	-17.53	
	LA upper bound	49.22	91.39	14.04	-1.01	8.08	14.45	35.28	18.94	
	RMS (individual)	51.22		10.75		4.24				
	Fraction (individual)	0.18		0.08		1.00				
	RMS (mean)	66.25						20.32	4.95	
	Fraction (mean)	0.29						0.25	1.00	

Table A.6: *Secondary Variables - DLS - LCMAS-2 - ROM - 1st Component - COM Position.*

Component Parameter	ROM 1st	Position COM	Comparison System	Inter-System: Vicon				Intra-System: Between Reps				Intra-System: Between Days				MCID				
				LCMAS-2 (Model)				Vicon				LCMAS-2 (Model)					Vicon			
				Day 1		Day 2		Day 1		Day 2		Day 1		Day 2			Day 1		Day 2	
ICC				0.888	0.830	12	12	0.589	0.233	0.143	0.587	0.866	0.654							
n								12	12	12	12		12	12						
SEM				0.003	0.004			0.006	0.012	0.007	0.004	0.004	0.003							
SDD				0.008	0.011			0.015	0.032	0.018	0.010	0.012	0.009							
SDD lower bound				-0.013	-0.014			-0.011	-0.036	-0.013	-0.010	-0.010	-0.010							
SDD upper bound				0.003	0.009			0.020	0.028	0.024	0.011	0.014	0.008							
$\bar{d}$				-0.005	-0.002			0.004	-0.004	0.005	0.001	0.002	-0.001							
$\bar{d}$ lower bound				-0.008	-0.006			0.000	-0.014	0.000	-0.003	-0.002	-0.004							
$\bar{d}$ upper bound				-0.003	0.001			0.009	0.007	0.010	0.004	0.006	0.002							
LA lower bound				-0.013	-0.014			-0.009	-0.036	-0.010	-0.010	-0.009	-0.010							
LA upper bound				0.003	0.009			0.018	0.028	0.021	0.012	0.013	0.009							
RMS (individual)				0.004				0.008		0.007										
Fraction (individual)				1.000				1.000		1.000										
RMS (mean)				0.002								0.018	0.018							
Fraction (mean)				1.000								1.000	1.000							

Table A.6: (cont.) Secondary Variables - DLS - LCMAS-2 - MKF - 2nd Component - Hip Angle.

Component Parameter MKF 2nd Hip Angle Marker	Comparison System	Inter-System: Vicon (Markers)		Intra-System: Between Repts				Intra-System: Between Days		MCID
		LCMAS-2 (Markers)		LCMAS-2 (Markers)		Vicon (Markers)		LCMAS-2 (Markers)		
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
ICC		0.862	0.866	0.996	0.994	0.996	0.976	0.989	0.975	
n		12	12	12	12	12	12	12	12	
SEM		10.12	10.64	1.66	2.13	0.82	2.22	3.87	3.10	
SDD		28.05	29.50	4.59	5.90	2.29	6.17	10.74	8.60	6.3
SDD lower bound		-28.99	-28.47	-4.31	-7.68	-1.89	-6.37	-11.25	-11.09	degrees
SDD upper bound		27.11	30.54	4.87	4.13	2.68	5.97	10.23	6.12	
$\bar{d}$		-0.94	1.03	0.28	-1.78	0.40	-0.20	-0.51	-2.48	
$\bar{d}$ lower bound		-10.03	-8.53	-1.26	-3.39	-0.33	-2.29	-4.13	-4.88	
$\bar{d}$ upper bound		8.15	10.60	1.82	-0.16	1.13	1.88	3.11	-0.08	
LA lower bound		-28.99	-28.47	-4.48	-6.76	-1.84	-6.63	-11.68	-9.89	
LA upper bound		27.11	30.54	5.04	3.20	2.64	6.23	10.66	4.93	
RMS (individual)		13.48		2.30		1.41				
Fraction (individual)		1.00		1.00		1.00				
RMS (mean)		13.43						3.58	2.98	
Fraction (mean)		1.00						1.00	1.00	

Component Parameter MKF 2nd Hip Angle	Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID
		LCMAS-2 (Markers)		LCMAS-2 (Markers)		Vicon		LCMAS-2 (Markers)		
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
ICC		0.931	0.927	0.996	0.994	0.997	0.981	0.989	0.987	
n		12	12	12	12	12	12	12	12	
SEM		7.81	8.43	1.66	2.13	0.96	2.35	3.87	2.80	
SDD		21.65	23.37	4.59	5.90	2.65	6.50	10.74	7.77	6.3
SDD lower bound		-22.49	-21.91	-4.31	-7.68	-2.19	-6.74	-11.25	-10.57	degrees
SDD upper bound		20.82	24.83	4.87	4.13	3.11	6.27	10.23	4.97	
$\bar{d}$		-0.84	1.46	0.28	-1.78	0.46	-0.24	-0.51	-2.80	
$\bar{d}$ lower bound		-7.85	-6.12	-1.26	-3.39	-0.38	-2.43	-4.13	-4.66	
$\bar{d}$ upper bound		6.18	9.03	1.82	-0.16	1.30	1.96	3.11	-0.94	
LA lower bound		-22.49	-21.91	-4.48	-6.76	-2.14	-7.01	-11.68	-8.54	
LA upper bound		20.82	24.83	5.04	3.20	3.06	6.54	10.66	2.94	
RMS (individual)		9.94		2.30		1.54				
Fraction (individual)		1.00		1.00		1.00				
RMS (mean)		9.88						3.58	2.64	
Fraction (mean)		1.00						1.00	1.00	

Table A.6: (cont.) *Secondary Variables - DLS - LCMAS-2 - MKF - 2nd Component - Hip Angle.*

Component Parameter	Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID
		Vicon (Markers)		Vicon (Markers)		Vicon (Markers)		Vicon (Markers)		
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
		Statistic								
MKF 2nd Hip Angle	ICC	0.984	0.988	0.984	0.976	0.997	0.981	0.975	0.987	
	n	12	12	12	12	12	12	12	12	
	SEM	2.79	2.44	0.82	2.22	0.96	2.35	3.10	2.80	
	SDD	7.73	6.75	2.29	6.17	2.65	6.50	8.60	7.77	
	SDD lower bound	-7.62	-6.33	-1.89	-6.37	-2.19	-6.74	-11.09	-10.57	6.3 degrees
	SDD upper bound	7.83	7.17	2.68	5.97	3.11	6.27	6.12	4.97	
	$\bar{d}$	0.10	0.42	0.40	-0.20	0.46	-0.24	-2.48	-2.80	
	$\bar{d}$ lower bound	-2.40	-1.76	-0.33	-2.29	-0.38	-2.43	-4.88	-4.66	
	$\bar{d}$ upper bound	2.61	2.61	1.13	1.88	1.30	1.96	-0.08	-0.94	
	LA lower bound	-7.62	-6.33	-1.84	-6.63	-2.14	-7.01	-9.89	-8.54	
	LA upper bound	7.83	7.17	2.64	6.23	3.06	6.54	4.93	2.94	
	RMS (individual)	3.68		1.41		1.54				
	Fraction (individual)	1.00		1.00		1.00				
	RMS (mean)	3.68						2.98	2.64	
	Fraction (mean)	1.00						1.00	1.00	

Table A.6: (cont.) Secondary Variables - DLS - LCMAS-2 - ROM - 2nd Component - Knee Angle.

Component Parameter	ROM 2nd Knee Angle Marker	Comparison System	Inter-System: Vicon (Markers)		Intra-System: Between Repts				Intra-System: Between Days		MCID
			LCMAS-2 (Markers)		LCMAS-2 (Markers)		Vicon (Markers)		LCMAS-2 (Markers)		
			Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
ICC		ICC	0.817	0.830	0.780	0.502	0.919	0.838	0.755	0.905	
n		n	12	12	12	12	12	12	12	12	
SEM		SEM	2.31	2.62	2.25	4.79	0.97	1.30	3.45	1.43	
SDD		SDD	6.39	7.26	6.24	13.27	2.69	3.60	9.56	3.97	8.0
SDD lower bound		SDD lower bound	-7.10	-9.71	-5.70	-14.80	-2.46	-4.19	-12.06	-4.72	degrees
SDD upper bound		SDD upper bound	5.69	4.82	6.78	11.74	2.92	3.01	7.07	3.22	
$\bar{d}$		$\bar{d}$	-0.70	-2.45	0.54	-1.53	0.23	-0.59	-2.49	-0.75	
$\bar{d}$ lower bound		$\bar{d}$ lower bound	-2.77	-4.80	-1.55	-5.91	-0.67	-1.75	-5.28	-2.00	
$\bar{d}$ upper bound		$\bar{d}$ upper bound	1.37	-0.09	2.62	2.85	1.13	0.56	0.29	0.50	
LA lower bound		LA lower bound	-7.10	-9.71	-5.89	-15.03	-2.53	-4.15	-11.08	-4.60	
LA upper bound		LA upper bound	5.69	4.82	6.96	11.98	3.00	2.97	6.09	3.10	
RMS (individual)		RMS (individual)	4.22		1.89		1.35				
Fraction (individual)		Fraction (individual)	1.00		1.00		1.00		3.35	1.24	
RMS (mean)		RMS (mean)	4.09						1.00	1.00	
Fraction (mean)		Fraction (mean)	1.00								

Component Parameter	ROM 2nd Knee Angle	Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID
			LCMAS-2 (Markers)		LCMAS-2 (Markers)		Vicon		LCMAS-2 (Markers)		
			Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
ICC		ICC	0.870	0.831	0.780	0.502	0.987	0.947	0.755	0.891	
n		n	12	12	12	12	12	12	12	12	
SEM		SEM	2.96	3.40	2.25	4.79	0.83	1.49	3.45	3.08	
SDD		SDD	8.19	9.42	6.24	13.27	2.31	4.13	9.56	8.53	8.0
SDD lower bound		SDD lower bound	-3.42	-6.73	-5.70	-14.80	-2.02	-5.05	-12.06	-8.96	degrees
SDD upper bound		SDD upper bound	12.96	12.12	6.78	11.74	2.59	3.21	7.07	8.11	
$\bar{d}$		$\bar{d}$	4.77	2.70	0.54	-1.53	0.28	-0.92	-2.49	-0.42	
$\bar{d}$ lower bound		$\bar{d}$ lower bound	2.11	-0.36	-1.55	-5.91	-0.47	-2.18	-5.28	-3.30	
$\bar{d}$ upper bound		$\bar{d}$ upper bound	7.42	5.75	2.62	2.85	1.04	0.34	0.29	2.45	
LA lower bound		LA lower bound	-3.42	-6.73	-5.89	-15.03	-2.05	-4.80	-11.08	-9.29	
LA upper bound		LA upper bound	12.96	12.12	6.96	11.98	2.62	2.96	6.09	8.45	
RMS (individual)		RMS (individual)	8.65		1.89		1.56				
Fraction (individual)		Fraction (individual)	1.00		1.00		1.00		3.35	2.65	
RMS (mean)		RMS (mean)	8.55						1.00	1.00	
Fraction (mean)		Fraction (mean)	1.00								

Table A.6: (cont.) *Secondary Variables - DLS - LCMAS-2 - ROM - 2nd Component - Knee Angle.*

Component Parameter	Comparison System	Inter-System: Vicon		Intra-System: Between Reps				Intra-System: Between Days		MCID
		Vicon (Markers)		Vicon (Markers)		Vicon (Markers)		Vicon (Markers)		
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
ROM 2nd Knee Angle	ICC	0.609	0.739	0.919	0.838	0.987	0.947	0.905	0.891	
	n	12	12	12	12	12	12	12	12	
	SEM	4.33	3.36	0.97	1.30	0.83	1.49	1.43	3.08	
	SDD	12.01	9.31	2.69	3.60	2.31	4.13	3.97	8.53	
	SDD lower bound	-6.54	-4.16	-2.46	-4.19	-2.02	-5.05	-4.72	-8.96	8.0 degrees
	SDD upper bound	17.48	14.45	2.92	3.01	2.59	3.21	3.22	8.11	
	$\bar{d}$	5.47	5.14	0.23	-0.59	0.28	-0.92	-0.75	-0.42	
	$\bar{d}$ lower bound	1.58	2.13	-0.67	-1.75	-0.47	-2.18	-2.00	-3.30	
	$\bar{d}$ upper bound	9.36	8.16	1.13	0.56	1.04	0.34	0.50	2.45	
	LA lower bound	-6.54	-4.16	-2.53	-4.15	-2.05	-4.80	-4.60	-9.29	
	LA upper bound	17.48	14.45	3.00	2.97	2.62	2.96	3.10	8.45	
	RMS (individual)	5.49		1.35		1.56				
	Fraction (individual)	1.00		1.00		1.00				
	RMS (mean)	5.43						1.24	2.65	
	Fraction (mean)	1.00						1.00	1.00	

Table A.6: (cont.) Secondary Variables - DLS - LCMAS-2 - MKF - 2nd Component - Knee Angle.

