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2014

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UNIVERSITY OF CALIFORNIA, IRVINE

Development of an Actuator Driven Cadaveric Wrist Testing System
For Carpal Kinematic Studies

DISSERTATION

submitted in partial satisfaction of the requirements for the degree of

DOCTOR OF PHILOSOPHY
in Biomedical Engineering

by Ryan J. Quigley

Dissertation Committee:
Professor Thay Q Lee, PhD, Co-Chair
Assistant Professor Elliot Hui, PhD, Co-Chair
Professor Ranjan Gupta, MD
Professor Vincent Caiozzo, PhD
Associate Clinical Professor Gregory Rafijah, MD

2014

DEDICATION

To my family and loving fiancé, I couldn't have done this without your patience, love, and support.

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ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to my advisor, Thay Q Lee. He committed a significant amount of time into training me, and developing me into whom I am today as a scientist. I will be forever indebted to him for his investment in me.

I would like to thank and acknowledge those on my dissertation committee. Dr. Ranjan Gupta has been a mentor to me, both in science and in medicine, for which I will be forever grateful. Dr. Gregory Rafijah has been a pleasure to work with on this project, and many other biomechanical projects. Lastly, I'd like to thank Dr. Vincent Caiozzo and Elliot Hui for their unbiased opinions and thoughts during the development of my project.

Additionally I would like to thank the members of the Orthopaedic Biomechanics Laboratory. I could not have completed my dissertation without the aid of Michelle McGarry. She invested as much time in my education as Dr. Lee. From her I have learned more than I can put into words. I would like to thank Chung Vo for his craftsmanship and aid in the assembly of my testing system. I would like to thank all the international fellows that I have worked with along the way. Each of them has expanded my orthopedic knowledge and experience

Lastly I would like to thank my loving family. My parents have been my biggest supporters while I have spent the first three decades of my life as a student. My loving fiancé has endured this process alongside me, for which I will forever cherish her. I could not have made it this far in my life without them.

CURRICULUM VITAE

Ryan J. Quigley

EDUCATION

University of California, Irvine
MD/PhD Candidate

Medical Degree, 2007-Present

Honors: Excellence in Basic Science, 2008

Expected Graduation Date: June, 2015

PhD in Biomedical Engineering, 2009-2014

Overall GPA: 3.97

University of California, Berkeley

Overall GPA: 3.92

Bachelor's of Science in Bioengineering with High Honors, May 2007

Honors: California Alumni Association Alumni Scholar – Robert C. Byrd Scholar –
Bioengineering Honor Society – National Society of Collegiate Scholars – National
Dean's List – Phi Beta Kappa

PUBLICATIONS

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3. Anatomical posterolateral corner reconstruction of the knee using cross tunnel on the Fibula head: A Cadaveric Study. Ishigooka H, McGarry M, Chen Y, Gupta A, **Quigley RJ**, Bui C, Lee T
4. Kinematics of the Posterolateral Corner of the Knee: A Cadaveric Study. Ishigooka H, McGarry M, Chen Y, Gupta A, **Quigley RJ**, Bui C, Lee T

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ABSTRACT OF THE DISSERTATION

Development of an Actuator Driven Cadaveric Wrist Testing System For Carpal Kinematic Studies

By

Ryan J Quigley

Doctor of Philosophy in Biomedical Engineering

University of California, Irvine, 2014

Professor Thay Q Lee, PhD, Co-Chair

Assistant Professor Elliot Hui, PhD, Co-Chair

Cadaver based joint simulators have been a backbone of orthopedic biomechanical experiments to simulate in vivo loading conditions and injury models in order to better understand intact joint kinematics, or develop new repair techniques. The purpose of this study was to develop a cadaver based wrist testing system capable of simulating grip in order to understand carpal kinematics under conditions that mimic the loading conditions seen in vivo. The testing system is based on linear actuators with in series load cells controlled by custom coded Labview software that are connected via sutures to the muscle tendons of wrist flexors/extensors and finger flexors, allowing fully customizable loading protocols. Carpal kinematics are measured using custom posts inserted into the carpus and digitized with a Microscribe 3DLX. Post-experimental dissection and digitization were used to create 3D models of the carpus at each testing position.

The system was validated by comparing the kinematics of the intact carpus in wrist flexion/extension and radial/ulnar deviation to data previously reported in the literature. Data from the new system was comparable to previous reports. Next the effect of grip on intact carpal

kinematics was investigated by loading flexor digitorum profundus. Grip caused significant flexion of the scaphoid and lunate with an average flexion of 0.8° for the scaphoid and 0.4° for the lunate. The last phase was to analyze the effect of repetitive grip on a wrist with a scapholunate interosseous ligament tear, an injury known to cause progressive degenerative changes following the initial tear. Following 500 cycles of grip, there were significant changes to the carpus including: increased scaphoid flexion, ulnar deviation, and pronation, lunate extension, widening of the scapholunate gap, and proximal translation of the head of the capitate. Utilizing these kinematic changes seen in cadavers, future studies can be performed to develop new repair strategies for this challenging injury. In conclusion, a validated cadaveric wrist testing system has been developed that has elucidated the effects of grip on the intact wrist, and provided significant information on the effect of functional stresses, such as repetitive grip, have on a wrist with a scapholunate interosseous ligament tear.

CHAPTER 1

Background

Introduction

Cadaver based joint simulators have been the backbone of orthopedic biomechanical experiments to simulate in vivo loading conditions and injury models in order to better understand intact joint kinematics, or develop new repair techniques. Every joint testing system has its limitation and flaws, with no one perfect system that can 100% accurately reproduce in vivo loading conditions. With that being said, various systems have been designed to perform kinematic studies of nearly every joint in the body, including, but not limited to, the shoulder¹⁻⁶, elbow⁷⁻¹¹, wrist¹²⁻¹⁶, knee¹⁷⁻²⁰, and AC joint²¹⁻²³. Each system often is designed to meet the specific requirements of the study at hand. This study aims to develop an actuator driven cadaveric wrist testing system capable of applying user customizable loading protocols for the investigation of carpal kinematics.

Wrist Anatomy

Osseous Structures

The wrist is a complex joint that consists of 8 carpal bones, divided into two rows, and arranged between the distal radius/ulna and the proximal metacarpals. The distal row is composed of the hamate, capitate, trapezoid, and trapezium and is considered to be a rigid unit with little intercarpal motion. The proximal row is composed of the scaphoid, lunate, triquetrum, and pisiform. Unlike the distal row, the proximal row does have a certain amount of intercarpal

motion but it is also distinguished because it has no direct muscular insertions onto it. Due to the lack of direct muscular insertions, it is referred to as an intercalated segment, meaning that the motion of the proximal row is determined solely by forces transmitted from the distal carpal row or the distal radius and ulna.

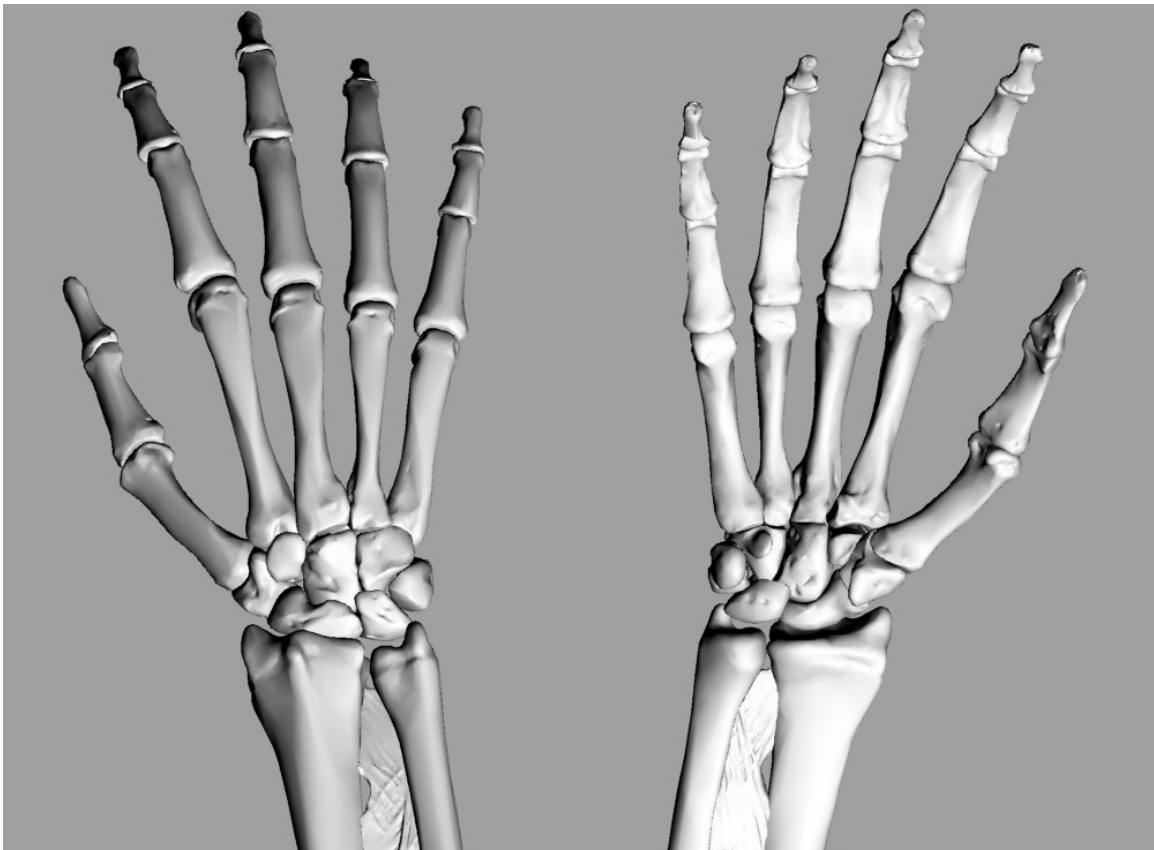


Figure 1-1. The skeletal anatomy of the human wrist and hand. Dorsal is shown on the left, volar on the right.

Distal Radius and Ulna

Proximally the carpus articulates with the distal radius and ulna (Figure 1-2). The distal radius has an ulnar inclination of 23° and a palmar inclination of 11° . The distal ulna is unique in that it does not articulate directly with the carpus; instead the articulation occurs through the triangular fibrocartilage complex (TFCC) that is attached to the distal ulna. The distal radius is the primary articular surface for the scaphoid and lunate. Radially the scaphoid sits in the

scaphoid fossa, while the lunate sits in the lunate fossa located ulnarly. The ulnar portion of the lunate also articulates with the TFCC along with the triquetrum.

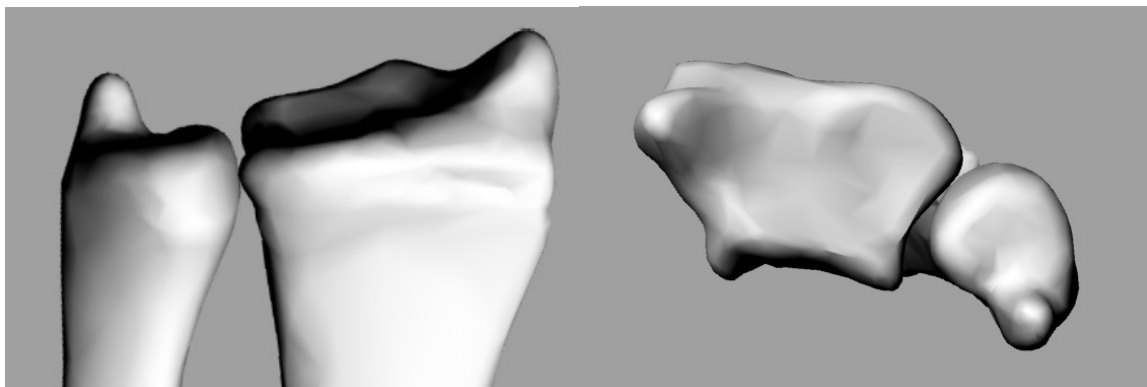


Figure 1-2. The distal radius and ulna. The left shows the dorsal surface, while the right shows the distal articular surface.

Scaphoid

The name scaphoid comes from the greek skaphos, meaning “boat” due to it’s shape (Figure 1-3). Anatomically the scaphoid is divided into three regions: the proximal pole, the waist, and the distal pole or tubercle. The scaphoid is mostly covered in articular cartilage and composed of 4 primary articular surfaces. Proximally its concave surface articulates with the distal radius in the scaphoid fossa to form the radioscaphoid joint. Also proximally, the scaphoid has a relative flat, crescentic surface that lies in the sagittal plane and articulates with the lunate to form the scapholunate joint. Distally the its concave surface articulates with the trapezium and trapezoid of the distal row, forming the scaphotrapezotrapezoid (STT) joint. The ulnar border of the scaphoid forms a convex articular surface where the radial aspect of the capitate sits, forming the scaphocapitate joint. The scaphoid sits in obliquely in both the sagittal and coronal planes, with its axis on average in 32° of flexion in the sagittal plane and an average of 40° of radial deviation in the coronal plane.

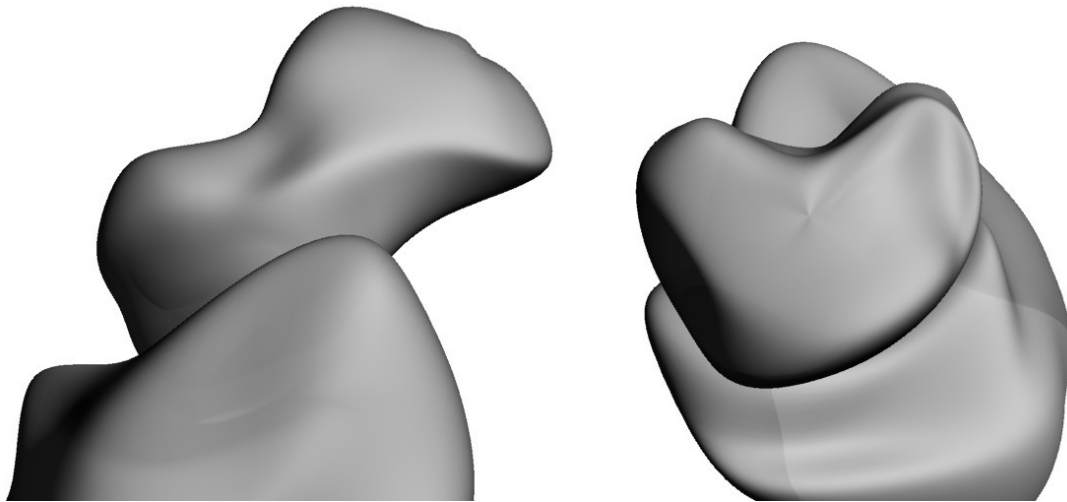


Figure 1-3. On the left is the scaphoid in the sagittal plane showing its oblique orientation, on the right is the lunate in the sagittal plane showing its crescentic cross section.