Component Parameter	Comparison System	Inter-System: Vicon (Markers)		Intra-System: Between Repts				Intra-System: Between Days		MCID
		Statistic	LCMAS-2 (Markers)	(Markers)		(Markers)		Vicon (Markers)		
				Day 1	Day 2	Day 1	Day 2			
MKF 2nd Knee Angle Marker	ICC		0.170	0.781	0.779	0.711	0.975	0.946	0.437	0.979
	n		12	12	12	12	12	12	12	12
	SEM		5.51	3.42	2.84	2.56	0.93	1.48	4.26	1.27
	SDD		15.27	9.48	7.87	7.11	2.57	4.10	11.80	3.53
	SDD lower bound		-16.62	-9.73	-9.82	-8.36	-2.87	-4.46	-11.23	-4.06
	SDD upper bound		13.93	9.23	5.92	5.85	2.27	3.73	12.37	3.01
	$\bar{d}$		-1.34	-0.25	-1.95	-1.25	-0.30	-0.37	0.57	-0.53
	$\bar{d}$ lower bound		-6.29	-3.32	-4.28	-3.51	-1.15	-1.73	-3.41	-1.67
	$\bar{d}$ upper bound		3.61	2.83	0.37	1.00	0.55	1.00	4.55	0.62
	LA lower bound		-16.62	-9.73	-9.14	-8.22	-2.91	-4.58	-11.70	-4.06
	LA upper bound		13.93	9.23	5.23	5.71	2.31	3.85	12.84	3.00
	RMS (individual)		4.22		1.89		1.35			
	Fraction (individual)		1.00		1.00		1.00		3.35	1.24
RMS (mean)		4.09						1.00	1.00	
Fraction (mean)		1.00								
Component Parameter	Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID
		Statistic	LCMAS-2 (Markers)	(Markers)		(Markers)		Vicon		
				Day 1	Day 2	Day 1	Day 2			
MKF 2nd Knee Angle	ICC		-0.053	0.518	0.779	0.711	0.998	0.993	0.437	0.982
	n		12	12	12	12	12	12	12	12
	SEM		11.52	8.98	2.84	2.56	0.62	1.24	4.26	2.83
	SDD		31.93	24.89	7.87	7.11	1.73	3.43	11.80	7.84
	SDD lower bound		-31.96	-25.50	-9.82	-8.36	-1.49	-3.73	-11.23	-6.68
	SDD upper bound		31.91	24.28	5.92	5.85	1.97	3.13	12.37	8.99
	$\bar{d}$		-0.03	-0.61	-1.95	-1.25	0.24	-0.30	0.57	1.15
	$\bar{d}$ lower bound		-10.38	-8.68	-4.28	-3.51	-0.32	-1.44	-3.41	-1.39
	$\bar{d}$ upper bound		10.32	7.46	0.37	1.00	0.80	0.84	4.55	3.69
	LA lower bound		-31.96	-25.50	-9.14	-8.22	-1.50	-3.83	-11.70	-6.68
	LA upper bound		31.91	24.28	5.23	5.71	1.98	3.23	12.84	8.99
	RMS (individual)		8.65		1.89		1.56			
	Fraction (individual)		1.00		1.00		1.00		3.35	2.65
RMS (mean)		8.55						1.00	1.00	
Fraction (mean)		1.00								

Table A.6: (cont.) *Secondary Variables - DLS - LCMAS-2 - MKF - 2nd Component - Knee Angle.*

Component Parameter		Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID
			(Markers)		Vicon		(Markers)		Vicon		
MKF 2nd	Knee Angle	Statistic	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
		ICC	0.792	0.833	0.975	0.946	0.998	0.993	0.979	0.982	
		n	12	12	12	12	12	12	12	12	
		SEM	6.77	6.21	0.93	1.48	0.62	1.24	1.27	2.83	
		SDD	18.78	17.21	2.57	4.10	1.73	3.43	3.53	7.84	
		SDD lower bound	-17.46	-17.58	-2.87	-4.46	-1.49	-3.73	-4.06	-6.68	4.5 to
		SDD upper bound	20.09	16.85	2.27	3.73	1.97	3.13	3.01	8.99	5.1
		$\bar{d}$	1.32	-0.36	-0.30	-0.37	0.24	-0.30	-0.53	1.15	degrees
		$\bar{d}$ lower bound	-4.77	-5.94	-1.15	-1.73	-0.32	-1.44	-1.67	-1.39	
		$\bar{d}$ upper bound	7.40	5.22	0.55	1.00	0.80	0.84	0.62	3.69	
		LA lower bound	-17.46	-17.58	-2.91	-4.58	-1.50	-3.83	-4.06	-6.68	
		LA upper bound	20.09	16.85	2.31	3.85	1.98	3.23	3.00	8.99	
		RMS (individual)	5.49		1.35		1.56				
		Fraction (individual)	1.00		1.00		1.00				
		RMS (mean)	5.43						1.24	2.65	
		Fraction (mean)	1.00						1.00	1.00	

Table A.7: Secondary Variables - SLS - LCMAS-2 - ROM - 1st Component - Hip Angle.

Component Parameter	ROM 1st Hip Angle Marker	Comparison System	Inter-System: Vicon (Markers)		Intra-System: Between Repts				Intra-System: Between Days		MCID
			LCMAS-2 (Markers)		LCMAS-2 (Markers)		Vicon (Markers)		LCMAS-2 (Markers)		
			Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
ICC			0.743	0.904	0.845	0.848	0.664	0.806	0.968	0.819	
n			12	12	12	12	12	12	12	12	
SEM			15.09	10.79	10.95	11.60	10.94	10.75	7.07	11.33	
SDD			41.83	29.91	30.35	32.16	30.33	29.79	19.58	31.41	31.6
SDD lower bound			-54.55	-51.83	-33.04	-31.44	-27.91	-24.97	-24.25	-26.88	degrees
SDD upper bound			29.11	7.98	27.67	32.88	32.75	34.61	14.91	35.95	
$\bar{d}$			-12.72	-21.92	-2.69	0.72	2.42	4.82	-4.67	4.53	
$\bar{d}$ lower bound			-26.28	-31.62	-12.81	-10.16	-7.72	-4.75	-10.53	-5.67	
$\bar{d}$ upper bound			0.84	-12.23	7.43	11.60	12.56	14.39	1.19	14.74	
LA lower bound			-54.55	-51.83	-33.91	-32.84	-28.87	-24.69	-22.75	-26.94	
LA upper bound			29.11	7.98	28.54	34.27	33.71	34.33	13.42	36.00	
RMS (individual)			12.80		6.33		5.73				
Fraction (individual)			1.00		1.00		1.00		9.74	8.98	
RMS (mean)			12.09						1.00	1.00	
Fraction (mean)			1.00								

Component Parameter	ROM 1st Hip Angle	Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID
			LCMAS-2 (Markers)		LCMAS-2 (Markers)		Vicon		LCMAS-2 (Markers)		
			Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
ICC			0.917	0.907	0.845	0.848	0.933	0.966	0.968	0.990	
n			12	12	12	12	12	12	12	12	
SEM			9.59	10.33	10.95	11.60	5.38	3.65	7.07	2.90	
SDD			26.59	28.64	30.35	32.16	14.90	10.11	19.58	8.03	31.6
SDD lower bound			-41.72	-48.30	-33.04	-31.44	-17.44	-9.51	-24.25	-8.17	degrees
SDD upper bound			11.46	8.98	27.67	32.88	12.36	10.71	14.91	7.88	
$\bar{d}$			-15.13	-19.66	-2.69	0.72	-2.54	0.60	-4.67	-0.14	
$\bar{d}$ lower bound			-23.75	-28.94	-12.81	-10.16	-7.30	-2.80	-10.53	-2.86	
$\bar{d}$ upper bound			-6.51	-10.37	7.43	11.60	2.21	4.00	1.19	2.57	
LA lower bound			-41.72	-48.30	-33.91	-32.84	-17.21	-9.89	-22.75	-8.52	
LA upper bound			11.46	8.98	28.54	34.27	12.12	11.09	13.42	8.24	
RMS (individual)			7.71		6.33		4.36				
Fraction (individual)			1.00		1.00		1.00		9.74	6.10	
RMS (mean)			7.15						1.00	1.00	
Fraction (mean)			1.00								

Table A.7: (cont.) Secondary Variables - SLS - LCMAS-2 - ROM - 1st Component - Hip Angle.

Component Parameter	ROM 1st Hip Angle	Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID
			Vicon		Vicon		Vicon		Vicon		
			(Markers)		(Markers)		(Markers)		(Markers)		
			Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
		ICC	0.884	0.979	0.664	0.806	0.933	0.966	0.819	0.990	
		n	12	12	12	12	12	12	12	12	
		SEM	9.17	4.27	10.94	10.75	5.38	3.65	11.33	2.90	
		SDD	25.40	11.84	30.33	29.79	14.90	10.11	31.41	8.03	
		SDD lower bound	-27.82	-9.57	-27.91	-24.97	-17.44	-9.51	-26.88	-8.17	31.6
		SDD upper bound	22.99	14.10	32.75	34.61	12.36	10.71	35.95	7.88	degrees
		$\bar{d}$	-2.41	2.27	2.42	4.82	-2.54	0.60	4.53	-0.14	
		$\bar{d}$ lower bound	-10.65	-1.57	-7.72	-4.75	-7.30	-2.80	-5.67	-2.86	
		$\bar{d}$ upper bound	5.82	6.10	12.56	14.39	2.21	4.00	14.74	2.57	
		LA lower bound	-27.82	-9.57	-28.87	-24.69	-17.21	-9.89	-26.94	-8.52	
		LA upper bound	22.99	14.10	33.71	34.33	12.12	11.09	36.00	8.24	
		RMS (individual)	8.49		5.73		4.36				
		Fraction (individual)	1.00		1.00		1.00				
		RMS (mean)	8.07						8.98	6.10	
		Fraction (mean)	1.00						1.00	1.00	

Table A.7: (cont.) Secondary Variables - SLS - LCMAS-2 - IC - 2nd Component - Hip Angle.