Lunate

The name lunate comes from the Latin luna or “crescent shaped” due to its crescent cross sectional shape in the sagittal plane (Figure 1-3). The lunate has 4 primary articular surfaces. Proximally it has a concave surface that articulates radially with the distal radius in the lunate fossa, and with the TFCC ulnarly. Distally its convex surface articulates with the spherical surface of the capitate forming a highly congruent capitolunate joint. The lunate also sometimes has a distal articular surface for the hamate, which is known as a Type II Lunate²⁴. Radially it has a flat crescentic surface in the sagittal plane that abuts the scaphoid, thus forming the other surface of the scapholunate joint. Ulnarly it articulates with the triquetrum to form

Capitate

The capitate acts as a linkage between the distal and proximal row through its proximal spherical head and the concave articulation formed for it by the scaphoid and lunate (Figure 1-4). The head of the capitate sits directly over the scapholunate joint. The distal surface articulates

with the 3rd metacarpal, where there is essentially zero joint motion. Radially it is linked to the trapezoid, while ulnarly it is linked to the hamate. Its dorsal and volar surfaces are non articular and serve for attachment sites for the dorsal and volar capsule/ligaments.

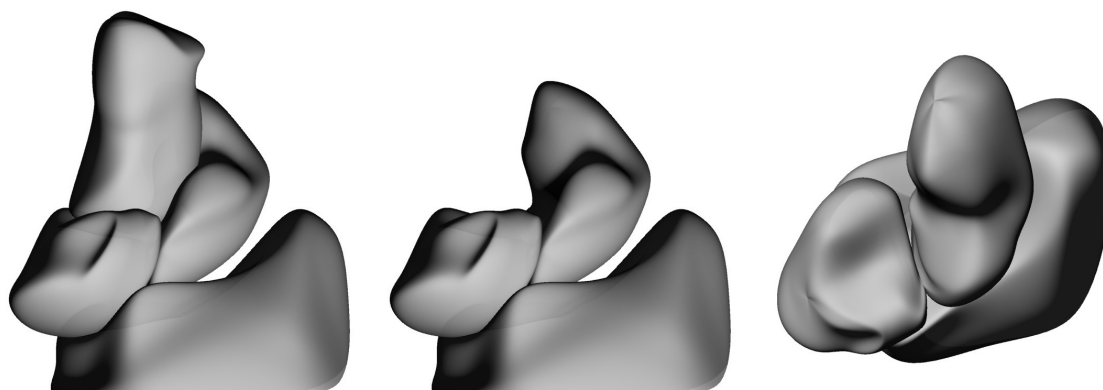


Figure 1-4. On the left is the capitate articulating with the concave surface formed by the scaphoid and lunate. The middle shows the “cup” formed by the scaphoid and lunate for the spherical capitate head to rest in. The right shows the relative location of the scapholunate joint just under the articulation for the capitate.

Ligaments

Besides its boney complexity, the wrist also has a complex set of ligaments divided into intrinsic and extrinsic ligaments. Intrinsic ligaments by definition are ligaments between carpal bones whereas extrinsic ligament are ligaments that originate from the radius or ulna before inserting onto a carpal bone. Similarly the ligaments of the wrist can be divided into dorsal and volar ligaments. The dorsal ligaments are primarily composed of a single extrinsic ligament, the dorsal radiocarpal ligament (DRC), and a single intrinsic ligament, the dorsal intercarpal ligament (DIC) that form a V shape from the dorsal radius to triquetrum to distal pole of the scaphoid and trapezoid.

Volarly the ligamentous anatomy is much more complex and considered to be more important to overall wrist stability. Overall the ligaments have the appearance of a series of U shaped supports. The extrinsic ligaments beginning radially include the radioscapohcapitate

(RSC), long radiolunate (LRL), short radiolunate (SRL), ulnolunate (UL), and ulnotriquetral (UT) ligaments. The intrinsic ligaments include ligaments that cross the midcarpal joint including the scaphotrapeziumtrapezoid (STT), scaphocapitate (SC), triquetrocapitate (TC), and triquetrohamate (TH).

The remaining intrinsic ligaments are referred to as interosseous ligaments, which connect adjacent carpal bones of the proximal and distal row, and have both volar and dorsal components. In the proximal row there is the scapholunate interosseous ligament (SLIL) and the lunotriquetral interosseous ligament (LTIL). The interosseous ligaments of the proximal row are U shaped ligaments with a volar, membranous (proximal), and dorsal components that effectively isolate the midcarpal joint from the radiocarpal joint. Both the SLIL and LTIO allow intercarpal within the proximal row. The distal row has a series of interosseous ligaments as well including the trapeziotrapezoid (TT), capitotrapezoid (CT), and capitolunate (CH) ligaments. Unlike the proximal row's interosseous ligaments, these do not have a membranous portion and instead have isolated volar and dorsal components. Another difference from those of the proximal row is that they do not allow significant intercarpal motion in the distal, causing the distal row to behave as a fixed unit.

Muscles

The muscles that are important for this study are the wrist flexors and extensors, and the finger flexors (Figure 1-5 and 1-6). The wrist flexors are located on the volar side of the forearm and originate from the medial epicondyle of the humerus through the common flexor tendon. The two main wrist flexors are the flexor carpi radialis (FCR) on the radial side, and the flexor carpi ulnaris (FCU) on the ulnar side. The wrist extensors are located on the dorsal aspect of the

forearm and originate from the lateral epicondyle of the humerus through the common extensor tendon. The main wrist extensors are the extensor carpi ulnaris (ECU) on the ulnar side of the wrist and the extensor carpi radialis brevis and longus (ECRB+L) on the radial side of the wrist. The finger flexors used in this study are the four heads of the flexor digitorum profundus (FDP). The tendons of FDP pass through the carpal tunnel and insert on the distal phalanx on digits II-V.

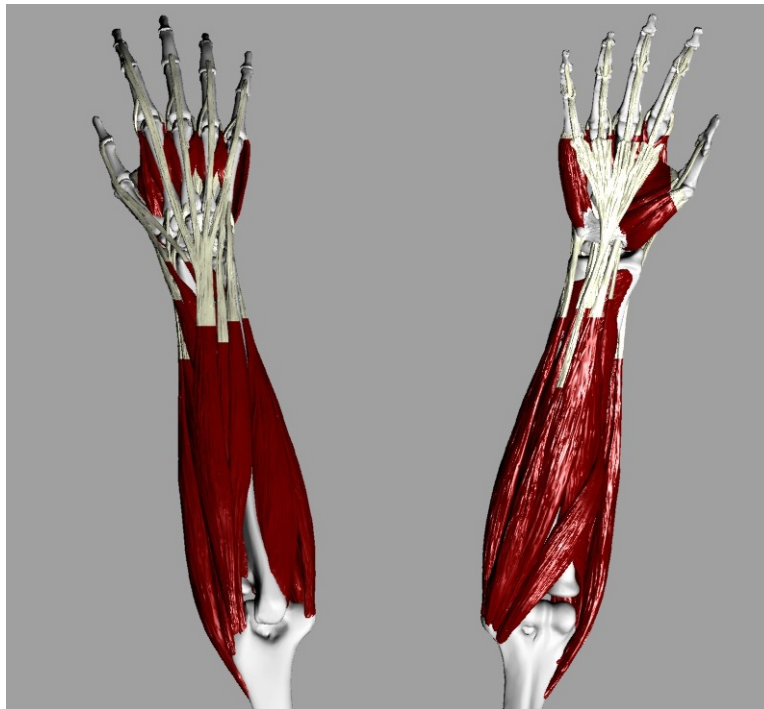


Figure 1-5. The muscular anatomy of the dorsal (left) and volar (right) aspect of the forearm and hand.

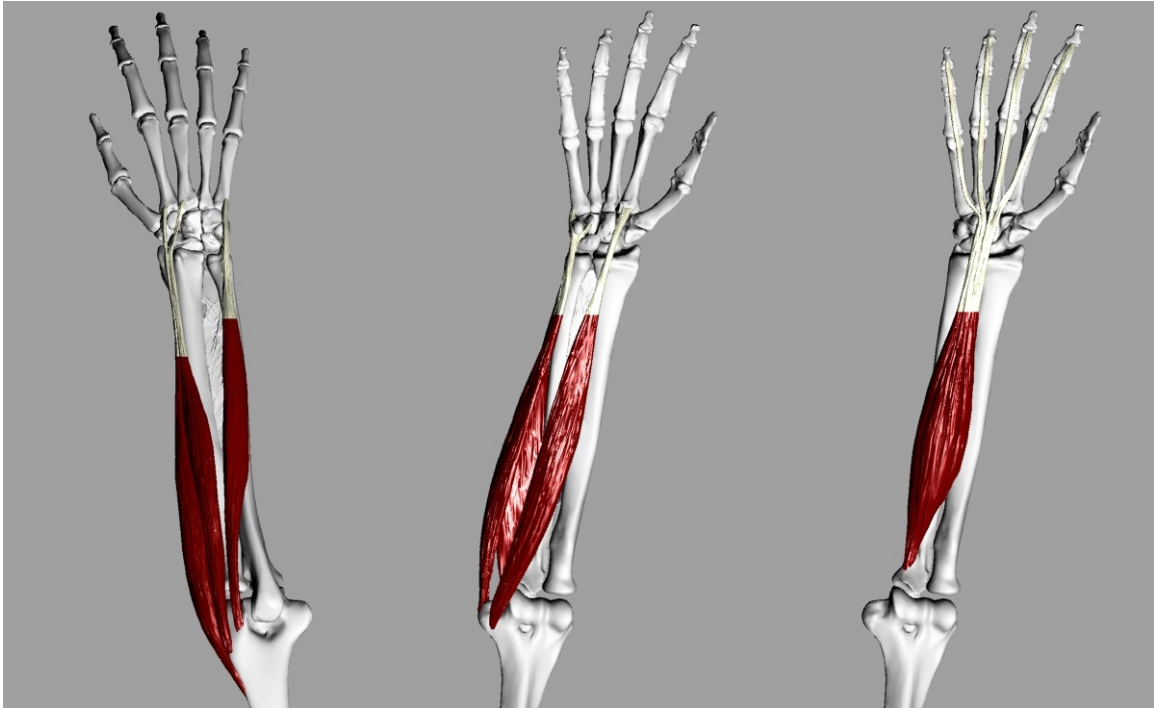


Figure 1-6. The left shows the anatomy of the wrist extensors, extensor carpi radialis longus and brevis, and extensor carpi ulnaris. The middle shows the anatomy of the wrist flexors, flexor carpi radialis, and flexor carpi ulnaris. The right shows the finger flexor, flexor digitorum profundus.

Kinematics of the Carpus

The original row theory described the proximal and distal rows as two fixed units that translated on each to achieve rotation²⁵. Later, the wrist was proposed to be consist of three columns: the central column of the hamate, capitate and lunate allowing flexion/extension; the lateral column of the scaphoid, trapezium, and trapezoid; and the medial column of the triquetrum and pisiform that allowed rotation²⁶. Later studies showed that there was relatively little motion between the distal carpal row (hamate, capitate, trapezoid, trapezium), and they instead acted as a fixed unit with wrist motion²⁷⁻²⁹. The proximal row showed significant intercarpal rotation compared to the bones of the distal row^{27, 29}. Despite the difference in angular rotation however, the direction of their rotation was similar with all wrist motions²⁸. In general the scaphoid had the greatest rotation, then the triquetrum, and last the lunate. With

flexion/extension the scaphoid rotated 90% of the total wrist rotation, the lunate rotated 50% and the triquetrum 65%³⁰. The proximal row then began to be described as an intercalated segment between the rigid distal row, and the radius^{29, 31}, whose kinematics were governed by the forces transmitted to it. With wrist flexion and radial deviation the proximal row flexed, while with wrist extension and ulnar deviation the proximal row extended.

The wrist range of motion in flexion-extension is 59° of extension to 79° of flexion (138° arc), and in radial/ulnar deviation the range is 21° radial deviation to 38° ulnar deviation (59° arc)³². Historically flexion/extension was thought to be the primary axis of rotation for the wrist given its larger arc compared to radial/ulnar deviation, but recent studies have suggested that the Dart Thrower's motion (radial extension to ulnar flexion) is the primary rotation axis of the wrist with the greatest arc¹². Regardless of the primary axis, the wrist can be thought of grossly as consisting of the radiocarpal joint and midcarpal joint. The relative contribution of each of these joints has been studied, and showed that with wrist flexion/extension approximately 50% of the rotation occurs at the radiolunate joint, and 50% at the capitulunate joint^{28, 33, 34}. Radiographic studies have also showed that the center of rotation for wrist flexion/extension and radial/ulnar deviation lies within the head of the capitate³⁵.

A basic explanation of proximal row carpal kinematics can be explained by two simple concepts. The scaphoid sits obliquely in the sagittal plane with its long axis flexed relative to the radius. This oblique orientation causes it to have a tendency to flex with compression from the distal row in wrist flexion or radial deviation. The scapholunate interosseous ligament connects to the lunate and because of it, flexion of the scaphoid leads to flexion of the lunate. This flexion is further transmitted to the triquetrum through the intact lunotriquetral ligament. Ulnarly the lunate is connected to the triquetrum through the lunotriquetral ligament. The triquetrum has a

helicoidal articulation with the hamate distally which causes it to have a tendency to extend in response to compression from the distal row with wrist extension and ulnar deviation. Extension of the triquetrum then leads to extension of the lunate through the intact lunotriquetral ligament.

Joint Testing Systems

The design of this wrist testing system was made by taking into consideration the designs of many cadaver testing systems that have been published previously. Although there are too many joint testing systems to discuss here, there were several basic design principles that each testing system had to consider. These design principles were: loading protocol, specimen positioning, kinematic measurements, and post experimental modeling.

The two basic loading protocols employed in kinematic studies are anatomical muscle loading through muscle tendons and joint compressive loading. Anatomical muscle loading has the advantage of simulating in vivo muscle contraction. A potential disadvantage however is that in vivo muscle loads are currently unknown, so assumptions must be made to determine what loads to apply to the muscle tendons. Joint compression loading relies on applying a compressive force across the joint through one or both of the bones in the joint. Joint compression loading relies upon on bony geometry to determine the joint kinematics, but does not account for in vivo muscle forces.

Specimen positioning can be accomplished by either static or dynamic positioning. Dynamic positioning involves changing the loads applied to the muscle tendons to achieve the desired joint position. Using muscle loads to achieve joint position mimics how joints move in vivo, however the required muscle loading for a specific position represents an indeterminate

problem. The muscle load required to reach a specific position can be affected by the direction the joint is moving from, and the current condition of the specimen. This results in non-repeatable loading conditions for a specific position across multiple testing conditions. Static specimen positioning involve positioning the joint, locking it in place, and then applying muscle loads through the muscle tendons. The advantage of this is that the exact same muscle loads can be applied to each position for each condition tested. The disadvantage of this is that it does not mimic how in vivo joint motion occurs.

The kinematic measurements made during testing can be made using several techniques including direct measurement with 3D digitizers, continuous measurements using electromagnetic devices, and optical tracking using markers embedded in bone with a series of cameras tracking its 3D location. Each has its advantages and disadvantages. Direct measurements are the simplest, although are not capable of providing continuous kinematic measurements. Electromagnetic and optical systems provide continuous kinematic measurements but are very expensive. Electromagnetic systems are also prone to interference from ferromagnetic materials, while optical systems are limited by the line of sight of the cameras.

Lastly, post experimental modeling can be achieved in two ways, either through direct digitization of the bones following experimentation or through 3D imaging such as a CT scan. Post experimental CT scans are very expensive and require special software to recreate 3D models of the bones from the CT scan, but can be done very rapidly. Direct digitization can be tedious, but does require access to a CT scanner and is significantly cheaper.

The disadvantages of cadaveric experiments are not insignificant however. Cadaveric specimens are often of advanced age, often with gross evidence of degenerative joint disease or

tissue degeneration. There is also an unknown previous injury history and medical history. In addition, there is great heterogeneity between cadaveric specimens in regards to their anatomy, making it difficult to make paired comparisons. There is also the issue of high costs associated with acquiring cadaveric joints, and maintaining an infrastructure to test and store them. Lastly, and most importantly, cadaveric experiments are unable to account for the biological process of healing, and only give insight to the effects of a particular repair technique at time zero.

Alternatives to cadaver-based studies include in vivo animal studies, finite element modeling, and radiographic based in vivo human studies. In vivo animal studies allow the biologic process of healing to be incorporated into experiments, but introduce the difficulty in finding animal models that accurately resemble the human anatomy. Two major anatomical issues include the relatively small size compared to humans, and the fact that most animals are quadriceps while humans are bipedal. This results in changes in joint loading and gait characteristics. Animal studies also come at a high cost, and raise ethical issues.

Finite element models provide a way to model joint mechanics and simulate the effect of certain injuries. The advantage is that once the model has been developed and validated, simple simulations can be performed quickly. The disadvantage is that all results from these models are theoretical. Secondly, the process of developing a new model and validating it is very computational involved and time consuming. These FEM models ultimately have to be validated by comparing to other studies such as in vivo radiographic studies or cadaveric studies, causing them to have trouble establishing stand-alone value.

The last alternative is radiographic in vivo human studies for joint kinematic studies. The techniques for this include plain film xrays, CT scans, MRIs, or biplane fluoroscopy. The

primary advantage of in vivo human studies is that the true in vivo loading conditions and joint positioning are being measured. It also offers the ability to study naturally occurring injuries as opposed to those artificially created in cadavers. Although having many advantages, there still are significant disadvantages including the high cost of these radiographic techniques, the need for IRB approval prior to any study, and the difficulty of recruiting volunteers of the desired demographic.

In spite of the disadvantages of cadaveric testing systems, there are still significant advantages. Cadaveric studies allow multiple testing conditions to be performed in a single specimen ranging from the intact condition, to a specific injury model, and then to the repaired condition. Having each specimen as its own internal control allows the researcher to isolate the independent variable of the injury and evaluate its effect. Cadaveric studies also an avenue to innovate new orthopedic techniques and test new orthopedic hardware prior to using it in vivo. Information gathered in cadavers can directly translate to changes in clinical practice, truly allowing translational medicine to occur. Lastly, there is the advantage that experiments can be done rapidly without recruiting human subjects, and still at a significantly lower cost compared to animal or human studies.

Objectives of Study

The purpose of this study was to develop a cadaver based wrist testing system in order to understand carpal kinematics under conditions that mimic the loading conditions seen in vivo. The testing system is based on linear actuators with in series load cells controlled by custom coded Labview software that are connected via sutures to the muscle tendons of wrist

flexors/extensors and finger flexors, allowing fully customizable loading protocols. Carpal kinematics are measured using custom posts inserted into the carpus and digitized with a Microscribe 3DLX. Post-experimental dissection and digitization were used to create 3D models of the carpus at each testing position.

Following completion of the testing system and methods, a three-armed study will be performed to both validate the testing system and investigate the effect of grip in the intact wrist and after an injury to the SLIL. The first arm of the study will be to measure the intact rotational kinematics of the scaphoid and lunate in the intact wrist. These measurements will be compared to data shown in other studies in order to validate our testing system. The second arm of the study will be to evaluate the effect of grip on the intact wrist. The effect grip has on the rotation of the scaphoid and lunate will be measured. Additionally, post experimental digitization and centroid calculation will be used to measure the effect grip has on the distance between the scaphoid and lunate at the SL joint and the proximal and distal location of the head of the capitate.

The third, and most significant arm, of the study will be investigating the effect of grip on the acutely torn SLIL wrist, and then to measure the effect of repetitive grip loading (500 cycles) on the kinematics of the carpus. A clinical study has shown that workers that required forceful lifting or gripping had significantly worse outcomes following repair for a torn SLIL, suggesting that grip can play a role scapholunate instability³⁶. The overall goal is to assess if repetitive grip loading is sufficient to worsen the kinematic disturbances seen after the acute injury, and, if so, to possibly determine a mechanism by which it does so.

CHAPTER 2

Development of an Actuator Driven Cadaveric Wrist Testing System

Testing System Design Summary

The goal of the custom testing system is to be able to track carpal kinematics under a variety of testing conditions while applying user defined loads to muscle tendons in an anatomic line of pull directly via linear actuators (Figure 2-1). A cadaveric upper extremity from the mid humerus to hand is mounted to the testing system and the wrist flexor and extensor tendons will be connected to the linear actuators through strings and running sutures placed in the tendon. The testing system has 8 linear actuators, which have a load cell mounted on the tip of the actuator, each of which is connected to a custom mount with two pulleys and a guide that passes a string from the actuator to the desired tendon in an anatomic line of pull. The actuators and load cells are connected to a PC running custom coded Labview (National Instruments) software. The user will input the desired load to the software, which will then make the linear actuator pull on the muscle tendon until it reaches the desired load. The testing will be performed in a quasi-static fashion whereby the wrist will be held in a fixed position and then the muscles loaded. At each position the kinematics of the distal radius, scaphoid, lunate, and capitate will be recorded using a Microscribe 3D digitizer.

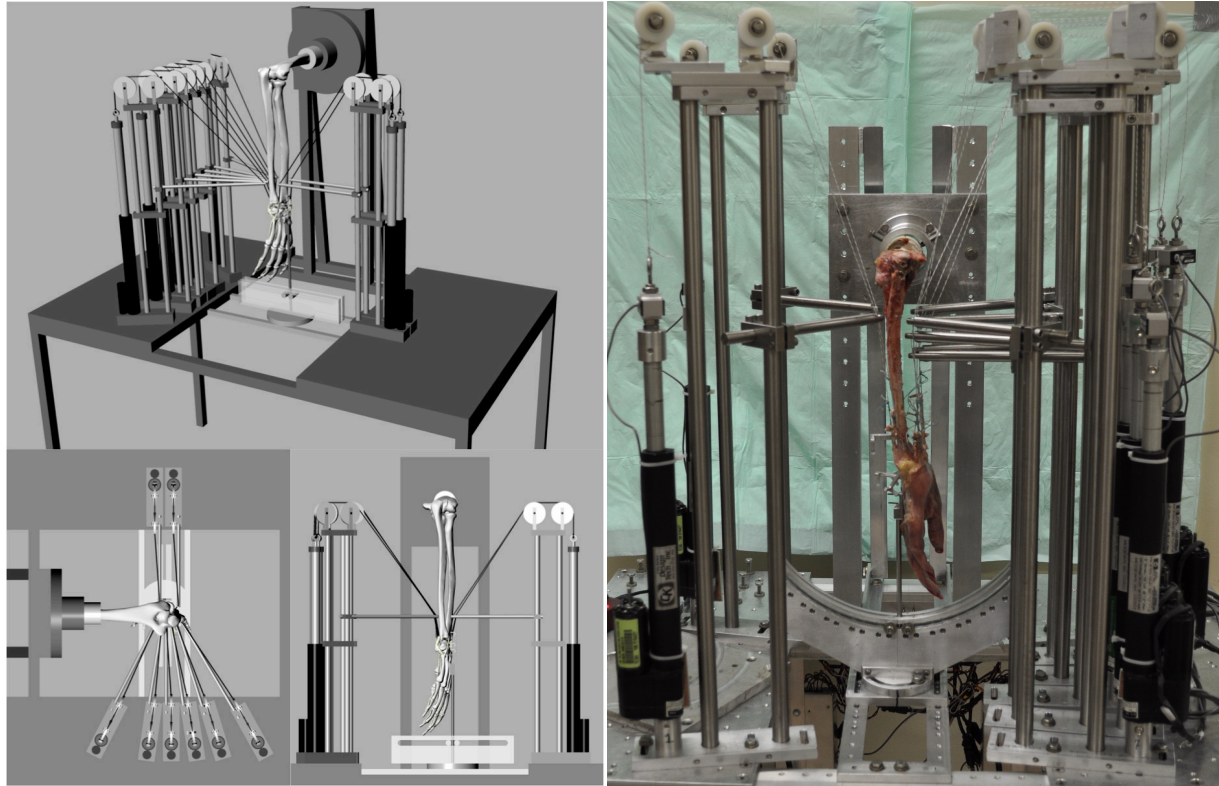


Figure 2-1. On the left is the design for the testing system and on the right is the finished system with a specimen mounted.

Testing System Components

Linear Actuators: The eight custom built linear actuators used in the testing system each have a 6 inch stroke length and are each capable of delivering 1300 N of force at a maximum rate of 1.5” per second. The actuators accept a pulse width modulation (PWM) signal. PWM signals are binary square waves that switch between an “ON” voltage and “OFF” voltage. The width, or amount of time, that the signal is “ON” is what determines the position of the actuator. The actuators accept a PWM from 1ms (fully retracted) to 2ms (fully extended) with a period of 7ms (Figure 2-2). Each actuator has a control board that requires 12V of direct current power supply, and then the wires carrying the PWM signal.

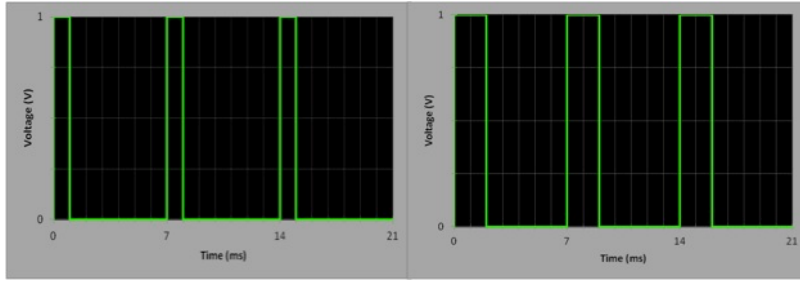


Figure 2-2. Example PWM square waves generated. 1 ms “ON” signal on the left for fully retracted, and 2 ms “ON” signal on the right for fully extended.

Load Cells: The load cells used have a range from -670N to 670N. Load cells are essentially calibrated strain gauges whose resistance alters as a function of force. A known excitation voltage of 10 V is applied across a bridge sensor and then the signal voltage is measured, -20 mV (maximum compression) to 20 mV (maximum tension) (Figure 2-3). The signal voltage is proportional to the load across the load cell, and once calibrated, the measured signal voltage is used to determine the actual load.

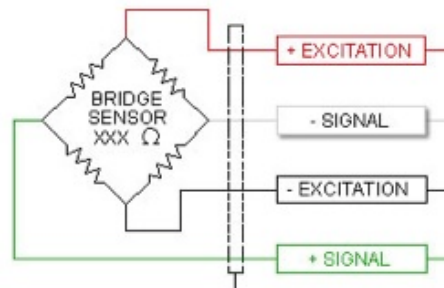


Figure 2-3. Diagram showing the bridge used in load cells

National Instruments PCI 6602 Counter/Timer Board & NI-DAQ: A National Instruments PCI card was installed in the PC capable of generating PWM and other counter signals. These signals can be generated in Labview. The NI-DAQ is connected to the PCI card by serial cable and contains the terminals that the actuator control boards can be connected to in order to deliver the PWM signals.