Component Parameter IC 2nd Hip Angle Marker	Comparison System Statistic	Inter-System: Vicon (Markers)		Intra-System: Between Repts				Intra-System: Between Days		MCID
		LCMAS-2 (Markers)		LCMAS-2 (Markers)		Vicon (Markers)		LCMAS-2 (Markers)	Vicon (Markers)	
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2			
ICC	ICC	-5.003	-3.861	0.925	0.788	0.949	0.925	0.968	0.967	
n	n	12	12	12	12	12	12	12	12	
SEM	SEM	10.13	9.94	1.95	3.05	2.03	2.50	1.61	2.24	
SDD	SDD	28.08	27.56	5.41	8.46	5.63	6.92	4.47	6.21	9.41 to
SDD lower bound	SDD lower bound	-28.36	-28.30	-5.58	-8.96	-4.89	-7.78	-5.23	-6.50	11.14
SDD upper bound	SDD upper bound	27.81	26.82	5.23	7.95	6.37	6.06	3.71	5.92	degrees
$\bar{d}$	$\bar{d}$	-0.27	-0.74	-0.17	-0.50	0.74	-0.86	-0.76	-0.29	
$\bar{d}$ lower bound	$\bar{d}$ lower bound	-9.38	-9.68	-2.00	-3.35	-1.11	-3.13	-2.19	-2.38	
$\bar{d}$ upper bound	$\bar{d}$ upper bound	8.83	8.19	1.66	2.34	2.58	1.41	0.67	1.80	
LA lower bound	LA lower bound	-28.36	-28.30	-5.81	-9.28	-4.95	-7.87	-5.16	-6.75	
LA upper bound	LA upper bound	27.81	26.82	5.46	8.27	6.42	6.15	3.64	6.17	
RMS (individual)	RMS (individual)	10.88		3.42		2.39				
Fraction (individual)	Fraction (individual)	1.00		1.00		1.00		2.27	2.68	
RMS (mean)	RMS (mean)	10.75						1.00	1.00	
Fraction (mean)	Fraction (mean)	1.00								

Component Parameter IC 2nd Hip Angle	Comparison System Statistic	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID
		LCMAS-2 (Markers)		LCMAS-2 (Markers)		Vicon		LCMAS-2 (Markers)	Vicon	
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2			
ICC	ICC	-2.242	-1.764	0.925	0.788	0.804	0.826	0.968	0.954	
n	n	12	12	12	12	12	12	12	12	
SEM	SEM	7.37	7.32	1.95	3.05	2.51	2.48	1.61	1.65	
SDD	SDD	20.44	20.28	5.41	8.46	6.96	6.89	4.47	4.57	9.41 to
SDD lower bound	SDD lower bound	-20.97	-20.20	-5.58	-8.96	-6.30	-8.17	-5.23	-5.94	11.14
SDD upper bound	SDD upper bound	19.91	20.36	5.23	7.95	7.62	5.60	3.71	3.20	degrees
$\bar{d}$	$\bar{d}$	-0.53	0.08	-0.17	-0.50	0.66	-1.28	-0.76	-1.37	
$\bar{d}$ lower bound	$\bar{d}$ lower bound	-7.16	-6.49	-2.00	-3.35	-1.66	-3.45	-2.19	-2.62	
$\bar{d}$ upper bound	$\bar{d}$ upper bound	6.09	6.65	1.66	2.34	2.98	0.89	0.67	-0.12	
LA lower bound	LA lower bound	-20.97	-20.20	-5.81	-9.28	-6.48	-7.98	-5.16	-5.24	
LA upper bound	LA upper bound	19.91	20.36	5.46	8.27	7.81	5.42	3.64	2.50	
RMS (individual)	RMS (individual)	7.80		3.42		2.69				
Fraction (individual)	Fraction (individual)	1.00		1.00		1.00		2.27	2.30	
RMS (mean)	RMS (mean)	7.62						1.00	1.00	
Fraction (mean)	Fraction (mean)	1.00								

Table A.7: (cont.) *Secondary Variables - SLS - LCMAS-2 - IC - 2nd Component - Hip Angle.*

Component Parameter IC 2nd Hip Angle	Comparison System	Inter-System: Vicon		Intra-System: Between Reps				Intra-System: Between Days		MCID
		Vicon (Markers)		Vicon (Markers)		Vicon (Markers)		Vicon (Markers)		
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
ICC	Statistic	0.897	0.909	0.949	0.925	0.804	0.826	0.967	0.954	
n		12	12	12	12	12	12	12	12	
SEM		3.15	3.04	2.03	2.50	2.51	2.48	2.24	1.65	
SDD		8.74	8.42	5.63	6.92	6.96	6.89	6.21	4.57	9.41 to
SDD lower bound		-9.00	-7.60	-4.89	-7.78	-6.30	-8.17	-6.50	-5.94	11.14
SDD upper bound		8.48	9.24	6.37	6.06	7.62	5.60	5.92	3.20	degrees
$\bar{d}$		-0.26	0.82	0.74	-0.86	0.66	-1.28	-0.29	-1.37	
$\bar{d}$ lower bound		-3.09	-1.91	-1.11	-3.13	-1.66	-3.45	-2.38	-2.62	
$\bar{d}$ upper bound		2.58	3.55	2.58	1.41	2.98	0.89	1.80	-0.12	
LA lower bound		-9.00	-7.60	-4.95	-7.87	-6.48	-7.98	-6.75	-5.24	
LA upper bound		8.48	9.24	6.42	6.15	7.81	5.42	6.17	2.50	
RMS (individual)		3.44		2.39		2.69				
Fraction (individual)		1.00		1.00		1.00				
RMS (mean)		3.42						2.68	2.30	
Fraction (mean)		1.00						1.00	1.00	

Table A.7: (cont.) Secondary Variables - SLS - LCMAS-2 - IC - 2nd Component - Knee Angle.

Component Parameter IC 2nd	Knee Angle Marker	Comparison System Statistic	Inter-System: Vicon (Markers)		Intra-System: Between Repts				Intra-System: Between Days		MCID
			LCMAS-2 (Markers)		LCMAS-2 (Markers)		Vicon (Markers)		LCMAS-2 (Markers)	Vicon (Markers)	
			Day 1	Day 2	Day 1	Day 2	Day 1	Day 2			
		ICC	0.955	0.945	0.972	0.977	0.998	0.998	0.994	0.999	
		n	12	12	12	12	12	12	12	12	
		SEM	2.81	3.09	1.27	1.11	0.53	0.54	0.83	0.49	
		SDD	7.79	8.56	3.53	3.07	1.48	1.49	2.31	1.37	6.17 to
		SDD lower bound	-7.61	-8.47	-3.85	-4.18	-1.58	-1.79	-2.39	-1.36	8.4
		SDD upper bound	7.97	8.65	3.21	1.97	1.37	1.19	2.23	1.38	degrees
		$\bar{d}$	0.18	0.09	-0.32	-1.10	-0.11	-0.30	-0.08	0.01	
		$\bar{d}$ lower bound	-2.35	-2.69	-1.50	-1.84	-0.60	-0.77	-0.86	-0.45	
		$\bar{d}$ upper bound	2.70	2.86	0.86	-0.36	0.39	0.16	0.70	0.47	
		LA lower bound	-7.61	-8.47	-3.95	-3.39	-1.63	-1.73	-2.49	-1.42	
		LA upper bound	7.97	8.65	3.31	1.18	1.42	1.13	2.33	1.44	
		RMS (individual)	3.77		1.48		1.57				
		Fraction (individual)	1.00		1.00		1.00		1.71	1.41	
		RMS (mean)	3.67						1.00	1.00	
		Fraction (mean)	1.00								

Component Parameter IC 2nd	Knee Angle	Comparison System Statistic	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID
			LCMAS-2 (Markers)		LCMAS-2 (Markers)		Vicon		LCMAS-2 (Markers)	Vicon	
			Day 1	Day 2	Day 1	Day 2	Day 1	Day 2			
		ICC	-0.007	-0.073	0.972	0.977	0.936	0.945	0.994	0.970	
		n	12	12	12	12	12	12	12	12	
		SEM	5.52	5.50	1.27	1.11	0.55	0.54	0.83	0.54	
		SDD	15.31	15.24	3.53	3.07	1.52	1.50	2.31	1.49	6.17 to
		SDD lower bound	-14.81	-14.91	-3.85	-4.18	-1.34	-1.45	-2.39	-1.38	8.4
		SDD upper bound	15.81	15.56	3.21	1.97	1.70	1.55	2.23	1.59	degrees
		$\bar{d}$	0.50	0.32	-0.32	-1.10	0.18	0.05	-0.08	0.10	
		$\bar{d}$ lower bound	-4.46	-4.62	-1.50	-1.84	-0.32	-0.45	-0.86	-0.40	
		$\bar{d}$ upper bound	5.47	5.26	0.86	-0.36	0.68	0.56	0.70	0.60	
		LA lower bound	-14.81	-14.91	-3.95	-3.39	-1.37	-1.51	-2.49	-1.44	
		LA upper bound	15.81	15.56	3.31	1.18	1.72	1.61	2.33	1.64	
		RMS (individual)	5.90		1.48		1.70				
		Fraction (individual)	1.00		1.00		1.00		1.71	2.36	
		RMS (mean)	5.75						1.00	1.00	
		Fraction (mean)	1.00								

Table A.7: (cont.) Secondary Variables - SLS - LCMAS-2 - IC - 2nd Component - Knee Angle.

Component Parameter IC 2nd Knee Angle	Comparison System	Inter-System: Vicon		Intra-System: Between Reps		Intra-System: Between Days		MCID	
		Vicon (Markers)		Vicon		Vicon (Markers)			
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2		
ICC	Statistic	0.029	-0.053	0.998	0.998	0.936	0.945	0.999	0.970
n		12	12	12	12	12	12	12	12
SEM		8.01	8.35	0.53	0.54	0.55	0.54	0.49	0.54
SDD		22.21	23.15	1.48	1.49	1.52	1.50	1.37	1.49
SDD lower bound		-21.88	-22.91	-1.58	-1.79	-1.34	-1.45	-1.36	-1.38
SDD upper bound		22.53	23.39	1.37	1.19	1.70	1.55	1.38	1.59
$\bar{d}$		0.33	0.24	-0.11	-0.30	0.18	0.05	0.01	0.10
$\bar{d}$ lower bound		-6.87	-7.27	-0.60	-0.77	-0.32	-0.45	-0.45	-0.40
$\bar{d}$ upper bound		7.52	7.74	0.39	0.16	0.68	0.56	0.47	0.60
LA lower bound		-21.88	-22.91	-1.63	-1.73	-1.37	-1.51	-1.42	-1.44
LA upper bound		22.53	23.39	1.42	1.13	1.72	1.61	1.44	1.64
RMS (individual)		8.59		1.57		1.70			
Fraction (individual)		1.00		1.00		1.00			
RMS (mean)		8.51						1.41	2.36
Fraction (mean)		1.00						1.00	1.00

Table A.8: Primary Variables - SLS - LCMAS-2 - ROM - 1st Component - COM Position.

Component Parameter	ROM 1st	Position COM	Comparison System	Inter-System: Vicon				Intra-System: Between Repts				Intra-System: Between Days				MCID
				LCMAS-2		Vicon		LCMAS-2		Vicon		LCMAS-2		Vicon		
				Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	(Model)		(Model)		
			ICC	0.952	0.863	0.068	0.663	0.477	0.068	0.005	0.213	12	0.0404 m			
			n	12	12	12	12	11	12	12	12					
			SEM	0.003	0.003	0.009	0.004	0.005	0.005	0.005	0.008	0.007				
			SDD	0.007	0.008	0.026	0.012	0.014	0.014	0.022	0.019					
			SDD lower bound	-0.009	-0.010	-0.032	-0.012	-0.014	-0.013	-0.018	-0.015					
			SDD upper bound	0.006	0.006	0.020	0.012	0.013	0.015	0.026	0.024					
			$\bar{d}$	-0.002	-0.002	-0.006	0.000	-0.001	0.001	0.004	0.005					
			$\bar{d}$ lower bound	-0.004	-0.005	-0.014	-0.004	-0.005	-0.004	-0.003	-0.001					
			$\bar{d}$ upper bound	0.001	0.001	0.002	0.004	0.004	0.006	0.011	0.010					
			LA lower bound	-0.009	-0.010	-0.030	-0.013	-0.015	-0.013	-0.018	-0.013					
			LA upper bound	0.006	0.006	0.018	0.013	0.014	0.015	0.026	0.022					
			RMS (individual)	0.004		0.007		0.007								
			Fraction (individual)	0.972		1.000		0.958								
			RMS (mean)	0.004						0.027	0.026					
			Fraction (mean)	1.000						1.000	1.000					

Component Parameter	ROM 2nd	Position COM	Comparison System	Inter-System: Vicon				Intra-System: Between Repts				Intra-System: Between Days				MCID
				LCMAS-2		Vicon		LCMAS-2		Vicon		LCMAS-2		Vicon		
				Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	(Model)		(Model)		
			ICC	0.837	0.879	0.512	0.479	0.594	0.314	-0.071	0.475	12	0.0404 m			
			n	12	12	12	12	11	12	12	12					
			SEM	0.006	0.004	0.010	0.011	0.007	0.012	0.011	0.009					
			SDD	0.018	0.012	0.027	0.032	0.020	0.032	0.031	0.025					
			SDD lower bound	-0.022	-0.011	-0.026	-0.033	-0.020	-0.029	-0.026	-0.026					
			SDD upper bound	0.013	0.014	0.029	0.031	0.021	0.036	0.036	0.023					
			$\bar{d}$	-0.005	0.002	0.001	-0.001	0.000	0.004	0.005	-0.001					
			$\bar{d}$ lower bound	-0.010	-0.002	-0.008	-0.012	-0.007	-0.007	-0.005	-0.010					
			$\bar{d}$ upper bound	0.001	0.006	0.010	0.009	0.008	0.015	0.015	0.007					
			LA lower bound	-0.022	-0.011	-0.027	-0.034	-0.021	-0.029	-0.026	-0.027					
			LA upper bound	0.013	0.014	0.030	0.032	0.022	0.037	0.036	0.024					
			RMS (individual)	0.007		0.013		0.013								
			Fraction (individual)	0.972		1.000		0.958								
			RMS (mean)	0.007						0.030	0.030					
			Fraction (mean)	1.000						1.000	1.000					

Table A.8: (cont.) *Primary Variables - SLS - LCMAS-2 - ROM - 2nd Component - COM relative to BOS Position.*

Component Parameter ROM 1st	Position COM relative to BOS	Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID
			LCMAS-2		LCMAS-2		Vicon		LCMAS-2		
			Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	(Model)	(Model)	
ICC			0.948	0.872	0.396	0.087	0.197	0.044	-0.336	-0.464	
n			12	12	12	12	11	12	12	12	
SEM			0.003	0.002	0.003	0.005	0.004	0.004	0.007	0.008	
SDD			0.008	0.005	0.010	0.015	0.011	0.012	0.019	0.022	
SDD lower bound			-0.013	-0.009	-0.010	-0.011	-0.011	-0.009	-0.016	-0.020	
SDD upper bound			0.003	0.000	0.009	0.019	0.010	0.015	0.021	0.024	
$\bar{d}$			-0.005	-0.005	-0.001	0.004	0.000	0.003	0.002	0.002	
$\bar{d}$ lower bound			-0.007	-0.006	-0.004	-0.001	-0.004	0.000	-0.004	-0.005	
$\bar{d}$ upper bound			-0.002	-0.003	0.003	0.008	0.004	0.006	0.009	0.009	
LA lower bound			-0.013	-0.009	-0.011	-0.010	-0.012	-0.007	-0.017	-0.020	
LA upper bound			0.003	0.000	0.009	0.018	0.011	0.014	0.021	0.025	
RMS (individual)			0.004		0.010		0.008				
Fraction (individual)			0.972		1.000		0.958		0.008	0.006	
RMS (mean)			0.003						1.000	1.000	
Fraction (mean)			1.000								

Component Parameter ROM 2nd	Position COM relative to BOS	Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID
			LCMAS-2		LCMAS-2		Vicon		LCMAS-2		
			Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	(Model)	(Model)	
ICC			0.763	0.878	0.492	0.557	0.655	0.361	0.810	0.686	
n			12	12	12	12	11	12	12	12	
SEM			0.012	0.005	0.011	0.009	0.010	0.009	0.008	0.011	
SDD			0.033	0.012	0.031	0.024	0.028	0.024	0.022	0.031	
SDD lower bound			-0.037	-0.017	-0.032	-0.019	-0.025	-0.020	-0.026	-0.035	
SDD upper bound			0.028	0.008	0.030	0.028	0.030	0.028	0.017	0.027	
$\bar{d}$			-0.005	-0.005	-0.001	0.004	0.003	0.004	-0.004	-0.004	
$\bar{d}$ lower bound			-0.015	-0.009	-0.011	-0.003	-0.007	-0.003	-0.011	-0.014	
$\bar{d}$ upper bound			0.006	-0.001	0.010	0.012	0.012	0.012	0.002	0.006	
LA lower bound			-0.037	-0.017	-0.033	-0.019	-0.026	-0.019	-0.025	-0.036	
LA upper bound			0.028	0.008	0.031	0.027	0.031	0.028	0.016	0.027	
RMS (individual)			0.007		0.014		0.012				
Fraction (individual)			0.972		1.000		0.958		0.014	0.013	
RMS (mean)			0.007						1.000	1.000	
Fraction (mean)			1.000								

Table A.8: (cont.) *Primary Variables - SLS - LCMAS-2 - MKF - 2nd Component - Hip Angle.*

Component Parameter	Comparison System	Inter-System: Vicon (Markers)		Intra-System: Between Reps				Intra-System: Between Days		MCID
		LCMAS-2 (Markers)		LCMAS-2 (Markers)		Vicon (Markers)		LCMAS-2 (Markers)		
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
MKF 2nd Hip Angle Marker	ICC	0.318	0.533	0.483	0.862	0.988	0.991	0.866	0.986	6.3 degrees
	n	12	12	12	12	12	12	12	12	
	SEM	9.63	8.57	2.65	1.74	1.60	1.38	2.03	2.42	
	SDD	26.69	23.76	7.36	4.83	4.43	3.82	5.62	6.71	
	SDD lower bound	-27.09	-24.33	-8.92	-5.74	-5.07	-3.76	-6.44	-7.36	
	SDD upper bound	26.29	23.19	5.80	3.92	3.79	3.89	4.80	6.05	
	$\bar{d}$	-0.40	-0.57	-1.56	-0.91	-0.64	0.07	-0.82	-0.65	
	$\bar{d}$ lower bound	-9.05	-8.27	-3.83	-2.43	-2.08	-1.23	-2.65	-2.88	
	$\bar{d}$ upper bound	8.25	7.13	0.71	0.61	0.79	1.36	1.00	1.58	
	LA lower bound	-27.09	-24.33	-8.55	-5.60	-5.08	-3.92	-6.45	-7.53	
	LA upper bound	26.29	23.19	5.43	3.77	3.79	4.06	4.80	6.22	
	RMS (individual)	10.88		3.42		2.39				
	Fraction (individual)	1.00		1.00		1.00		2.27	2.68	
	RMS (mean)	10.75						1.00	1.00	
	Fraction (mean)	1.00								

Component Parameter	Comparison System	Inter-System: Vicon		Intra-System: Between Reps				Intra-System: Between Days		MCID
		LCMAS-2 (Markers)		LCMAS-2 (Markers)		Vicon		LCMAS-2 (Markers)		
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
MKF 2nd Hip Angle	ICC	0.480	0.611	0.483	0.862	0.982	0.986	0.866	0.988	6.3 degrees
	n	12	12	12	12	12	12	12	12	
	SEM	7.57	7.18	2.65	1.74	1.66	1.50	2.03	1.90	
	SDD	21.00	19.91	7.36	4.83	4.59	4.17	5.62	5.28	
	SDD lower bound	-21.30	-19.67	-8.92	-5.74	-5.13	-4.20	-6.44	-6.65	
	SDD upper bound	20.69	20.15	5.80	3.92	4.05	4.14	4.80	3.90	
	$\bar{d}$	-0.31	0.24	-1.56	-0.91	-0.54	-0.03	-0.82	-1.37	
	$\bar{d}$ lower bound	-7.11	-6.21	-3.83	-2.43	-2.05	-1.44	-2.65	-2.91	
	$\bar{d}$ upper bound	6.50	6.70	0.71	0.61	0.97	1.38	1.00	0.16	
	LA lower bound	-21.30	-19.67	-8.55	-5.60	-5.20	-4.38	-6.45	-6.11	
	LA upper bound	20.69	20.15	5.43	3.77	4.12	4.32	4.80	3.37	
	RMS (individual)	7.80		3.42		2.69				
	Fraction (individual)	1.00		1.00		1.00		2.27	2.30	
	RMS (mean)	7.62						1.00	1.00	
	Fraction (mean)	1.00								

Table A.8: (cont.) *Primary Variables - SLS - LCMAS-2 - MKF - 2nd Component - Hip Angle.*

Component Parameter	Comparison System	Inter-System: Vicon		Intra-System: Between Reps		Intra-System: Between Days		MCID
		Vicon (Markers)		Vicon (Markers)		Vicon (Markers)		
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
MKF 2nd Hip Angle	ICC	0.977	0.982	0.988	0.991	0.982	0.986	0.988
	n	12	12	12	12	12	12	12
	SEM	2.85	2.54	1.60	1.38	1.66	1.50	1.90
	SDD	7.90	7.05	4.43	3.82	4.59	4.17	5.28
	SDD lower bound	-7.81	-6.23	-5.07	-3.76	-5.13	-4.20	-6.65
	SDD upper bound	8.00	7.86	3.79	3.89	4.05	4.14	3.90
	$\bar{d}$	0.09	0.81	-0.64	0.07	-0.54	-0.03	-1.37
	$\bar{d}$ lower bound	-2.47	-1.47	-2.08	-1.23	-2.05	-1.44	-2.91
	$\bar{d}$ upper bound	2.65	3.10	0.79	1.36	0.97	1.38	0.16
	LA lower bound	-7.81	-6.23	-5.08	-3.92	-5.20	-4.38	-6.11
	LA upper bound	8.00	7.86	3.79	4.06	4.12	4.32	3.37
	RMS (individual)	3.44		2.39		2.69		
	Fraction (individual)	1.00		1.00		1.00		
	RMS (mean)	3.42					2.68	2.30
	Fraction (mean)	1.00					1.00	1.00