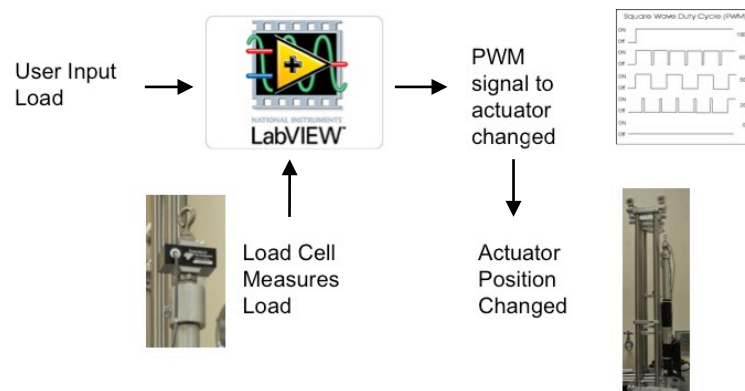
National Instruments cDAQ9174 and NI 9237: The cDAQ9174 is a chassis that connects to the PC via usb and can hold up to four NI 9237 cartridges. Each NI 9237 can accept 4 analog inputs from load cells or other devices. The two NI 9237 are each connected to four load cells on the linear actuators. The NI 9237 can be programmed in Labview to deliver the appropriate excitation voltage for each load cell and then measure the signal voltage in order to determine the load across the load cell.

National Instruments Labview Software: Custom coded software was developed to measure the load from each load cell and deliver appropriate PWM signals to each linear actuator in order to achieve the desired force for each muscle tendon. The code was developed from the ground up to achieve the specific aims of the project. Items developed include: tarring of the load cells, load cell signal noise cancellation, customizable starting positions for actuators, application of small preloads to assure simultaneous loading for all tendons, ability to cycle loads between a high and low for prescribed number of cycles, and optimization of our proportional-integral-derivative controller algorithm for stability and responsiveness.

Microscribe 3DLX: The Microscribe is a 3D digitizer that records the location of the point it is touching whenever a foot pedal is depressed. The Microscribe is used to digitize three points on the posts that are anchored into the radius, scaphoid, lunate, and capitate. Using these digitized points on each bone custom coordinate systems can be created in order to make anatomic measurements of flexion/extension, pronation/supination, and radial/ulnar deviation. Post experimental digitization of the entire boney surface of these bones along with the three points on the post is also used to create 3D reconstructions of the boney kinematics at each testing position.

Labview Control Software

To simulate musculature contracture, loads will be applied directly to the tendons of the wrist flexors and extensors by linear actuators. Krackow stitches in each muscle tendon will be used to connect strings running from the linear actuators to the tendons to apply force. The force applied is a fixed number, but how the actuator gets from unloaded to its desired load is based upon the algorithm used to control the actuator. A basic explanation of this system is that of a simple feedback loop (Figure 2-4). The user inputs a desired force and the computer calculates where it should move the actuator to in order to achieve that load based on its algorithm. After the computer has moved the actuator then the load cell measures the actual force and determines how far it is from the desired load. This error is then fed back into the algorithm and the computer adjusts the actuator again to get closer to the desired load. This process continues until the actual load has reached the desired load.

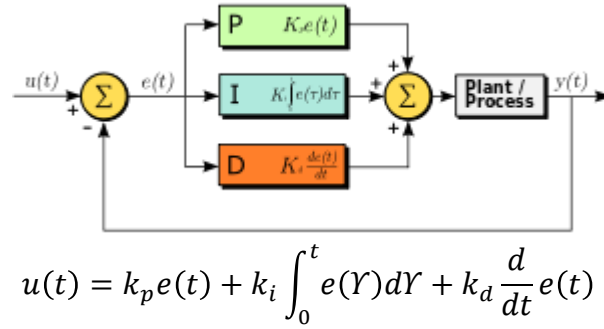


2-4. Overview of system operation

One of the simplest types of control algorithm is a constant rate controller. The actuator moves at a constant rate (distance per unit of time) until it achieves its load. This type of controller is prone to overshoot and can become very unstable however. The response to an error

is the same, no matter the magnitude of the error. A much more stable algorithm bases its response on the magnitude, duration, and change of error. This type of algorithm is referred to as a PID algorithm, proportional-integral-derivative. While this algorithm does not apply a constant loading rate, it can be optimized to prevent overshoot, and remain stable against disturbances.

PID algorithms are regarded as a very robust control algorithm for processes and require no knowledge of the underlying process. The PID algorithm (Figure 2-5) runs in a loop and controls the input value to a process by measuring the difference between the desired output of the process and the actual output, or the error, at each cycle. The control uses the error in three terms in order to alter the input to the process to minimize the error of the system. The first term is the proportional term. In the proportional term the current error, $e(t)$, is multiplied by a user specified constant, k_p , thereby altering the input to the process by a value that is proportional to the current error. The second term is the integral control. Integral control is based on the accumulation of past errors and is determined by multiply the integral of all previous errors up until time t , $k_i \int_0^t e(Y) dY$, by the user specified constant k_i . The integral term allows the process to increase its response to errors that persist over time. The last term is the derivative term. The derivative term alters the input of the process by multiplying a user specified constant, k_d , on the current rate of change of the error by the derivative of error, $\frac{d}{dt} e(t)$. The combination of these three terms determines the control signal sent to the linear actuator.



$e(t)$ = Error = Set Point – Present Value

k_p = proportional gain

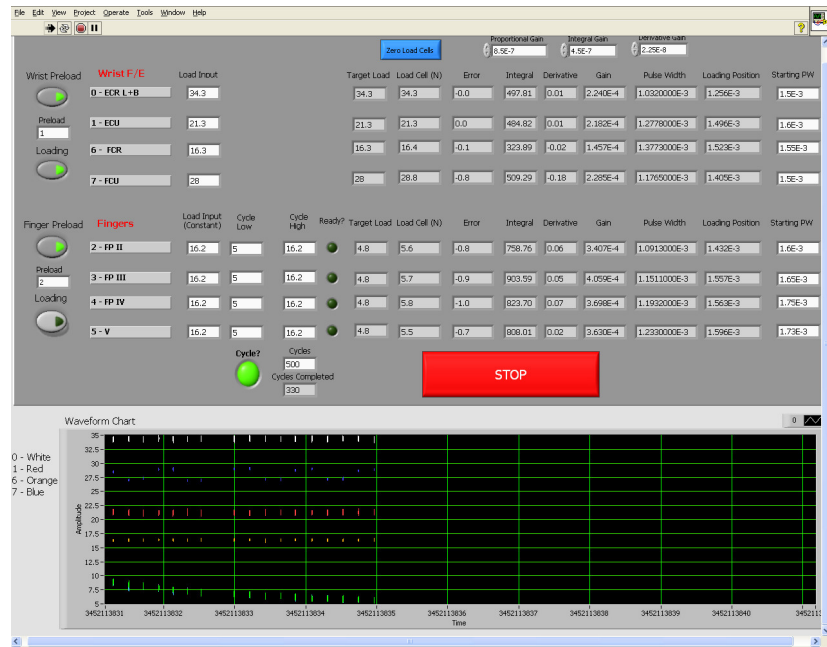
k_i = integral gain

k_d = derivative gain

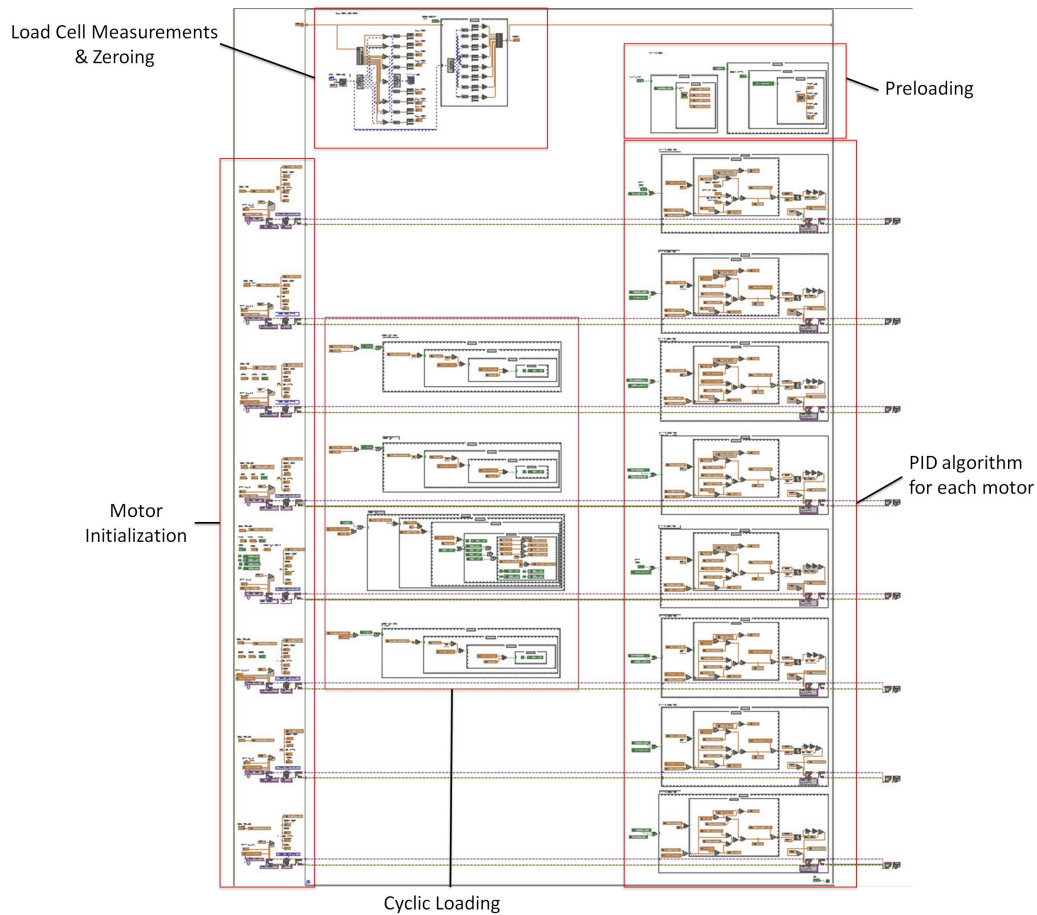
Figure 2-5. The mathematical equation governing the PID algorithm.

A fundamental explanation of how a PID algorithm behaves is that the further the measured output is from the desired output, the more it will change the input to the system in order to achieve the desired output. As the measured output approaches the desired output, the PID algorithm makes much smaller changes to the input. This behavior of PID algorithms is responsible for its ability to control many types of systems, however in terms of applying force it does create the issue of variable rate of loading. The loading rate is dependent on the error, integral of the error, and derivative of the error, as well as their respective user defined controls. This is an inherent limitation to our system. We believe that the stability and robustness of the PID system outweighs the disadvantages of variable rate of loading.

The actuators will be controlled by custom Labview software with a custom PID controller algorithm built for it. The custom Labview controller for the actuators is shown in Figures 2-6 and 2-7. The controller allows constant loads to be applied to FCU, FCR, ECU, and ECRB+L as well as the four heads of FDP to simulate grip. Each actuator has the ability to be turned off or on independently without affecting the performance of the other actuators.



2-6. Labview control interface where user can input loads, cycles, and turn actuators on/off



2-7. Labview code.

The most important part of a PID algorithm however is the determination of the user specified constants k_p , k_i , and k_d . Optimization of these parameters is paramount in order to create a stable system that can apply a specified force. Optimization of the loop can be performed using any number of software based or trial and error methods. A common method that we chose to use was the Ziegler-Nichols PID optimization technique³⁷. This method relies up first setting k_p , k_i , and k_d all to zero and then slowing increasing k_p until the system begins to oscillate with a fixed amplitude. This value of k_p is then referred to as the ultimate gain, or K_U . The period of the oscillations at K_U is referred to as the oscillation period, to T_U . Ratios of K_U and T_U that were empirically derived by the original innovators are used to determine the appropriate values of k_p , k_i , and k_d (Table 1). For our software/hardware the K_u was determined to be 1.42×10^{-6} with a T_U of 2.27 s^{-1} . Using the ratios from the Ziegler-Nichols method k_p was set to 8.5×10^{-7} , k_i was set to 4.5×10^{-7} and k_d was set to 2.4×10^{-7} .

	K_p	K_i	K_d
Ziegler-Nichols Method	$0.60 K_U$	$1.2 K_U / T_U$	$0.075 K_U * T_U$
Values Used	8.5×10^{-7}	4.5×10^{-7}	2.4×10^{-7}

Table 2-1. The ratios of K_U and T_U used in the Ziegler-Nichols method to create a stable PID algorithm.

In addition to applying constant loads to the tendons, the system is designed to be able to cyclically load the finger flexors in order to simulate repetitive grip as would be seen in vivo. To accomplish this, the user inputs the high and low load for each cycle as well as the number of cycles to be completed. During the cycles, all four heads of the FDP are loaded and ranged from the low load to the high load. During each cycle the system waits until all 4 tendons have reached the desired high or low load before switching loads. This accomplishes smooth cyclic

loading to the FDP to simulate repetitive gripping as would be seen in patients performing activities of daily living.

Muscle Loads

The muscle loads used in this study are based off of physiological cross sectional area (PCSA) of the muscles as cross sectional area is proportional to the maximum contractile force that a muscle can deliver³⁸. As absolute values of muscle forces are unknown in vivo, studies often use ratios based either off of PCSA or EMG studies. A total load of 100N was chose to be applied to the wrist flexors and extensors (FCU, FCR, ECU, ECRB+L), which was distributed to each muscle tendon based upon their cross sectional areas³⁹ (Table 2-2). The four heads of FDP were loaded evenly, with their load being determined by their average PCSA and the N/mm² that was applied to the wrist flexors/extensors.