Table A.8: (cont.) *Primary Variables - SLS - LCMAS-2 - ROM - 2nd Component - Knee Angle.*

Component Parameter		Comparison System	Inter-System: Vicon (Markers)		Intra-System: Between Repts				Intra-System: Between Days		MCID
			LCMAS-2 (Markers)		LCMAS-2 (Markers)		Vicon (Markers)		LCMAS-2 (Markers)	Vicon (Markers)	
ROM 2nd	Knee Angle Marker	Statistic	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
		ICC	0.615	0.506	0.710	0.760	0.672	0.900	0.362	0.923	
		n	12	12	12	12	12	12	12	12	
		SEM	1.49	1.62	0.77	0.84	1.43	0.69	1.29	0.91	
		SDD	4.13	4.50	2.13	2.32	3.96	1.91	3.58	2.52	8.0 degrees
		SDD lower bound	-2.56	-3.48	-2.42	-2.74	-4.52	-1.56	-3.75	-2.15	
		SDD upper bound	5.71	5.53	1.84	1.91	3.39	2.27	3.40	2.90	
		$\bar{d}$	1.57	1.02	-0.29	-0.42	-0.57	0.36	-0.18	0.38	
		$\bar{d}$ lower bound	0.23	-0.44	-0.98	-1.15	-1.85	-0.25	-1.38	-0.44	
		$\bar{d}$ upper bound	2.91	2.48	0.41	0.32	0.72	0.96	1.03	1.19	
		LA lower bound	-2.56	-3.48	-2.44	-2.69	-4.54	-1.51	-3.89	-2.15	
		LA upper bound	5.71	5.53	1.86	1.85	3.41	2.22	3.54	2.90	
		RMS (individual)	3.77		1.48		1.57				
		Fraction (individual)	1.00		1.00		1.00		1.71	1.41	
		RMS (mean)	3.67						1.00	1.00	
		Fraction (mean)	1.00								

Component Parameter		Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID
			LCMAS-2 (Markers)		LCMAS-2 (Markers)		Vicon		LCMAS-2 (Markers)	Vicon	
ROM 2nd	Knee Angle	Statistic	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
		ICC	0.352	0.468	0.710	0.760	0.880	0.951	0.362	0.925	
		n	12	12	12	12	12	12	12	12	
		SEM	3.34	3.30	0.77	0.84	1.74	1.23	1.29	1.96	
		SDD	9.25	9.15	2.13	2.32	4.82	3.40	3.58	5.44	8.0 degrees
		SDD lower bound	-2.50	-2.40	-2.42	-2.74	-4.45	-3.27	-3.75	-5.61	
		SDD upper bound	16.01	15.89	1.84	1.91	5.18	3.52	3.40	5.27	
		$\bar{d}$	6.75	6.74	-0.29	-0.42	0.37	0.13	-0.18	-0.17	
		$\bar{d}$ lower bound	3.75	3.78	-0.98	-1.15	-1.25	-1.02	-1.38	-2.01	
		$\bar{d}$ upper bound	9.75	9.71	0.41	0.32	1.98	1.27	1.03	1.67	
		LA lower bound	-2.50	-2.40	-2.44	-2.69	-4.61	-3.41	-3.89	-5.84	
		LA upper bound	16.01	15.89	1.86	1.85	5.34	3.66	3.54	5.50	
		RMS (individual)	5.90		1.48		1.70				
		Fraction (individual)	1.00		1.00		1.00		1.71	2.36	
		RMS (mean)	5.75						1.00	1.00	
		Fraction (mean)	1.00								

Table A.8: (cont.) *Primary Variables - SLS - LCMAS-2 - ROM - 2nd Component - Knee Angle.*

Component Parameter	Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID
		Vicon (Markers)		Vicon (Markers)		Vicon		Vicon (Markers)	Vicon	
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2			
ROM 2nd Knee Angle	ICC	Statistic	0.342	0.223	0.672	0.900	0.880	0.951	0.923	0.925
	n		12	12	12	12	12	12	12	12
	SEM		3.56	3.91	1.43	0.69	1.74	1.23	0.91	1.96
	SDD		9.87	10.83	3.96	1.91	4.82	3.40	2.52	5.44
	SDD lower bound		-4.69	-5.11	-4.52	-1.56	-4.45	-3.27	-2.15	-5.61
	SDD upper bound		15.04	16.55	3.39	2.27	5.18	3.52	2.90	5.27
	$\bar{d}$		5.18	5.72	-0.57	0.36	0.37	0.13	0.38	-0.17
	$\bar{d}$ lower bound		1.98	2.21	-1.85	-0.25	-1.25	-1.02	-0.44	-2.01
	$\bar{d}$ upper bound		8.38	9.23	0.72	0.96	1.98	1.27	1.19	1.67
	LA lower bound		-4.69	-5.11	-4.54	-1.51	-4.61	-3.41	-2.15	-5.84
	LA upper bound		15.04	16.55	3.41	2.22	5.34	3.66	2.90	5.50
	RMS (individual)		8.59		1.57		1.70			
	Fraction (individual)		1.00		1.00		1.00			
	RMS (mean)		8.51						1.41	2.36
	Fraction (mean)		1.00						1.00	1.00

Table A.8: (cont.) *Primary Variables - SLS - LCMAS-2 - MKF - 2nd Component - Knee Angle.*

Component Parameter	Comparison System	Inter-System: Vicon (Markers)				Intra-System: Between Repts				Intra-System: Between Days		MCID
		Statistic	LCMAS-2 (Markers)		Day 2	Day 1	LCMAS-2 (Markers)		Day 2	Day 1	Vicon (Markers)	
			Day 1	Day 2			Day 1	Day 2				
MKF 2nd Knee Angle Marker	ICC		0.929	0.957		0.967	0.980	0.982	0.988	0.978	0.989	
	n		12	12		12	12	12	12	12	12	
	SEM		3.15	2.56		1.17	1.15	1.47	1.17	1.48	1.51	
	SDD		8.73	7.10		3.24	3.18	4.08	3.24	4.10	4.17	
	SDD lower bound		-8.59	-6.81		-2.36	-2.84	-3.75	-3.12	-4.49	-4.71	4.5 to
	SDD upper bound		8.86	7.39		4.12	3.51	4.41	3.36	3.71	3.64	5.1
	$\bar{d}$		0.14	0.29		0.88	0.33	0.33	0.12	-0.39	-0.54	degrees
	$\bar{d}$ lower bound		-2.69	-2.01		-0.05	-0.72	-1.03	-0.97	-1.75	-1.90	
	$\bar{d}$ upper bound		2.97	2.59		1.81	1.39	1.69	1.21	0.98	0.83	
	LA lower bound		-8.59	-6.81		-1.98	-2.91	-3.88	-3.25	-4.59	-4.76	
	LA upper bound		8.86	7.39		3.74	3.58	4.53	3.49	3.82	3.68	
	RMS (individual)		3.77			1.48		1.57				
	Fraction (individual)		1.00			1.00		1.00		1.71	1.41	
	RMS (mean)		3.67							1.00	1.00	
	Fraction (mean)		1.00									

Component Parameter	Comparison System	Inter-System: Vicon				Intra-System: Between Repts				Intra-System: Between Days		MCID
		Statistic	LCMAS-2 (Markers)		Day 2	Day 1	LCMAS-2 (Markers)		Day 2	Day 1	Vicon	
			Day 1	Day 2			Day 1	Day 2				
MKF 2nd Knee Angle	ICC		0.909	0.902		0.967	0.980	0.967	0.991	0.978	0.956	
	n		12	12		12	12	12	12	12	12	
	SEM		3.22	3.75		1.17	1.15	1.77	0.98	1.48	2.78	
	SDD		8.93	10.38		3.24	3.18	4.90	2.71	4.10	7.71	
	SDD lower bound		-6.63	-10.25		-2.36	-2.84	-5.47	-2.82	-4.49	-5.93	4.5 to
	SDD upper bound		11.22	10.51		4.12	3.51	4.33	2.59	3.71	9.48	5.1
	$\bar{d}$		2.29	0.13		0.88	0.33	-0.57	-0.11	-0.39	1.78	degrees
	$\bar{d}$ lower bound		-0.60	-3.24		-0.05	-0.72	-2.18	-1.03	-1.75	-0.55	
	$\bar{d}$ upper bound		5.19	3.50		1.81	1.39	1.05	0.80	0.98	4.10	
	LA lower bound		-6.63	-10.25		-1.98	-2.91	-5.55	-2.93	-4.59	-5.40	
	LA upper bound		11.22	10.51		3.74	3.58	4.41	2.70	3.82	8.96	
	RMS (individual)		5.90			1.48		1.70				
	Fraction (individual)		1.00			1.00		1.00		1.71	2.36	
	RMS (mean)		5.75							1.00	1.00	
	Fraction (mean)		1.00									

Table A.8: (cont.) *Primary Variables - SLS - LCMAS-2 - MKF - 2nd Component - Knee Angle.*

Component Parameter	Comparison System	Inter-System: Vicon		Intra-System: Between Repts				Intra-System: Between Days		MCID
		Vicon (Markers)		Vicon (Markers)		Vicon (Markers)		Vicon (Markers)		
		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	
MKF 2nd Knee Angle	ICC	0.915	0.875	0.982	0.988	0.967	0.991	0.989	0.956	
	n	12	12	12	12	12	12	12	12	
	SEM	3.86	4.72	1.47	1.17	1.77	0.98	1.51	2.78	
	SDD	10.69	13.09	4.08	3.24	4.90	2.71	4.17	7.71	4.5 to
	SDD lower bound	-8.54	-13.25	-3.75	-3.12	-5.47	-2.82	-4.71	-5.93	5.1
	SDD upper bound	12.85	12.93	4.41	3.36	4.33	2.59	3.64	9.48	degrees
	$\bar{d}$	2.16	-0.16	0.33	0.12	-0.57	-0.11	-0.54	1.78	
	$\bar{d}$ lower bound	-1.31	-4.40	-1.03	-0.97	-2.18	-1.03	-1.90	-0.55	
	$\bar{d}$ upper bound	5.62	4.09	1.69	1.21	1.05	0.80	0.83	4.10	
	LA lower bound	-8.54	-13.25	-3.88	-3.25	-5.55	-2.93	-4.76	-5.40	
	LA upper bound	12.85	12.93	4.53	3.49	4.41	2.70	3.68	8.96	
	RMS (individual)	8.59		1.57		1.70				
	Fraction (individual)	1.00		1.00		1.00				
	RMS (mean)	8.51						1.41	2.36	
	Fraction (mean)	1.00						1.00	1.00	

BIBLIOGRAPHY

- [1] Yi Abdel-Aziz. Direct Linear Transformation from Comparator Coordinates into Object Space Coordinates in Close-Range Photogrammetry. In *Proceedings The Symposium on Close-Range Photogrammetry, American Society of Photogrammetry*, 1971.
- [2] Felix Angst, André Aeschlimann, and Gerold Stucki. Smallest Detectable and Minimal Clinically Important Differences of Rehabilitation Intervention with Their Implications for Required Sample Sizes Using WOMAC and SF-36 Quality of Life Measurement Instruments in Patients with Osteoarthritis of the Lower Extremities. *Arthritis Care & Research*, 45(4):384–391, 2001.
- [3] Elizabeth Arendt and Randall Dick. Knee Injury Patterns Among Men and Women in Collegiate Basketball and Soccer NCAA Data and Review of Literature. *The American Journal of Sports Medicine*, 23(6):694–701, 1995.
- [4] Richard Baker. ISB recommendation on definition of joint coordinate systems for the reporting of human joint motion—part I: ankle, hip and spine. *Journal of Biomechanics*, 36(2):300–302, 2003.
- [5] Donald L. Bartel, Dwight T. Davy, and Tony M. Keaveny. *Orthopaedic Biomechanics: Mechanics and Design in Musculoskeletal Systems*. Prentice Hall, 2006.
- [6] Nathaniel A. Bates, Kevin R. Ford, Gregory D. Myer, and Timothy E. Hewett. Impact Differences in Ground Reaction Force and Center of Mass Between the First and Second Landing Phases of a Drop Vertical Jump and Their Implications for Injury Risk Assessment. *Journal of Biomechanics*, 46(7):1237–1241, 2013.
- [7] Judith F. Baumhauer, Denise M. Alosa, Per A.F.H. Renström, Saul Trevino,

- Bruce Beynnon, et al. A Prospective Study of Ankle Injury Risk Factors. *The American Journal of Sports Medicine*, 23(5):564–570, 1995.
- [8] Thor F. Besier, Daina L. Sturnieks, Jacque A. Alderson, and David G. Lloyd. Repeatability of gait data using a functional hip joint centre and a mean helical knee axis. *Journal of Biomechanics*, 36(8):1159–1168, 2003.
- [9] Bruce D. Beynnon and Braden C. Fleming. Anterior cruciate ligament strain in-vivo: A review of previous work. *Journal of Biomechanics*, 31(6):519–525, 1998.
- [10] J. Martin Bland and Douglas G. Altman. Statistical Methods for Assessing Agreement Between Two Methods of Clinical Measurement. *The Lancet*, 327(8476):307–310, 1986.
- [11] J. Martin Bland and Douglas G. Altman. Measuring agreement in method comparison studies. *Statistical Methods in Medical Research*, 8(2):135–160, 1999.
- [12] Barry P. Boden, John A. Feagin Jr, and William E. Garrett Jr. Mechanisms of Anterior Cruciate Ligament Injury. *Orthopedics*, 23(6):573, 2000.
- [13] Michelle C. Boling, Darin A. Padua, Stephen W. Marshall, Kevin Guskiewicz, Scott Pyne, and Anthony Beutler. A Prospective Investigation of Biomechanical Risk Factors for Patellofemoral Pain Syndrome the Joint Undertaking to Monitor and Prevent ACL Injury (JUMP-ACL) Cohort. *The American Journal of Sports Medicine*, 37(11):2108–2116, 2009.
- [14] Bruno Bonnechere, Bart Jansen, P. Salvia, H. Bouzahouene, L. Omelina, Fedor Moiseev, Victor Sholukha, Jan Cornelis, Marcel Rooze, and S. Van Sint Jan. Validity and reliability of the Kinect within functional assessment activities: comparison with standard stereophotogrammetry. *Gait & Posture*, 39(1):593–598, 2014.

- [15] Scott C.E. Brandon and Kevin J. Deluzio. Robust features of knee osteoarthritis in joint moments are independent of reference frame selection. *Clinical Biomechanics*, 26(1):65–70, 2011.
- [16] Anne Bruton, Joy H. Conway, and Stephen T. Holgate. Reliability: What is it, and how is it measured? *Physiotherapy*, 86(2):94–99, 2000.
- [17] Robert J. Butler, Phillip J. Plisky, Corey. Southers, Christopher Scoma, and Kyle B. Kiesel. Biomechanical analysis of the different classifications of the Functional Movement Screen deep squat test. *Sports Biomechanics/International Society of Biomechanics in Sports*, 9(4):270, 2010.
- [18] C-Motion. Online Visual 3D Documentation Wiki - Expressions. <http://c-motion.com/v3dwiki/index.php?title=Expressions> (last accessed: 10-05-2015).
- [19] Massimo Camplani and Luis Salgado. Adaptive Spatio-Temporal Filter for Low-Cost Camera Depth Maps. In *Emerging Signal Processing Applications (ESPA), 2012 IEEE International Conference on*, pages 33–36. IEEE, 2012.
- [20] Massimo Camplani and Luis Salgado. Efficient Spatio-Temporal Hole Filling Strategy for Kinect Depth Maps. In *IS&T/SPIE Electronic Imaging*, pages 82900E–82900E. International Society for Optics and Photonics, 2012.
- [21] A. Caraffa, G. Cerulli, M. Proietti, G. Aisa, and A. Rizzo. Prevention of anterior cruciate ligament injuries in soccer. *Knee Surgery, Sports Traumatology, Arthroscopy*, 4(1):19–21, 1996.
- [22] Don B. Chaffin. Development of Computerized Human Static Strength Simulation Model for Job Design. 1997.
- [23] Don B. Chaffin and Gunnar Andersson. *Occupational Biomechanics*. Wiley New York, 1984.

- [24] Don B. Chaffin, Gunnar Andersson, and Bernard J. Martin. Occupational Biomechanics. *Toronto, Ontario, Canada: John Wiley & Sons Inc*, 1991.
- [25] R.F. Chandler, Charles E. Clauser, John T. McConville, H.M. Reynolds, and John W. Young. Investigation of Inertial Properties of the Human Body. Technical report, DTIC Document, 1975.
- [26] Jonathan D. Chappell and Orr Limpisvasti. Effect of a Neuromuscular Training Program on the Kinetics and Kinematics of Jumping Tasks. *The American Journal of Sports Medicine*, 36(6):1081–1086, 2008.
- [27] Miguel Christophy, Maurice Curtin, Nur Adila Faruk Senan, Jeffrey C. Lotz, and Oliver M. O’Reilly. On the modeling of the intervertebral joint in multibody models for the spine. *Multibody System Dynamics*, 30(4):413–432, 2013.
- [28] Kay M. Crossley, Kim L. Bennell, Sallie M. Cowan, and Sally Green. Analysis of Outcome Measures for Persons with Patellofemoral Pain: Which are Reliable and Valid? *Archives of Physical Medicine and Rehabilitation*, 85(5):815–822, 2004.
- [29] Kay M. Crossley, Wan-Jing Zhang, Anthony G. Schache, Adam Bryant, and Sallie M. Cowan. Performance on the Single-Leg Squat Task Indicates Hip Abductor Muscle Function. *The American Journal of Sports Medicine*, 39(4):866–873, 2011.
- [30] Michael J. Decker, Michael R. Torry, Douglas J. Wyland, William I. Sterett, and J. Richard Steadman. Gender differences in lower extremity kinematics, kinetics and energy absorption during landing. *Clinical Biomechanics*, 18(7):662–669, 2003.
- [31] Scott L. Delp, Frank C. Anderson, Allison S. Arnold, Peter Loan, Ayman Habib, Chand T. John, Eran Guendelman, and Darryl G. Thelen. OpenSim:

- Open-source software to create and analyze dynamic simulations of movement. *IEEE Transactions on Biomedical Engineering*, 54(11):1940–1952, 2007.
- [32] Guillaume Desroches, Laurence Chèze, and Raphaël Dumas. Expression of Joint Moment in the Joint Coordinate System. *ASME Journal of Biomechanical Engineering*, 132(11):114503, 2010.
- [33] Sheila A. Dugan. Sports-Related Knee Injuries in Female Athletes: What Gives? *American Journal of Physical Medicine & Rehabilitation*, 84(2):122–130, 2005.
- [34] Raphaël Dumas and Laurence Chèze. Letter to the Editor: Joint Moments in the Joint Coordinate System, Euler or Dual Euler Basis. *ASME Journal of Biomechanical Engineering*, 136(5):055501–1–05501–2, 2014.
- [35] Carl F. Ettlinger, Robert J. Johnson, and Jasper E. Shealy. A Method to Help Reduce the Risk of Serious Knee Sprains Incurred in Alpine Skiing. *The American Journal of Sports Medicine*, 23(5):531–537, 1995.
- [36] Soroush Falahati. *OpenNI Cookbook*. Packt Publishing Ltd, 2013.
- [37] Kevin R. Ford, Gregory D. Myer, and Timothy E. Hewett. Valgus Knee Motion During Landing in High School Female and Male Basketball Players. *Medicine and Science in Sports and Exercise*, 35(10):1745–1750, 2003.
- [38] Kevin R. Ford, Gregory D. Myer, Harrison E. Toms, and Timothy E. Hewett. Gender Differences in the Kinematics of Unanticipated Cutting in Young Athletes. *Medicine and Science in Sports and Exercise*, 37(1):124–129, 2005.
- [39] Yukihiisa Fukuda, Savio L-Y Woo, John C. Loh, Eiichi Tsuda, Peter Tang, Patrick J. McMahon, and Richard E. Debski. A quantitative analysis of

- valgus torque on the ACL: a human cadaveric study. *Journal of Orthopaedic Research*, 21(6):1107–1112, 2003.
- [40] J. Fuller, L.-J. Liu, M.C. Murphy, and R.W. Mann. A comparison of lower-extremity skeletal kinematics measured using skin-and pin-mounted markers. *Human Movement Science*, 16(2):219–242, 1997.
- [41] Stanton A. Glantz. *Primer of Biostatistics*. McGraw-Hill, 7th edition, 2012.
- [42] Benjamin M. Goerger, Stephen W. Marshall, Anthony I. Beutler, J. Troy Blackburn, John H. Wilckens, and Darin A. Padua. Anterior cruciate ligament injury alters preinjury lower extremity biomechanics in the injured and uninjured leg: the jump-acl study. *British Journal of Sports Medicine*, pages bjsports–2013, 2014.
- [43] John Goetschius, Helen C. Smith, Pamela M. Vacek, Leigh Ann Holterman, Sandra J. Shultz, Timothy W. Tourville, James Slauterbeck, Robert J. Johnson, and Bruce D. Beynnon. Application of a Clinic-Based Algorithm as a Tool to Identify Female Athletes at Risk for Anterior Cruciate Ligament Injury A Prospective Cohort Study With a Nested, Matched Case-Control Analysis. *The American Journal of Sports Medicine*, 40(9):1978–1984, 2012.
- [44] Letha Y. Griffin, Julie Agel, Marjorie J. Albohm, Elizabeth A. Arendt, Randall W. Dick, William E. Garrett, James G. Garrick, Timothy E. Hewett, Laura Huston, Mary Lloyd Ireland, et al. Noncontact Anterior Cruciate Ligament Injuries: Risk Factors and Prevention Strategies. *Journal of the American Academy of Orthopaedic Surgeons*, 8(3):141–150, 2000.
- [45] Edward S. Grood and Wilfredo J. Suntay. A Joint Coordinate System for the Clinical Description of Three-Dimensional Motions: Application to the Knee. *ASME Journal of Biomechanical Engineering*, 105(2):136–144, 1983.