<u>Muscle</u>	<u>Physiological Cross Sectional Area (mm²)</u>	<u>Muscle Force (N)</u>
Flexor Carpi Ulnaris	342	28.0
Flexor Carpi Radialis	199	16.3
Extensor Carpi Ulnaris	260	21.3
Extensor Carpi Radialis Brevis	273	22.4
Extensor Carpi Radialis Longus	146	12.0
Flexor Digitorum Profundus II	177	16.2
Flexor Digitorum Profundus III	223	16.2
Flexor Digitorum Profundus IV	172	16.2
Flexor Digitorum Profundus IV	220	16.2

Table 2-2. PCSA values from Lieber, 1992. 100N was divided to FCU, FCR, ECU, ECRB, and ECRL based on PCSA. The 4 heads of FDP were loaded evenly based upon their average PCSA and the N/mm² that was applied to the wrist flexor/extensors.

Specimen Preparation

Fresh frozen cadaveric upper limbs from mid humerus to hand were thawed overnight prior to dissection. Care was taken to preserve the wrist and elbow capsule during dissection. All remaining soft tissue from midhumerus to the wrist was removed, preserving the tendons of extensor carpi radialis longus & brevis (ECR L+B), extensor carpi ulnaris (ECU), flexor carpi radialis (FCR), flexor carpi ulnaris (FCU), and the 4 tendons of flexor digitorum profundus (FDP). All tendons are isolated proximal to the wrist, taking care to preserve their distal sheaths. A Krackow stitch is then placed in each tendon using #5 Fiberwire (Arthrex, Inc., Naples, FL) allowing tension to be applied to the tendon by pulling on the strands of the Fiberwire. Later these Krackow stitches will be used to connect the muscle tendons to the linear actuators with strings.

The distal humerus is potted in a polyvinylchloride (PVC) pipe using plaster of Paris and two wood screws that run perpendicular to each other. The elbow is pinned at 90° of flexion and the forearm is locked at neutral pronation/supination by inserting two Kirschner wires through the distal radius into the ulna. The specimen is then mounted into the jig by inserting the PVC pipe containing the distal humerus into the mounting cylinder on the jig and secured using 8 pressure screws. The Krackow stitches placed earlier into the tendons of the wrist flexor/extensors and finger flexors are then connected to cables of the linear actuators. These cables run over two pulleys and connect to the linear actuators that will apply the load. The direction of each line of pull is adjusted using aluminum guides to ensure each tendon is loaded anatomically.

A rod is then connected to the dorsal aspect of the third metacarpal by passing two screws through the bone from the volar aspect. The screws are then attached to the rod and tightened with nuts. During the volar approach to the third metacarpal to drill and pass the screws, care was taken to preserve the tendons of the finger flexors and the transverse carpal ligament proximally. Once secured to the dorsal aspect of the 3rd metacarpal, this rod will be used to control the position of the wrist by placing it through a guide consisting of two parallel plates.

Custom posts were created in order to track the kinematics of the carpal bones and distal radius with a Microscribe 3DLX. Each of the posts have a threaded screw at one end to insert into the bone and then the other end of the post has two aluminum arms that stick out at 90° from each other. At the center of each post and at the tip of each arm and at the main a small indentation was machined into the aluminum that allowed repeatable positioning of the Microscribe probe. Each position the three points on the post of each bone are digitized with the Microscribe in order to create a local coordinate system on each bone for future 3D modeling, and also to make anatomical rotation measurements. These posts are inserted into the distal radius, scaphoid, lunate, and capitate. A small dorsal capsulotomy is performed in order to expose the dorsal aspect of the scaphoid, lunate, and SLIL. The capsulotomy is performed similar to the original proposed by Berger⁴⁰; however it is made smaller and does not sacrifice any portion of the DRC or DIC (Figure 2-8). Following the capsulotomy the SLIL was visually inspected to confirm that it was intact and for evidence of advanced degenerative arthritis or gross instability. Any specimen with a torn SLIL or evidence of instability was excluded. Prior to inserting the post, k-wires are inserted into the bones and the wrist is ranged in order to assure the posts will not impinge on each other or surrounding bones, and that they do not violate the midcarpal or radiocarpal joints. The posts in each of the distal radius, lunate, and capitate are

placed such that one wing of the post is pointing ulnar and the other is pointing distal. The post in the scaphoid is placed with one wing pointing radial and the other pointing distal (Figure 2-8).

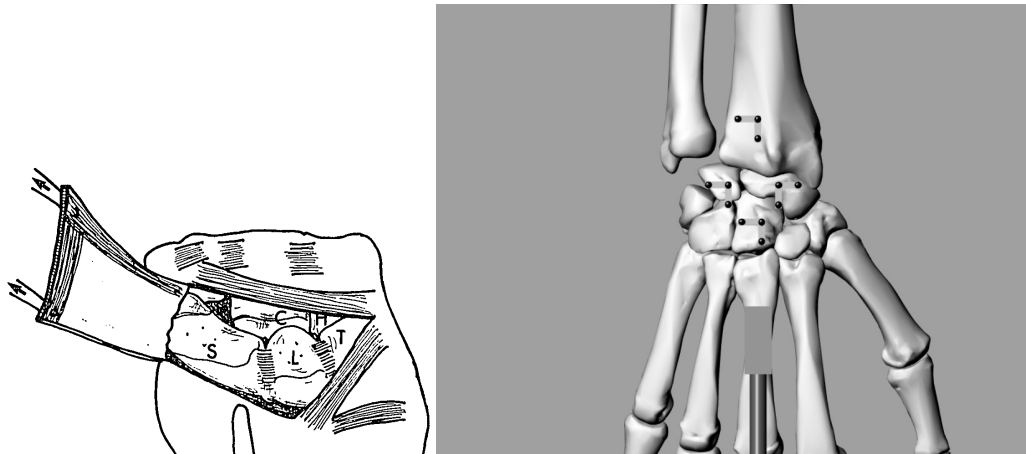


Figure 2-8. On the left is a larger example of the dorsal capsulotomy used to expose the scaphoid and lunate to insert the tracking posts⁴⁰. The right shows the tracking posts inserted into the radius, scaphoid, lunate, and capitate

Quasi-Static Wrist Positioning

Repeatable positioning of a joint is paramount to kinematic studies. Previous studies in carpal kinematics have used both dynamic⁴¹⁻⁴⁸ and quasi static positioning of the wrist⁴⁹. Both are capable of repeatable positioning of the wrist although they do so in different ways. Dynamic studies involve applying loads directly to the muscle tendons of wrist flexors/extensors in order to move the wrist to a desired position. Quasi-static studies involve positioning the wrist and holding it in place using external hardware and then applying loads to the muscles tendons. While it can be argued that loading the muscle tendons to position the wrist, as is done in dynamic testing, more closely represents physiological conditions, these dynamic motions require complex computer algorithms to determine the load required to be applied to each tendon in order to obtain the desired wrist position. The largest problem with dynamic testing is there is not a single combination of muscle loads that achieve a given wrist position. There are an infinite

number of muscle loading combinations that can achieve a single wrist position, and which one is selected by the computer algorithm is sensitive to many parameters such as the starting position of the wrist, the direction the wrist is moving in, the speed the wrist is moving at, user assumptions, and many other conditions. In the end dynamic systems do create repeatable positioning of the wrist; however, the muscle load at a single position can be variable from cycle to cycle. Quasi-static studies involve positioning the specimen in the desired position, constraining it in this position, and then loading the muscles to a desired load. This has the advantage of both controlling the positioning of the wrist and the loading conditions at each position. By controlling both the positioning and muscle loading it allows us to isolate the dependent variable of carpal kinematics.

Global wrist motion is measured by comparing the angle between the shaft of the radius and the third metacarpal. Flexion and extension of the wrist occur in the sagittal plane while radial and ulnar deviation of the wrist occur in the coronal plane. During testing the wrist will be moved through from 45° flexion to 30° extension in 15° and from 10° radial deviation to 20° ulnar deviation in 10° increments⁴¹⁻⁴³. Prior to muscle loading the wrist will be locked into a fixed position by locking a bar extending from the dorsal aspect of the third metacarpal into a fixed angle of flexion/extension or radial/ulnar deviation in a rotating arc guide consisting of two parallel plates (Figure 2-9). This plate can be rotated into various anatomic planes, but for the purpose of this study it was used in the flexion/extension plane, and radial/ulnar deviation plane. Future studies are possible to use in other planes such as the dart thrower's motion⁵⁰ (extension with radial deviation to flexion with ulnar deviation).

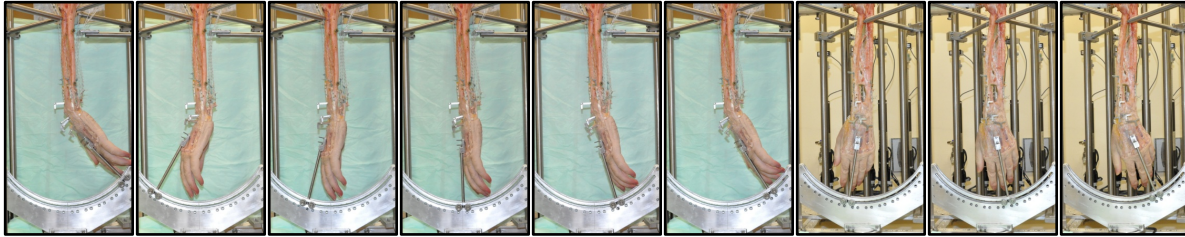


Figure 2-9. Positions tested showing the angle control guide at the bottom of the pictures.

Kinematic Measurements

The three points on each post inserted into the radius, scaphoid, lunate, and capitate will be measured at each testing position/condition. The 3 points on each post form a 90° and the post in the distal radius is placed so that the two arms are facing distal and ulnar. A new anatomic coordinate system is then formed using these three points on the radius such that the axes are (+X) Ulnar, (+Y) Distal, (+Z) Anterior. This is accomplished by calculating the inverse rotation matrix from the three points in the radius and then multiplying it by a vector formed from the origin on the radius post to the location of the point being transformed (Figure 2-10). Conversion of all points measured from the posts in the scaphoid, lunate, and capitate into the custom radius coordinate system via coordinate transformation allows accurate anatomic measurements to be made. Also, by creating a local coordinate on the specimen itself it removes the possibility of errors that could be caused if the specimen were moved, either due to muscle loading or incidentally, during testing.

$$(P_x, P_y, P_z)_{X_R} = [R_{Rad}^{-1}]_{Exp} \cdot [(P_x, P_y, P_z)_{X_{MS}} - (O_x^R, O_y^R, O_z^R)_{X_{MS}}]$$

Where,

$(P_x, P_y, P_z)_{X_R}$ = coordinates of point in the new radius coordinate system, X_R

$[R_{Rad}^{-1}]_{Exp}$ = inverse of rotation matrix for radius coordinate system

$(P_x, P_y, P_z)_{X_{MS}}$ = coordinates of any point in the Microscribe coordinate system, X_{MS}

$(O_x^R, O_y^R, O_z^R)_{X_{MS}}$ = coordinates of origin point on the Radius Post in X_{MS}

Figure 2-10. The coordinate transformation equation

Once in the radius coordinate system, measurement of the anatomic rotations of the scaphoid and lunate can be made by using the 3 points on each bone (Figure 2-11). For flexion/extension the angle of the posts in the anterior-distal compared to vertical is measured using the arcsine function. For radial/ulnar deviation the angle of the posts in the ulnar-distal plane was used. For pronation/supination the angle of the posts in the ulnar-anterior plane was used. Examples of rotation in each plane are seen in Figure 2-12. Due to the variability in the angle that the posts are placed in each specimen, data was normalized relative to the rotational position of the scaphoid and lunate at neutral wrist flexion/extension.

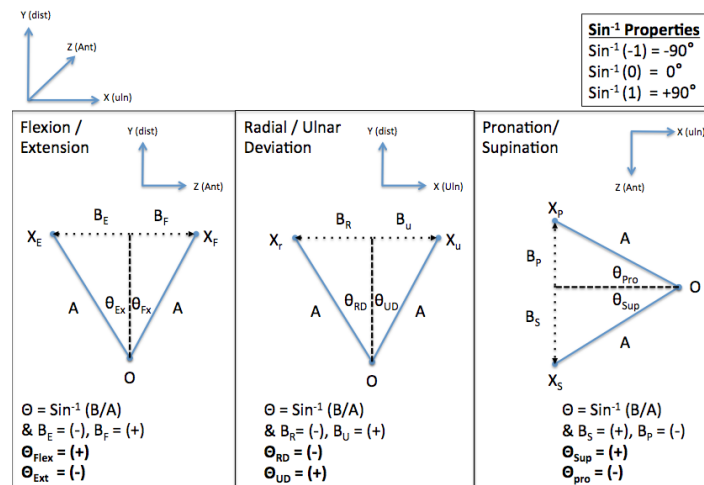
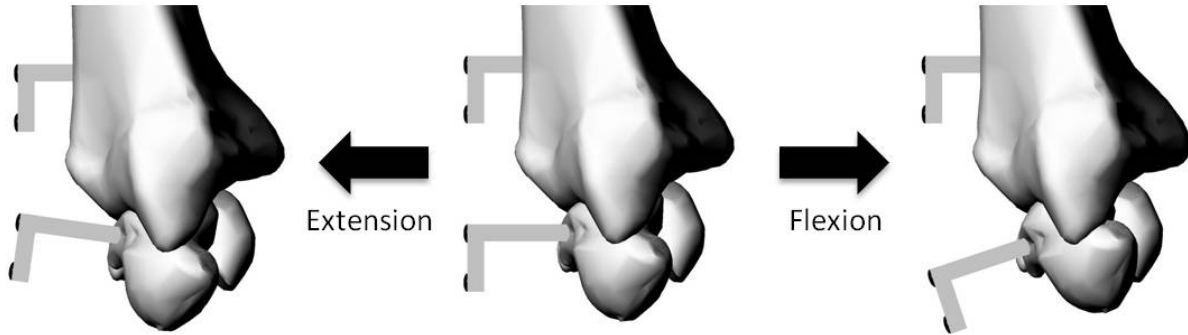


Figure 2-11. Arcsine calculations for anatomical rotations.