- [46] Timothy E. Hewett, Kevin R. Ford, and Gregory D. Myer. Anterior Cruciate Ligament Injuries in Female Athletes Part 2, A Meta-Analysis of Neuromuscular Interventions Aimed at Injury Prevention. *The American Journal of Sports Medicine*, 34(3):490–498, 2006.
- [47] Timothy E. Hewett, Thomas N. Lindenfeld, Jennifer V. Riccobene, and Frank R. Noyes. The Effect of Neuromuscular Training on the Incidence of Knee Injury in Female Athletes A Prospective Study. *The American Journal of Sports Medicine*, 27(6):699–706, 1999.
- [48] Timothy E. Hewett, Gregory D. Myer, and Kevin R. Ford. Decrease in Neuromuscular Control About the Knee with Maturation in Female Athletes. *The Journal of Bone & Joint Surgery*, 86(8):1601–1608, 2004.
- [49] Timothy E. Hewett, Gregory D. Myer, and Kevin R. Ford. Anterior Cruciate Ligament Injuries in Female Athletes Part 1, Mechanisms and Risk Factors. *The American Journal of Sports Medicine*, 34(2):299–311, 2006.
- [50] Timothy E. Hewett, Gregory D. Myer, Kevin R. Ford, Robert S. Heidt, Angelo J. Colosimo, Scott G. McLean, Antonie J. Van den Bogert, Mark V. Paterno, and Paul Succop. Biomechanical Measures of Neuromuscular Control and Valgus Loading of the Knee Predict Anterior Cruciate Ligament Injury Risk in Female Athletes: A Prospective Study. *The American Journal of Sports Medicine*, 33(4):492–501, 2005.
- [51] Timothy E. Hewett, Amanda L. Stroupe, Thomas A. Nance, and Frank R. Noyes. Plyometric Training in Female Athletes Decreased Impact Forces and Increased Hamstring Torques. *The American Journal of Sports Medicine*, 24(6):765–773, 1996.
- [52] John H. Hollman, Christy M. Galardi, I-Hsuan Lin, Brandon C. Voth, and Crystal L. Whitmarsh. Frontal and transverse plane hip kinematics and

- gluteus maximus recruitment correlate with frontal plane knee kinematics during single-leg squat tests in women. *Clinical Biomechanics*, 29(4):468–474, 2014.
- [53] Brian Hudson. Hole Filling. <http://people.clarkson.edu/~hudsonb/courses/cs611/> (last accessed: 12-1-2015).
- [54] Laura J. Huston and Edward M. Wojtys. Neuromuscular Performance Characteristics in Elite Female Athletes. *The American Journal of Sports Medicine*, 24(4):427–436, 1996.
- [55] Roman Jaeschke, Joel Singer, and Gordon H. Guyatt. Measurement of Health Status: Ascertaining the Minimal Clinically Important Difference. *Controlled Clinical Trials*, 10(4):407–415, 1989.
- [56] Håkan Jonsson, Johan Kärrholm, and Lars-Gunnar Elmqvist. Kinematics of active knee extension after tear of the anterior cruciate ligament. *The American Journal of Sports Medicine*, 17(6):796–802, 1989.
- [57] Seung-kook Jun, Xiaobo Zhou, Daniel K. Ramsey, and Venkat N. Krovi. A Comparative Study of Human Motion Capture and Computational Analysis Tools. In *presented at the International Conference on Rehabilitation Robotics, Seattle, Washington USA*, 2013.
- [58] Akihiro Kanamori, Savio L-Y Woo, C. Benjamin Ma, Jennifer Zeminski, Theodore W. Rudy, Guoan Li, and Glen A. Livesay. The Forces in the Anterior Cruciate Ligament and Knee Kinematics During a Simulated Pivot Shift Test: A Human Cadaveric Study Using Robotic Technology. *Arthroscopy: The Journal of Arthroscopic & Related Surgery*, 16(6):633–639, 2000.
- [59] Julia Kar and Peter M. Quesada. A Numerical Simulation Approach to Studying Anterior Cruciate Ligament Strains and Internal Forces Among

- Young Recreational Women Performing Valgus Inducing Stop-Jump Activities. *Annals of Biomedical Engineering*, 40(8):1679–1691, 2012.
- [60] Julia Kar and Peter M. Quesada. A Musculoskeletal Modeling Approach for Estimating Anterior Cruciate Ligament Strains and Knee Anterior–Posterior Shear Forces in Stop-Jumps Performed by Young Recreational Female Athletes. *Annals of Biomedical Engineering*, 41(2):338–348, 2013.
- [61] John C. Kennedy, Ian J. Alexander, and Keith C. Hayes. Nerve supply of the human knee and its functional importance. *The American Journal of Sports Medicine*, 10(6):329–335, 1982.
- [62] Kouros Khoshelham and Sander Oude Elberink. Accuracy and Resolution of Kinect Depth Data for Indoor Mapping Applications. *Sensors*, 12(2):1437–1454, 2012.
- [63] Ali Kiapour, Ata M. Kiapour, Vikas Kaul, Carmen E. Quatman, Samuel C. Wordeman, Timothy E. Hewett, Constantine K. Demetropoulos, and Vijay K. Goel. Finite Element Model of the Knee for Investigation of Injury Mechanisms: Development and Validation. *Journal of Biomechanical Engineering*, 136(1):011002, 2014.
- [64] Ata M. Kiapour, Vikas Kaul, Ali Kiapour, Carmen E. Quatman, Samuel C. Wordeman, Timothy E. Hewett, Constantine K. Demetropoulos, and Vijay K. Goel. The Effect of Ligament Modeling Technique on Knee Joint Kinematics: A Finite Element Study. *Applied Mathematics*, 4(5A):91–97, 2013.
- [65] Anthony W. Kim, Adam M. Rosen, Victoria A. Brander, and Thomas S. Buchanan. Selective Muscle Activation Following Electrical Stimulation of the Collateral Ligaments of the Human Knee Joint. *Archives of Physical Medicine and Rehabilitation*, 76(8):750–757, 1995.

- [66] Scott M. Lephart, Cheryl M. Ferris, Bryan L. Riemann, Joseph B. Myers, and Freddie H. Fu. Gender Differences in Strength and Lower Extremity Kinematics During Landing. *Clinical Orthopaedics and Related Research*, 401:162–169, 2002.
- [67] Jan E. Lexell and David Y. Downham. How to Assess the Reliability of Measurements in Rehabilitation. *American Journal of Physical Medicine & Rehabilitation*, 84(9):719–723, 2005.
- [68] David G. Lloyd. Rationale for Training Programs to Reduce Anterior Cruciate Ligament Injuries in Australian Football. *Journal of Orthopaedic & Sports Physical Therapy*, 31(11):645–654, 2001.
- [69] David G. Lloyd and Thomas S. Buchanan. Strategies of muscular support of varus and valgus isometric loads at the human knee. *Journal of Biomechanics*, 34(10):1257–1267, 2001.
- [70] T.-W. Lu and J.J. O’Connor. Bone position estimation from skin marker co-ordinates using global optimisation with joint constraints. *Journal of Biomechanics*, 32(2):129–134, 1999.
- [71] Bert R. Mandelbaum, Holly J. Silvers, Diane S. Watanabe, John F. Knarr, Stephen D. Thomas, Letha Y. Griffin, Donald T. Kirkendall, and William Garrett. Effectiveness of a Neuromuscular and Proprioceptive Training Program in Preventing Anterior Cruciate Ligament Injuries in Female Athletes 2-Year Follow-up. *The American Journal of Sports Medicine*, 33(7):1003–1010, 2005.
- [72] Keith L. Markolf, Daniel M. Burchfield, Matthew M. Shapiro, Michael F. Shepard, Gerald A.M. Finerman, and James L. Slauterbeck. Combined Knee Loading States that Generate High Anterior Cruciate Ligament Forces. *Journal of Orthopaedic Research*, 13(6):930–935, 1995.

- [73] Keith L. Markolf, Adrian Graff-Radford, and H.C. Amstutz. In vivo knee stability. A quantitative assessment using an instrumented clinical testing apparatus. *The Journal of Bone & Joint Surgery*, 60(5):664–674, 1978.
- [74] Genaro T. Marzan and H. M. Karara. A computer program for direct linear transformation solution of the collinearity condition, and some applications of it. In *Proceedings of the Symposium on Close-Range Photogrammetric Systems*, pages 420–476. American Society of Photogrammetry Falls Church, 1975.
- [75] Jenny McConnell. Management of patellofemoral problems. *Manual Therapy*, 1(2):60–66, 1996.
- [76] Scott G. McLean, Susanne W. Lipfert, and Antonie J. van den Bogert. Effect of Gender and Defensive Opponent on the Biomechanics of Sidestep Cutting. *Medicine and Science in Sports and Exercise*, 36(6):1008–1016, 2004.
- [77] Kenneth P. Moses, John C. Banks, Pedro B. Nava, and Darrell K. Petersen. *Atlas of Clinical Gross Anatomy*. Elsevier Health Sciences, 2005.
- [78] Vernon B. Mountcastle. *Medical Physiology*. CV Mosby St. Louis, 1980.
- [79] MSDN. Kinect for Windows Product Blog. <http://blogs.msdn.com/b/kinectforwindows/archive/2012/12/07/inside-the-newest-kinect-for-windows-sdk-infrared-control.aspx> (last accessed: 12-3-2015).
- [80] Allan Munro, Lee Herrington, and Michael Carolan. Reliability of Two-Dimensional Video Assessment of Frontal Plane Dynamic Knee Valgus During Common Athletic Screening Tasks. *Journal of Sport Rehabilitation*, 21(1):7–11, 2012.

- [81] Gregory D. Myer, Jensen L. Brent, Kevin R. Ford, and Timothy E. Hewett. Real-time assessment and neuromuscular training feedback techniques to prevent ACL injury in female athletes. *Strength and Conditioning Journal*, 33(3):21–35, 2011.
- [82] Gregory D. Myer, Kevin R. Ford, and Timothy E. Hewett. The effects of gender on quadriceps muscle activation strategies during a maneuver that mimics a high ACL injury risk position. *Journal of Electromyography and Kinesiology*, 15(2):181–189, 2005.
- [83] Gregory D. Myer, Kevin R. Ford, Jane Khoury, Paul Succop, and Timothy E. Hewett. Biomechanics laboratory-based prediction algorithm to identify female athletes with high knee loads that increase risk of ACL injury. *British Journal of Sports Medicine*, pages 245–252, 2010.
- [84] Gregory D. Myer, Kevin R. Ford, Jane Khoury, Paul Succop, and Timothy E. Hewett. Clinical correlates to laboratory measures for use in non-contact anterior cruciate ligament injury risk prediction algorithm. *Clinical Biomechanics*, 25(7):693–699, 2010.
- [85] Gregory D. Myer, Kevin R. Ford, Jane Khoury, Paul Succop, and Timothy E. Hewett. Development and Validation of a Clinic-Based Prediction Tool to Identify Female Athletes at High Risk for Anterior Cruciate Ligament Injury. *The American Journal of Sports Medicine*, 38(10):2025–2033, 2010.
- [86] Gregory D. Myer, Kevin R. Ford, Scott G. McLean, and Timothy E. Hewett. The Effects of Plyometric Versus Dynamic Stabilization and Balance Training on Lower Extremity Biomechanics. *The American Journal of Sports Medicine*, 34(3):445–455, 2006.
- [87] Gregory D. Myer, Benjamin W. Stroube, Christopher A. DiCesare, Jensen L.

- Brent, Kevin R. Ford, Robert S. Heidt, and Timothy E. Hewett. Augmented Feedback Supports Skill Transfer and Reduces High-Risk Injury Landing Mechanics a Double-Blind, Randomized Controlled Laboratory Study. *The American Journal of Sports Medicine*, 41(3):669–677, 2013.
- [88] Casey A. Myers and David Hawkins. Alterations to movement mechanics can greatly reduce anterior cruciate ligament loading without reducing performance. *Journal of Biomechanics*, 43(14):2657–2664, 2010.
- [89] G. Myklebust, S. Maehlum, I. Holm, and R. Bahr. A prospective cohort study of anterior cruciate ligament injuries in elite Norwegian team handball. *Scandinavian Journal of Medicine & Science in Sports*, 8(3):149–153, 1998.
- [90] Julia K. Nichols and Oliver M. O’Reilly. Verifying the Equivalence of Representations of Joint Moment Vectors with Application to Biomechanical Motion Capture Data from a Drop Vertical Jump Task. (in submission).
- [91] Julia K. Nichols, Mark P. Sena, Oliver M. O’Reilly, Brian T. Feeley, and Jeffrey C. Lotz. Low-Cost Motion Capture: A Comparison to Vicon. Orthopaedic Research Society 61st Annual Meeting, Las Vegas, NV, 2015.
- [92] J.A. Nyland, D.N.M. Caborn, R. Shapiro, and D.L. Johnson. Fatigue after eccentric quadriceps femoris work produces earlier gastrocnemius and delayed quadriceps femoris activation during crossover cutting among normal athletic women. *Knee Surgery, Sports Traumatology, Arthroscopy*, 5(3):162–167, 1997.
- [93] Edward Nyman and Charles W. Armstrong. Real-time feedback during drop landing training improves subsequent frontal and sagittal plane knee kinematics. *Clinical Biomechanics*, 30(9):988–994, 2015.
- [94] Oliver M. O’Reilly. The Dual Euler Basis: Constraints, Potentials, and

- Lagrange's Equations in Rigid Body Dynamics. *ASME Journal of Applied Mechanics*, 74(2):256–258, 2007.
- [95] Oliver M. O'Reilly. *Intermediate Engineering Dynamics: A Unified Approach to Newton-Euler and Lagrangian Mechanics*. Cambridge University Press, New York, 2008.
- [96] Oliver M. O'Reilly. On the Formulation of Cost Functions for Torque-Optimized Control of Rigid Bodies. *Automatica*, 50(10):2723–2725, 2014.
- [97] Oliver M. O'Reilly, Mark P. Sena, Brian T. Feeley, and Jeffrey C. Lotz. On Representations for Joint Moments Using a Joint Coordinate System. *ASME Journal of Biomechanical Engineering*, 135(11):114504–1–114504–4, 2013.
- [98] Gabrielle Rankin and Maria Stokes. Reliability of assessment tools in rehabilitation: an illustration of appropriate statistical analyses. *Clinical Rehabilitation*, 12(3):187–199, 1998.
- [99] C. Reinschmidt, A.J. van den Bogert, N. Murphy, A. Lundberg, and B.M. Nigg. Tibiocalcaneal motion during running, measured with external and bone markers. *Clinical Biomechanics*, 12(1):8–16, 1997.
- [100] C. Reinschmidt, A.J. van den Bogert, B.M. Nigg, A. Lundberg, and N. Murphy. Effect of Skin Movement on the Analysis of Skeletal Knee Joint Motion During Running. *Journal of Biomechanics*, 30(7):729–732, 1997.
- [101] G. Robertson, G. Caldwell, J. Hamill, G. Kamen, and S. Whittlesey. *Research Methods in Biomechanics*. Human Kinetics, Second edition, 2013.
- [102] Susan L. Rozzi, Scott M. Lephart, William S. Gear, and Freddie H. Fu. Knee Joint Laxity and Neuromuscular Characteristics of Male and Female

- Soccer and Basketball Players. *The American Journal of Sports Medicine*, 27(3):312–319, 1999.
- [103] Anthony G. Schache and Richard Baker. On the expression of joint moments during gait. *Gait & Posture*, 25(3):440–452, 2007.
- [104] Anne Schmitz, Mao Ye, Robert Shapiro, Ruigang Yang, and Brian Noehren. Accuracy and repeatability of joint angles measured using a single camera markerless motion capture system. *Journal of Biomechanics*, 47(2):587–591, 2014.
- [105] Robert A. Schultz, Douglas C. Miller, C.S. Kerr, and Lyle Micheli. Mechanoreceptors in human cruciate ligaments. A histological study. *The Journal of Bone & Joint Surgery*, 66(7):1072–1076, 1984.
- [106] Michael J. Schutte, E.J. Dabezies, M.L. Zimny, and L.T. Happel. Neural anatomy of the human anterior cruciate ligament. *The Journal of Bone & Joint Surgery*, 69(2):243–247, 1987.
- [107] Jamie Shotton, Andrew Fitzgibbon, Mat Cook, Toby Sharp, Richard Moore, Alex Kipman, and Andrew Blake. Real-Time Human Pose Recognition in Parts from Single Depth Images. <http://research.microsoft.com/pubs/145347/BodyPartRecognition.pdf> (last accessed: 11-30-2015).
- [108] Patrick E. Shrout and Joseph L. Fleiss. Intraclass Correlations: Uses in Assessing Rater Reliability. *Psychological Bulletin*, 86(2):420, 1979.
- [109] Pete B. Shull, Amy Silder, Rebecca Shultz, Jason L. Dragoo, Thor F. Besier, Scott L. Delp, and Mark R. Cutkosky. Six-Week Gait Retraining Program Reduces Knee Adduction Moment, Reduces Pain, and Improves Function for Individuals with Medial Compartment Knee Osteoarthritis. *Journal of Orthopaedic Research*, 31(7):1020–1025, 2013.

- [110] Mashhour Solh and Ghassan AlRegib. Hierarchical Hole-Filling (HHF): Depth Image Based Rendering without Depth Map Filtering for 3D-TV. In *Multimedia Signal Processing (MMSP), 2010 IEEE International Workshop on*, pages 87–92. IEEE, 2010.
- [111] M. Solomonow, R. Baratta, B.H. Zhou, H. Shoji, W. Bose, C. Beck, and R. D’ambrosia. The synergistic action of the anterior cruciate ligament and thigh muscles in maintaining joint stability. *The American Journal of Sports Medicine*, 15(3):207–213, 1987.
- [112] Rita Stagni, Silvia Fantozzi, Angelo Cappello, and Alberto Leardini. Quantification of soft tissue artefact in motion analysis by combining 3D fluoroscopy and stereophotogrammetry: a study on two subjects. *Clinical Biomechanics*, 20(3):320–329, 2005.
- [113] Erik E. Stone, Mairead Butler, Aaron McRuer, Alison Gray, Justin Marks, and Marjorie Skubic. Evaluation of the Microsoft Kinect for screening ACL injury. In *Engineering in Medicine and Biology Society (EMBC), 2013 35th Annual International Conference of the IEEE*, pages 4152–4155. IEEE, 2013.
- [114] C. Buz Swanik, Scott M. Lephart, Frank P. Giannantonio, and Freddie H. Fu. Reestablishing Proprioception and Neuromuscular Control in the ACL-Injured Athlete. *Journal of Sport Rehabilitation*, 5:162–206, 1997.
- [115] C.C. Teitz. Video analysis of ACL injuries: Prevention of noncontact ACL injuries. *American Academy of Orthopaedic Surgeons, Rosemont, IL*, 1999.
- [116] D.E. Toutoungi, T.W. Lu, A. Leardini, F. Catani, and J.J. O’Connor. Cruciate ligament forces in the human knee during rehabilitation exercises. *Clinical Biomechanics*, 15(3):176–187, 2000.
- [117] A.J. van den Bogert and J.J. de Koning. On Optimal Filtering for Inverse

- Dynamics Analysis. Proceedings of the IXth Biennial Conference of the Canadian Society for Biomechanics, Vancouver, pages 214–215, 1996.
- [118] Antonie J. van den Bogert and Anne Su. A weighted least squares method for inverse dynamic analysis. *Computer Methods in Biomechanics and Biomedical Engineering*, 11(1):3–9, 2008.
 - [119] Arem Von Porat, Ewa M. Roos, and Harald Roos. High prevalence of osteoarthritis 14 years after an anterior cruciate ligament tear in male soccer players: a study of radiographic and patient relevant outcomes. *Annals of the Rheumatic Diseases*, 63(3):269–273, 2004.
 - [120] Benjamin K. Weeks, Christopher P. Carty, and Sean A. Horan. Kinematic predictors of single-leg squat performance: a comparison of experienced physiotherapists and student physiotherapists. *BioMedCentral Musculoskeletal Disorders*, 13(1):207, 2012.
 - [121] Joseph P. Weir. Quantifying Test-Retest Reliability Using the Intraclass Correlation Coefficient and the SEM. *The Journal of Strength & Conditioning Research*, 19(1):231–240, 2005.
 - [122] David A. Winter. *Biomechanics and Motor Control of Human Movement*. John Wiley & Sons, 1990.
 - [123] Edward M. Wojtys, Laura J. Huston, Harold J. Sock, James P. Boylan, and James A. Ashton-Miller. Gender Differences in Muscular Protection of the Knee in Torsion in Size-Matched Athletes. *Journal of Bone and Joint Surgery*, 85(5):782, 2003.
 - [124] Ge Wu, Frans C.T. van der Helm, H.E.J. (DirkJan) Veeger, Mohsen Makhsous, Peter Van Roy, Carolyn Anglin, Jochem Nagels, Andrew R. Karduna, Kevin McQuade, Xuguang Wang, Frederick W. Werner, and Bryan

- Buchholz. ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion. Part II: shoulder, elbow, wrist and hand. *Journal of Biomechanics*, 38(5):981–992, 2005.
- [125] Satoshi Yamaguchi, Masako Kitamura, Tomohiro Ushikubo, Atsushi Murata, Ryuichiro Akagi, and Takahisa Sasho. Effect of Laterally Wedged Insoles on the External Knee Adduction Moment across Different Reference Frames. *PloS One*, 10(9):e0138554, 2015.
- [126] J. Yamazaki, T. Muneta, Y.J. Ju, and I. Sekiya. Differences in kinematics of single leg squatting between anterior cruciate ligament-injured patients and healthy controls. *Knee Surgery, Sports Traumatology, Arthroscopy*, 18(1):56–63, 2010.
- [127] Jia-Yuan You, You-Li Chou, Chii-Jeng Lin, and Fong-Chin Su. Effect of slip on movement of body center of mass relative to base of support. *Clinical Biomechanics*, 16(2):167–173, 2001.
- [128] Bohdanna T. Zazulak, Patricia L. Ponce, Stephen J. Straub, Michael J. Medvecky, Lori Avedisian, and Timothy E. Hewett. Gender Comparison of Hip Muscle Activity During Single-Leg Landing. *Journal of Orthopaedic & Sports Physical Therapy*, 35(5):292–299, 2005.
- [129] Brian L. Zeller, Jean L. McCrory, W. Ben Kibler, and Timothy L. Uhl. Differences in Kinematics and Electromyographic Activity Between Men and Women During the Single-Legged Squat. *The American Journal of Sports Medicine*, 31(3):449–456, 2003.