Flexion & Extension



Radial & Ulnar Deviation



Pronation & Supination

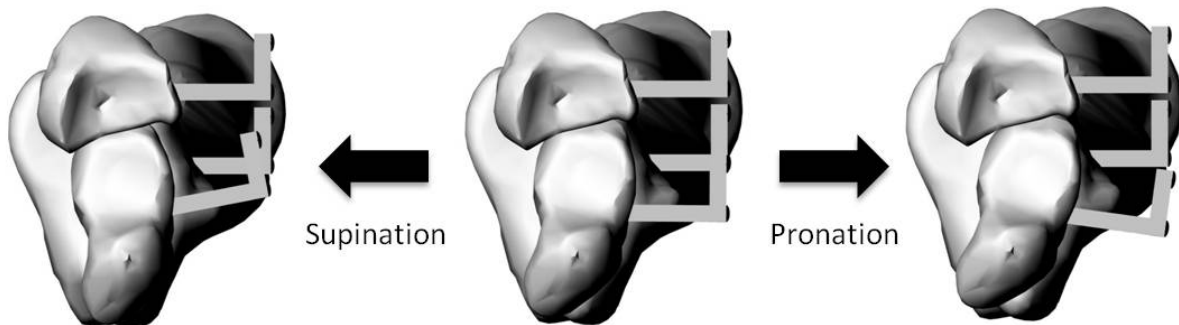


Figure 2-12. Example of the scaphoid rotating in each anatomical plane.

3D Modeling and Centroid Calculations

Following testing, the scaphoid, lunate, and capitate are dissected from the surrounding connective tissue and isolated, taking care to preserve the position of the posts in each bone.

Once the bones are isolated, 3D digitization of the bones is performed by digitizing between 71 and 81 points on the surface of each bone, organized into cross sectional cuts. There were 76

points digitized on the distal radius (6 cross sectional cuts beginning just proximal to Lister's tubercle), 81 on the scaphoid (7 cross sectional cuts), 71 on the lunate (6 cross sectional cuts), and 81 on the capitate (7 cross sectional cuts) (Figure 2-13). The three points on each post in each bone are recorded during the digitization process so that a local coordinate system can be created for each bone. Points on the surface of each bone are then transformed into the local coordinate system of the bone (Figure 2-14). Converting these surface points' location in the local coordinate system relative to the post in the bone allows the points to be transformed in the radius coordinate at each testing condition based on the position of the post at that particular testing condition (Figure 2-15).

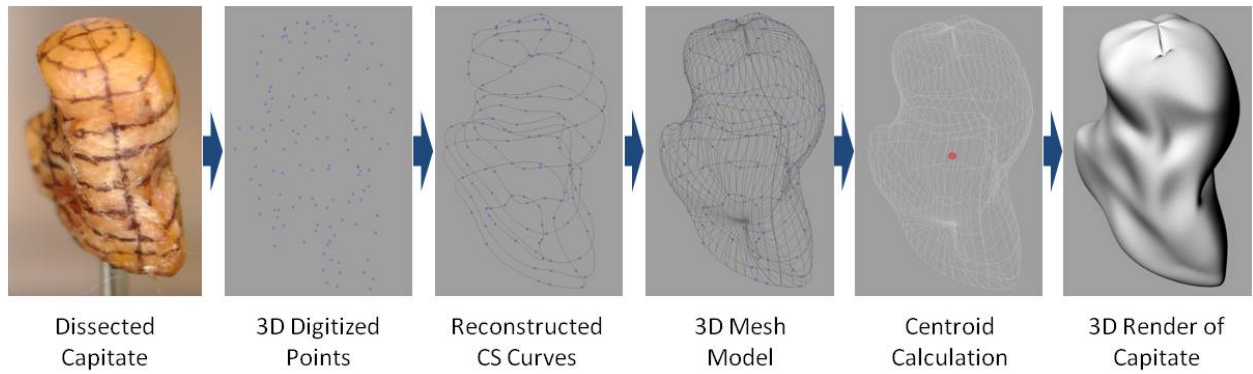


Figure 2-13. Digitization process example for the capitate

$$(P_x, P_y, P_z)_{X_{SC}} = [R_{SC}^{-1}]_{Geometry} \cdot [(P_x, P_y, P_z)_{X_{MS}} - (O_x^{SC}, O_y^{SC}, O_z^{SC})_{X_{MS}}]$$

Where,

$(P_x, P_y, P_z)_{X_{SC}}$ = coordinates of point in the scaphoid coordinate system, X_{SC}

$[R_{SC}^{-1}]_{Geometry}$ = inverse of rotation matrix for scaphoid coordinate system

$(P_x, P_y, P_z)_{X_{MS}}$ = coordinates of a point on the scaphoid in X_{MS}

$(O_x^R, O_y^R, O_z^R)_{X_{MS}}$ = coordinates of origin point on the Radius Post in X_{MS}

Figure 2-14. The coordinate transformation equation

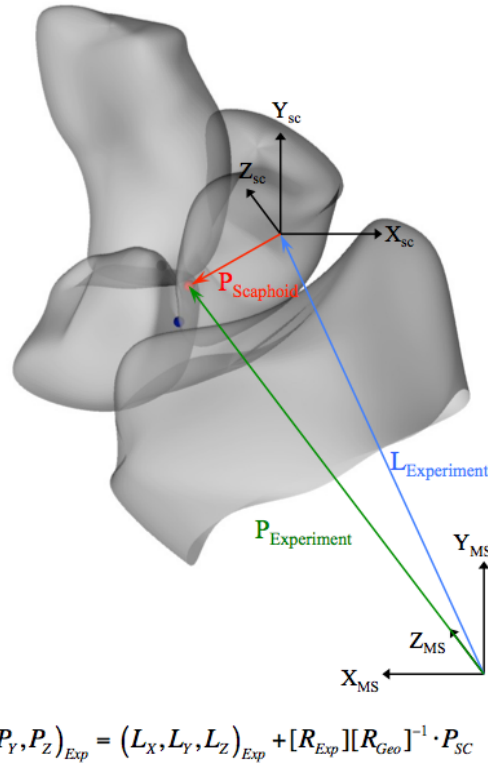


Figure 2-15. Post-experimental coordinate transformation

In addition to being able to reconstruct 3D models of the bones at each testing conditions, the specimen specific geometry is used to make anatomic measurements that are not possible during testing. Highlighting the scapholunate joint, the three most important anatomic measurements, besides the rotations that have been previously calculated, are the distance between the scaphoid and lunate at the joint, or SL gap, and the location of the capitate head. Calculation of the SL gap is done by first determining a fixed position on the face of both the face of the scaphoid and lunate at the joint. In order to determine a standardized way of calculating a fixed point on the on the scaphoid and lunate at the SL joint we chose to calculate the centroid of each face based upon the 3D digitization performed previously. Each face was outlined using the remnants of the SLIL as the outer perimeter on the proximal portion of the face and the border between the articulating surface of the SL joint and the capitate. The centroid of each face in the local coordinate system was then determined using Rhinoceros 3D Modeling

software (Figure 2-14). Once two fixed points in the scaphoid and lunate are determined then these points can be similarly transformed into the radius coordinate system at each testing condition in order to measure the distance between them. For the head of the capitate, a centroid was calculated based upon the geometry of the head of the capitate. The spherical portion of the proximal head of the capitate that is proximal to the articulation with the hamate was used to calculate the centroid (Figure 2-16). Once again, using Rhinoceros 3D Modeling software, the centroid of the capitate head was calculated. This centroid is then transformed into the radius coordinate system for each testing condition in order to measure the location of the head of the capitate throughout testing (Figure 2-15).

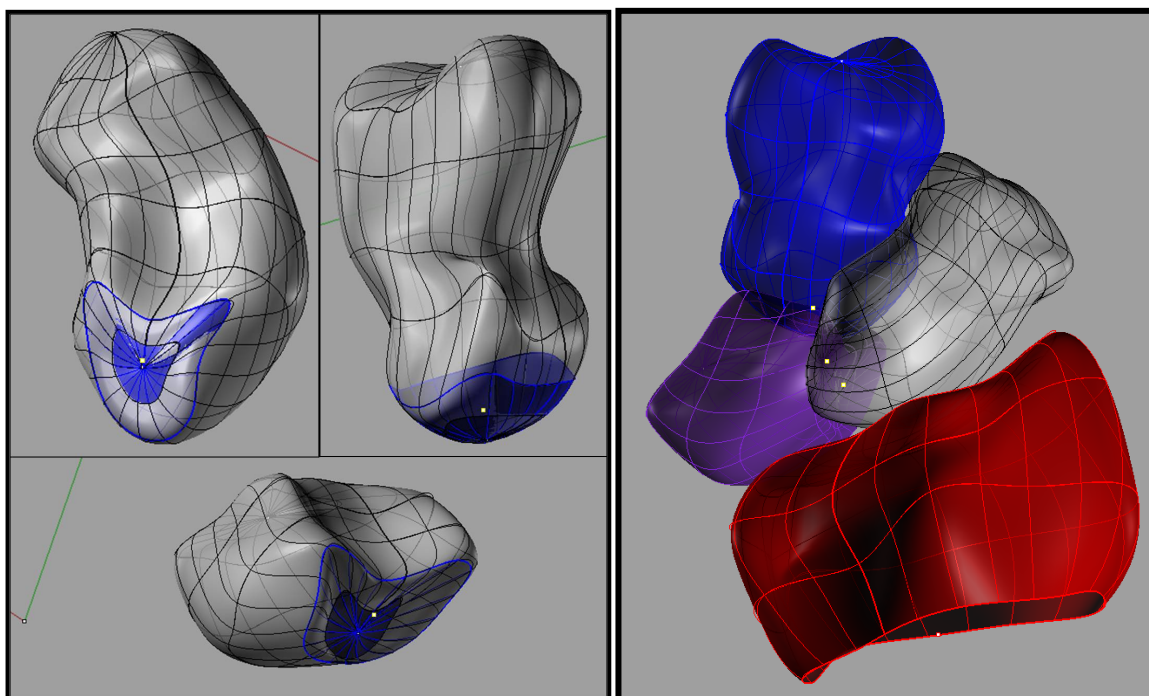


Figure 2-16. On the Left shows the calculation of each individual centroid in the scaphoid, capitate, and lunate. The right shows the 3D reconstruction of the bones with their centroid at a specific testing position.

Muscle Loading

Prior to beginning any specimen testing, a loading protocol had to be developed that resulted in repeatable carpal kinematic measurements. The simplest loading protocol would be to

apply loads to the tendons, starting from an unloaded position. One disadvantage of using linear actuators to apply muscle loads from the unloaded position is that when using multiple motors it is possible that each muscle tendon is loaded at different times. This problem arises because of how the actuator applies load to each tendon. Each actuator applies load by translating the cable attached to each muscle tendon until the tension in the cable and tendon as measured by the load cell was equal to the desired load. Simultaneous muscle loading under these circumstances is only possible if each actuator has to travel the same distance prior to loading, which is dependent on the length of cable used and the positioning of the wrist. Since non-simultaneous loading was inevitable if the tendons were loaded from an unloaded position, the effect of loading the wrist flexors/extensors in different orders was tested. This was tested by positioning the wrist at neutral position then loading the four muscle tendons consecutively in all possible orders for a total of 24 different muscle loading orders. For each muscle loading order, the 3 points on the tracking post for the scaphoid, lunate, capitate, and radius were digitized using the Microscribe. Each loading condition was repeated two times, and the average was taken. In general, carpal kinematic measurements for each muscle loading order were not comparable, with the maximum change between loading conditions being 2.22mm for a single point on a tracking post, well above our threshold of measurement repeatability of <1mm, and an average error of 1.06mm for all points.

In order to resolve the issue of unrepeatable kinematic measurements due to asynchronous muscle loading, a loading protocol was developed that involved applying a 1N preload to all tendons prior to loading them to their final loading. The idea was that applying 1N to each of the four wrist flexor/extensor tendons would not be enough to fully overcome the weight of the hand that was distracting the wrist due to gravity. The total of 4N would be only be

able to overcome 0.41kg of mass, less than the mass of the human hand, preventing full compression of the carpus. It can also be thought of applying a residual resting tension to the tendons that they would experience in vivo. Once all 4 tendons are preloaded under tension, the tendons are then loaded to their final loads simultaneously. In order to confirm that this results in repeatable kinematic measurements, the wrist was then placed at neutral and a preload of 1N was applied to all 4 tendons. The tendons were then loaded to their final loads and the 3 points on the tracking post of the scaphoid, lunate, capitate, and radius were digitized with the Microscribe. Following digitization the loads were decreased to the 1N preload prior to reloading the tendons and repeating the kinematic measurements. This process was repeated for 10 trials, and the maximum difference between trials was computed for each tracking point. This loading protocol resulted in highly repeatable kinematic measurements. The maximum change between trials was 0.29mm with an average of 0.20mm. Based upon these results, the 1N preload was incorporated into the loading protocol.

Specimen Positioning

Once a consistent loading protocol had been developed, it had to be confirmed that the wrist could be positioned consistently while under preload to allow repeatable kinematic measurements. To confirm repeatable positioning, the specimens were positioned under preload at each of the follow positions (30 F, 15 F, Neutral, 15 E, 30 E) using a digital goniometer, then fully loaded. The 3 points on the tracking posts in each of the scaphoid, lunate, capitate, and radius were then digitized. Following digitization the specimen loading was decreased to the 1N preload and the wrist was ranged from 30 F to 30 E prior to repositioning at the same position again using the digital goniometer. The specimen was then loaded again, and kinematic

measurements were repeated. This process was repeated 10 times for each position. This resulted in a maximum change between trials of 0.65mm.

Lastly, it had to be confirmed that the kinematic measurements were independent of the direction that the wrist was moved from (i.e. if the wrist is moved to neutral from a flexed position vs. from an extended position). To evaluate this, the wrist was positioned five times at neutral from an extended position, and five times at neutral from a flexed position. The wrist flexors and extensors were then loaded and kinematic measurements were made. The maximum difference between any two trials for a given digitized point was calculated. The maximum error was 0.39mm, with an average error across all trials of 0.18mm. These trials showed that the direction the wrist was moved from did not have a significant effect on our kinematic measurements.

Final Specimen Positioning and Loading Protocol

The wrist will be tested from 30° of extension to 45° of flexion, in 15° increments and from 10° radial deviation to 20° of ulnar deviation, in 10° increments. Global wrist positioning was measured by measuring the angle of the rod off the 3rd metacarpal as compared to the axis of the radius. Specimens were mounted such that the axis of the radius was vertical and the angle of the 3rd metacarpal, and therefore the global wrist position, was measured using a digital goniometer. At each position the wrist will be positioned with a 1N preload on the FCU, FCR, ECU, ECRB+L to simulate resting muscle tension during passive wrist motion. The wrist will be locked in a fixed position by constraining a bar extending from the third metacarpal in a guide consisting of two parallel plates to set the final wrist testing position. The FCU, FCR, ECU, and ECRB+L will then be loading to their final loads as shown in Table 2. Once the system has

reached a stable equilibrium of ± 0.1 N, the 3D location of the three points on the post in the radius, scaphoid, lunate, and capitate are recorded with the Microscribe. The ECU, FCR, ECU, and ECRB+L are then released to the preload of 1N and then reloaded for a second trial of kinematic measurements. The trials are compared to assure there is repeatability of < 1 mm between trials. The average between the two trials is used for kinematic calculations.

CHAPTER 3

Testing System Validation: Kinematics of the Intact Wrist

Background

The first step in our studies is to validate our custom testing system by comparing the kinematics of the intact carpus in our system to what has been previously reported in the literature. The kinematics of the intact carpus have been investigated quite thoroughly, providing a large amount of data for comparison^{14, 30, 41, 51-56}. Studies have been performed using a variety of techniques including injection of radiopaque markers for radiographic measurements^{14, 51}, optical trackers⁵², electromagnetic tracking devices⁵³, and CT scans^{30, 56}. Despite the wide breath of techniques used, there is still relative agreement amongst regarding the intact kinematics of the wrist (Table 3-3 & 3-4). Averaging previous data suggests that for each degree of wrist flexion the scaphoid flexes 0.7° , while the lunate flexes 0.5° . For each degree of wrist extension the scaphoid extends 0.9° while the lunate extends 0.5° . Each degree of wrist radial deviation causes 0.3° of scaphoid radial deviation and 0.3° of lunate radial deviation. Each degree of wrist ulnar deviation causes 0.5° of scaphoid ulnar deviation and 0.5° of lunate ulnar deviation. It has also been shown that wrist radial deviation causes flexion of the scaphoid and lunate, while ulnar deviation causes extension⁴¹⁻⁴³.

This study was designed to closely model that of Werner et al⁵³ and Short et al⁴¹ as their testing methodology was most similar to the newly designed system. We therefore chose the same range of motion as those studies in order to directly compare our data. The system for their studies was a dynamic testing system, so small differences are to be expected, but we expect relatively strong agreement with their previous studies. For the remaining studies that had

different ranges of testing position, we will compare the percent rotation of the scaphoid and lunate compared to the overall wrist rotation for each rotational plane.

Methods

Specimen Preparation

10 fresh frozen cadaveric upper extremities were used for this study. The mean age was 63, with a range of 45-72. All 10 upper extremities were male, with 6 being left arms, and 4 being right arms. Specimens were dissected and prepared as described in Chapter 2. During dissection all arms were inspected for SLIL tears as well as any gross instability or degenerative arthritis. All wrists were also passively ranged to assure they could achieve an extension of 30°, flexion of 45°, radial deviation of 10°, and ulnar deviation of 20°. During testing specimens were kept moist with normal saline with prevent desiccation.

Testing Positions

The wrist is moved through a range of motion from 30° of extension to 45° of flexion in 15° increments and from 10° of radial deviation to 20° of ulnar deviation in 10° increments. This range was chosen because it is comparable to what has been used in previous studies⁴¹⁻⁴³ and also because this represented the range of motion that most specimens could easily achieve. Tracking posts were placed in the radius, scaphoid, lunate, and capitate. At each testing position, first the FCU, FCR, ECU, and ECRB+L were loaded to their final loads (Table 2-2). Kinematic measurements are then taken by digitizing the 3 points on each tracking post in the scaphoid, lunate, capitate, and distal radius to calculate its rotation in the 3 anatomical planes of flexion/extension, radial/ulnar deviation, and pronation/supination as described in Chapter 2. The muscle tendons were then unloaded and a second trial was performed to assure repeatability of

<1 mm between trials. Due to variability between specimens in the precise angle the posts were placed relative to the bones, the position of the data reported to normalized to the position of the bone at neutral wrist position.

Statistics

The relative rotation of the scaphoid and lunate in flexion/extension, radial/ulnar deviation, and pronation/supination were compared using a paired student t-test with Bonferoni correction to account for multiple comparisons. Significance was set at $p < 0.05$.

Results

The flexion and extension of scaphoid and lunate with wrist flexion/extension had the greatest rotation compared to all other planes (Figure 3-1). The scaphoid and lunate both followed global wrist motion, flexing with wrist flexion and extending with wrist extension. Moving from neutral wrist position into 30° of extension, both the scaphoid and lunate extended with the wrist. The scaphoid extended $24.5 \pm 1.5^\circ$ compared to neutral compared with the lunate which extended by $15.4 \pm 2.7^\circ$. Greater motion is also seen in the scaphoid compared to the lunate as the wrist is moved from neutral to 45° of flexion. The scaphoid flexed $35.2 \pm 1.7^\circ$ while the lunate flexed $24.1 \pm 2.7^\circ$. The scaphoid more closely followed global wrist motion compared to the lunate however. The relative rotation of each of the scaphoid and lunate per degree of wrist flexion and extension was uniform throughout wrist flexion and extension, resulting in 0.8° and 0.5° degrees of flexion/extension of the scaphoid and lunate, respectively, per degree of wrist flexion/extension.

As the wrist is moved in radial and ulnar deviation there is still significant motion of both the scaphoid and lunate in flexion extension, though this out of plane motion was had smaller magnitudes compared to wrist flexion/extension (Figure 3-1). Both the scaphoid and lunate flexed with wrist radial deviation, while extending with wrist ulnar deviation. Moving the wrist from neutral to 10° radial deviation the scaphoid flexed $9.1 \pm 1.7^\circ$, while the lunate flexed $7.9 \pm 1.9^\circ$. Going from neutral to 20° ulnar deviation resulted in $7.3 \pm 1.3^\circ$ of scaphoid extension, and $8.8 \pm 2.4^\circ$ of lunate extension. The relative rotation the scaphoid and lunate per degree of wrist radial and ulnar deviation was 0.6° and 0.6° degrees of flexion/extension, respectively. Compared with wrist flexion/extension however, with wrist radial/ulnar deviation the rotation of the scaphoid and lunate was less uniform, showing relatively small changes from neutral to 10° extension.

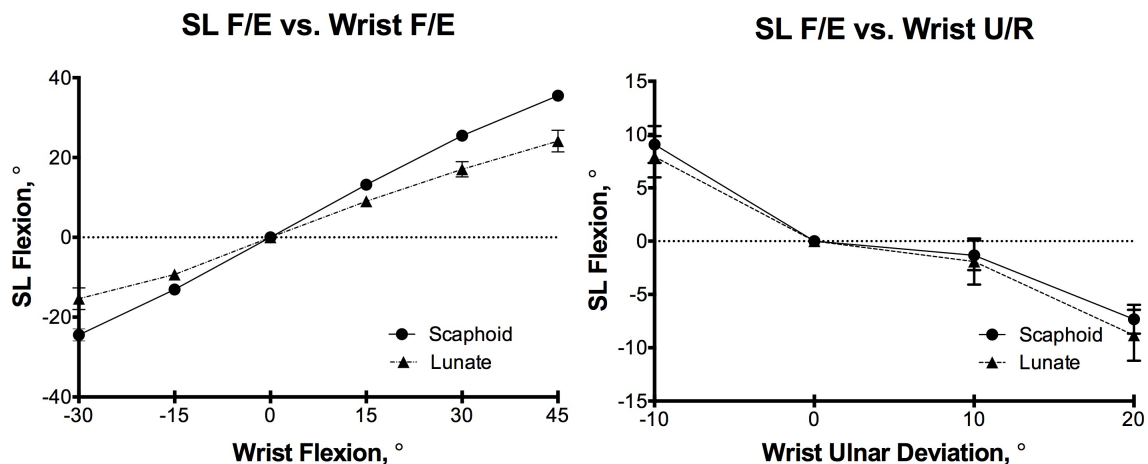


Figure 3-1. The flexion and extension of the scaphoid and lunate in the intact wrist with wrist flexion/extension (left) and wrist radial/ulnar deviation (right).

With wrist flexion/extension, the out of plane rotation of the scaphoid and lunate in the radial/ulnar deviation plane was much smaller compared to flexion/extension (Figure 3-2). Both the scaphoid and lunate radially deviated with wrist extension and ulnarly deviated with wrist flexion. The magnitudes of these rotations were similar as well. At 30° of wrist extension the

scaphoid radially deviated $3.3 \pm 1.6^\circ$ and the lunate radially deviated $2.1 \pm 1.5^\circ$. At 45° of wrist flexion the scaphoid ulnarly deviated $12.0 \pm 4.3^\circ$ and the lunate ulnarly deviated $7.6 \pm 2.5^\circ$. For each degree of wrist flexion/extension the scaphoid and lunate had 0.2° and 0.1° of radial/ulnar deviation, respectively.

Moving the wrist in the plane of radial and ulnar deviation, the scaphoid and lunate followed global wrist motion by radially deviating with radial deviation and ulnarly deviating with ulnar deviation (Figure 3-2). At 10° of wrist radial deviation the scaphoid and lunate radially deviated $2.4 \pm 1.0^\circ$ and $1.1 \pm 1.2^\circ$, respectively. At 20° of wrist ulnar deviation the scaphoid and lunate ulnarly deviated $8.3 \pm 1.4^\circ$ and deviated $6.0 \pm 1.5^\circ$, respectively. For each degree of wrist radial/ulnar deviation the scaphoid and lunate had 0.4° and 0.2° of radial/ulnar deviation, respectively.

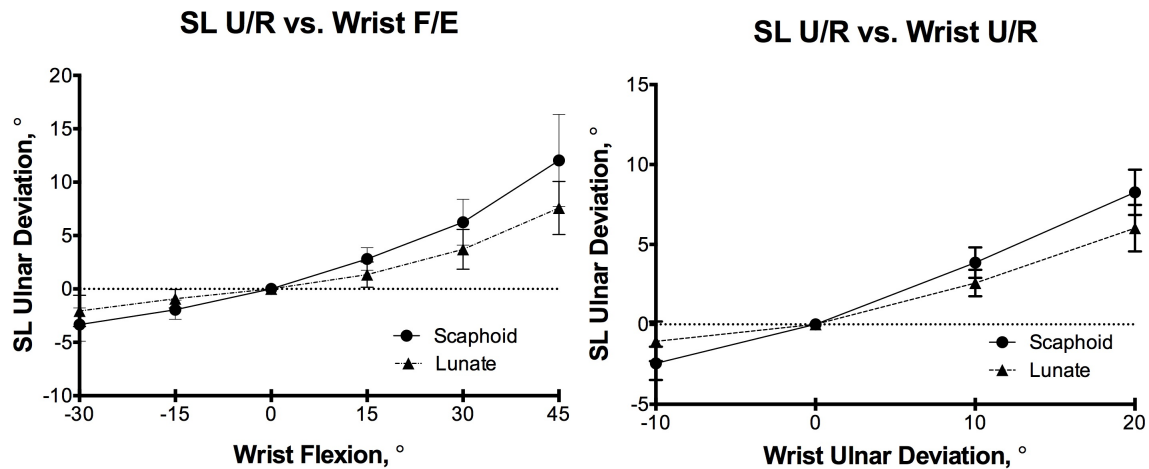


Figure 3-2. The ulnar and radial deviation of the scaphoid and lunate with wrist flexion/extension (left) and wrist radial/ulnar deviation (right).

The rotation of the scaphoid and lunate in the plane of pronation/supination had much smaller magnitudes compared to the other planes (Figure 3-3). Wrist flexion/extension had no significant effect on the pronation/supination of the lunate, with a total change of $< 1^\circ$ from 30° wrist extension to 45° wrist flexion. The scaphoid supinated with wrist flexion, but had little

change with wrist extension. At 45° flexion the scaphoid supinated $7.3 \pm 1.7^\circ$, while supinating only $0.8 \pm 1.4^\circ$ at 30° extension. Similarly, the rotation of the scaphoid and lunate in the plane of pronation/supination with wrist radial/ulnar deviation was minimal. The total range of motion for the scaphoid and lunate was 3.9° and 1.4° , respectively, as the wrist was moved from 10° radial deviation to 20° ulnar deviation. With the wrist in radial deviation the scaphoid tended to supinate, while the lunate tended to pronate. In wrist extension the converse was true, with the scaphoid tending to pronate, and the lunate tending to supinate. These changes were all very small in magnitude compared to the motion of the scaphoid and lunate in the planes of flexion/extension, and radial/ulnar deviation.

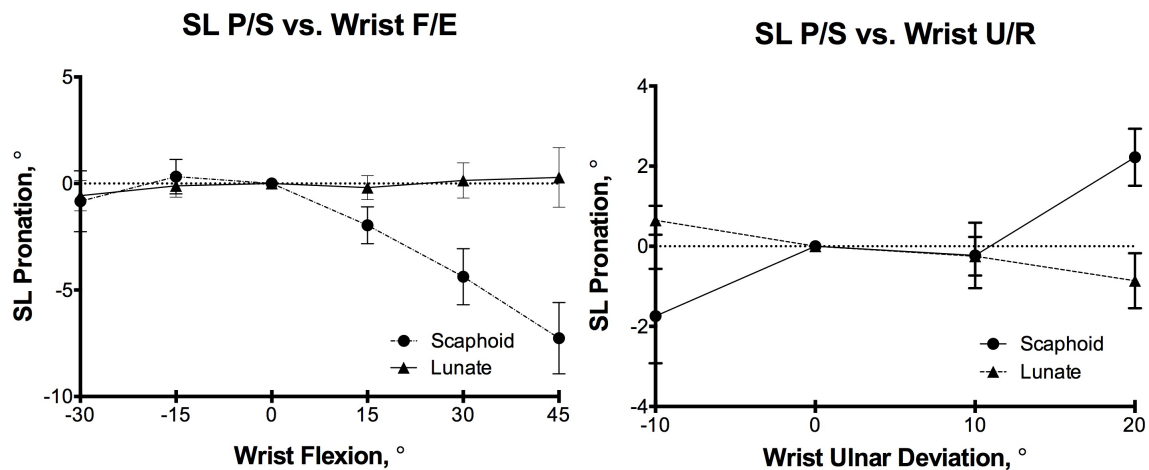


Figure 3-3. The pronation and supination of the scaphoid and lunate in the intact wrist with wrist flexion/extension (left) and wrist radial/ulnar deviation (right).

The predominant axis of rotation for the scaphoid for each wrist motion is seen in Table 3-1. With flexion and extension the primary rotation of the scaphoid was flexion and extension, respectively, which were significantly greater than its rotation in radial/ulnar deviation and pronation/supination. With radial deviation the predominant rotation of the scaphoid was flexion, which was significantly greater than the radial deviation and supination of the scaphoid. With

ulnar deviation the two dominant axes were extension and ulnar deviation, both of which were significantly greater than the pronation of the scaphoid.

	Flexion (+) / Extension (-)	UD (+) / RD (-)	Pronation (+) / Supination (-)
30° Wrist Extension	-24.5 ± 1.5° *#	-3.3 ± 1.5°	-0.8 ± 1.4°
45° Wrist Flexion	35.4 ± 1.2° *#	12.0 ± 4.3°	-7.2 ± 1.7°
10° Wrist RD	9.0 ± 1.7° *#	-2.4 ± 1.0°	-1.7 ± 1.2°
20° Wrist UD	-7.3 ± 1.3° #	8.3 ± 1.4° #	2.2 ± 0.7°

Table 3-1. Scaphoid rotational magnitudes with each wrist motion. * $p < 0.05$ vs. UD/RD, # $p < 0.05$ vs. P/S.

The predominant axis of rotation for the lunate for each wrist motion is seen in Table 3-2. With flexion and extension the primary rotation of the lunate was flexion and extension, respectively, which were significantly greater than its rotation in radial/ulnar deviation and pronation/supination. With wrist radial deviation the predominant rotation of the lunate was flexion, which was significantly greater than the radial deviation and pronation of the lunate. With ulnar deviation the two dominant axes were extension and ulnar deviation, both of which were significantly greater than the supination of the lunate.

	Flexion (+) / Extension (-)	UD (+) / RD (-)	Pronation (+) / Supination (-)
30° Wrist Extension	-15.3 ± 2.7° *#	-2.1 ± 1.5°	-0.5 ± 0.5°
45° Wrist Flexion	24.1 ± 2.3° *#	7.6 ± 2.5°	0.3 ± 1.4°
10° Wrist RD	8.0 ± 1.9° *#	-1.0 ± 1.2°	0.6 ± 0.4°
20° Wrist UD	-8.8 ± 2.4° #	6.0 ± 1.4° #	-0.8 ± 0.7°

Table 3-2. Lunate rotational magnitudes with each wrist motion. * $p < 0.05$ vs. UD/RD, # $p < 0.05$ vs. P/S.

Discussion

This study showed the newly developed testing system was capable of producing very repeatable carpal kinematic measurements across wrist flexion/extension and radial/ulnar deviation. Because of the relatively small size and compact arrangement, the kinematics of each carpal bone were relatively unknown until the 1970s²⁹ and 1980s²⁷. Recent innovations in 3D tracking devices have allowed the implementation of electromagnetic and optical tracking of each carpal bone in cadavers; while improved biplane x-ray techniques and CT scans have shown insight into the carpal kinematics in vivo.

Our study also showed that the primary plane of rotation for the scaphoid and lunate is flexion and extension. This held true with both flexion/extension of the wrist and radial/ulnar deviation of the wrist. With flexion and extension of the wrist there was relatively little out of plane motion of the scaphoid and lunate in radial/ulnar deviation and pronation/supination. Wrist radial deviation continued to show that scaphoid and lunate flexion was the dominant rotation as well. Wrist ulnar deviation showed that there was relatively equal rotation of the scaphoid and lunate in extension and ulnar deviation, both significantly greater than the pronation/supination.

Comparing our results to what has been published in the literature showed our data was similar to what has been seen in the literature^{14, 30, 41, 51-56}. The total range of scaphoid and lunate flexion and extension as the wrist was moved from 30° of extension to 45° of flexion was very similar to values seen in the study this study was based on (Table 3-3). The range of flexion and extension of both bones as the wrist was moved from 10° of radial deviation to 20° of ulnar deviation did show some inconsistencies compared to previous studies (Table 3-4).

Wrist Extension (30°) to Wrist Flexion (45°)

	Current Study	Short et al. ⁴¹
Scaphoid F/E	60.0 ± 2.4°	59°
Lunate F/E	34.6 ± 3.3°	37°

Table 3-3. Total range of flexion and extension rotation of the scaphoid and lunate with the wrist flexion/extension

Wrist Radial Deviation (10°) to Wrist Ulnar Deviation (20°)

	Current Study	Short et al. ⁴¹
Scaphoid F/E	16.4 ± 1.8°	20°
Lunate F/E	18.0 ± 2.8°	19°

Table 3-4. Total range of flexion and extension of the scaphoid and lunate with the wrist radial/ulnar deviation

While only one study to our knowledge used the same range of wrist positions from 45° to 30° extension and 10 radial deviation to 20° ulnar deviation, many studies have evaluated the relative rotation of the scaphoid and lunate compared to global wrist rotation as seen in Tables 3-5 and 3-6. These studies have been performed with a variety of testing systems, as well as in vivo and cadavers. Our data correlates well with the published data. The relative flexion of the scaphoid with wrist flexion was greater than the average repeated value, but it was within the range of what has been previously reported. Also the ulnar deviation of the lunate seen in this study averaged 26%, which is much lower than the average reported value of 54%. Although this is quite low, it is worth noting that the range of reported values is 29-85%, leaving controversy as to what it's true motion is.

	Flexion		Extension	
	Scaphoid (%)	Lunate (%)	Scaphoid (%)	Lunate (%)
Savelberg et al ⁵¹	62	39	92	58
Kobayashi et al ¹⁴	63	36	87	50
Patterson et al ⁵²	61	63	58	22
Werner et al ⁵³	88	51	95	38
Horii et al ⁵⁴	72	55	85	48
Ritt et al ⁵⁵	66	38	87	49
Wolfe et al ⁵⁶	73	46	99	68
Moojen et al ³⁰	62	31	87	66
Average	68	45	86	50
This Study	78	47	81	45

Table 3-5. The percentage of scaphoid or lunate rotation as compared to the total wrist rotation from neutral to extension and flexion compared to previous studies.

	Ulnar Deviation		Radial Deviation	
	Scaphoid (%)	Lunate (%)	Scaphoid (%)	Lunate (%)
Savelberg et al ⁵¹	29	29	15	15
Kobayashi et al ¹⁴	75	85	45	45
Horii et al ⁵⁴	45	50	30	30
Ritt et al ⁵⁵	45	50	27	11
Moojen et al ³⁰	50	57	26	24
Average	49	54	29	25
This Study	42	26	24	23

Table 3-6. The percentage of scaphoid or lunate rotation as compared to the total wrist rotation from neutral to ulnar deviation and radial deviation compared to previous studies.

Conclusion

The newly designed wrist testing system produced highly repeatable measurements of carpal kinematics. This new testing system was built from the ground up with newly developed specimen positioning, loading protocols, tracking device design, and kinematic measurements. In order to produce repeatable kinematic measurements, all elements of this system must function accurately. Our data shows that the system functions well, and is capable of recording the subtle kinematic changes of the carpus with wrist motion. In addition, the magnitude of our data are in line with what has been published prior. This concordance with published literature validates the

testing system, and will allow future studies to be directly compared with what have been published in the literature using other testing systems.

CHAPTER 4

Effect of Grip on the Intact Wrist

Background

Grip is a vital function of the human hand in vivo. Many activities of daily living are not possibly without the ability to grip an object, make it arguably the most important mechanical function of the human musculoskeletal system. It also acts as a significant pain generator in those with midcarpal or radiocarpal arthritis. Grip is a synchronous process of wrist extension, ulnar deviation, contraction of the intrinsic hand muscles, and contraction of flexor digitorum profundus/superficialis⁵⁷. Grip fundamentally alters the mechanical environment of the proximal row through altered force transduction from the distal row. The flexor digitorum profundus/superficialis insert on the distal and middle phalanx of digits II-IV. Loading FDP/FDS results in a compressive force that transmitted along the axis of the metacarpals⁵⁸. This force is not negligible however, as it has been estimated the force transmitted to the distal row is 10x the force applied to the fingers by FDP/FDS⁵⁸. This compressive force is then transferred to the rigid distal row of the carpus where it articulates with the proximal row. The load transfer occurs at three primary joints: the scaphotrapeziotrapezoid joint (STT), the capitulunate joint, and the triquetrohamate joint.

The kinematics of the proximal row under axial compression have been debated for many years with two opposing theories. Kauer^{29, 59} argued that under compressive loads the proximal row kinematics are a balance of the scaphoid collapsing into flexion due to its oblique orientation in the sagittal plane while the lunate extends due to its palmar wedge shape and the proximally translated capitate head. Weber⁶⁰ agreed that the proximal row is a balance between flexion and

extension moments, but argued that it was the helicoidal configuration of the triquetrohamate joint that caused extension, not the shape of the lunate. Previous cadveric studies have shown that grip or axial loading causes small amounts of scaphoid and lunate flexion. It is thought that the compressive force at the STT on the distal scaphoid causes the scaphoid to flex. This flexion is thereby transferred to the lunate through the intact scapholunate interosseous ligament.

Clinically grip has significant implications as it can be a pain generator for those with arthritis, and has also been shown to exacerbate carpal instabilities⁶¹. In spite of its relative clinical importance, there have been very few studies to date that have evaluated the kinematics of the carpus under compressive loads⁶²⁻⁶⁴. These studies have been limited however by their small number of testing positions, and limited kinematic measurements. Another large limitation is that no study to date has simulated grip by loading the FDP or FDS, instead relying upon axial compression of the carpus. The purpose of this study will be to measure rotational and translation kinematics of the scaphoid, lunate, and capitate in the intact wrist during grip applied by directly loading the FDP tendons via linear actuators. We hypothesize that grip will result in flexion of the scaphoid and lunate, as well as proximal translation of the capitate, and widening of the scapholunate joint.

Methods

Experimental Design

To assess the effect of grip on carpal kinematics the four heads of FDP will be loaded across all wrist testing positions (30° of extension to 45° of flexion, in 15° increments and from 10° radial deviation to 20° of ulnar deviation, in 10° increments). At each testing position, first the FCU, FCR, ECU, and ECRB+L were loaded to their final loads (Table 2-2). Kinematic

measurements are then taken by digitizing the 3 points on each tracking post in the scaphoid, lunate, capitate, and distal radius to calculate its rotation in the 3 anatomical planes of flexion/extension, radial/ulnar deviation, and pronation/supination as described in Chapter 2. Following digitization at each position with only the wrist flexors/extensors loaded, the 4 tendons of FDP were loaded to 16.2N each, per their PCSA. Loading of FDP begins with the fingers fully extended, allowing simulation of the full tendon excursion of FDP during the simulated grip. For the FDP loading all actuators are brought to a preload of 0.5 N prior to loading to their final load of 16.2 N to assure that all tendons are loaded simultaneously. Once the FDP loads are stable within ± 0.1 N, kinematic measurements are taken by digitizing the 3 points on each tracking post in the scaphoid, lunate, capitate, and distal radius. The FDP is then unloaded fully to allow the fingers to be manually extended to full extension. A second trial is then performed with Microscribe measurements repeated. The trials are compared to assure repeatability of < 1 mm and the average between the two trials is used for kinematic calculations.

Specimen Preparation

10 fresh frozen cadaveric upper extremities were used for this study. The mean age was 63, with a range of 45-72. All 10 upper extremities were male, with 6 being left arms, and 4 being right arms. Specimens were dissected and prepared as described in Chapter 2. During dissection all arms were inspected for SLIL tears as well as any gross instability or degenerative arthritis. All wrists were also passively ranged to assure they could achieve an extension of 30° , flexion of 45° , radial deviation of 10° , and ulnar deviation of 20° . During testing specimens were kept moist with normal saline with prevent desiccation.

Post Experimental Dissection and Centroid Calculation

Following testing specimens were dissected free of soft tissue to isolate the scaphoid, capitate, lunate, and distal radius. Care was taken not to disturb the tracking posts in each bone. Each bone was digitized using the protocol outlined in Chapter 2. Following digitization, the centroid of the scapholunate face of the scaphoid, scapholunate face of the lunate, and head of the capitate were determined using Rhinoceros 3D modeling software. Using the relative position of the centroid for each bone to its respective tracking post coordinate transformations were made to calculate the position of the centroid for each bone at every testing condition as outline in Chapter 2. In addition to tracking the centroid of each bone, the gap between the scaphoid and lunate at the scapholunate joint was measured between the centroid of the scaphoid and lunate in 3 anatomical axes.

Data Analysis and Statistics

Data was compared for the intact wrist, and intact wrist with grip. All graphs are reported as the change from the intact condition. Statistical analysis was performed using a Repeated Measures ANOVA with Tukey Post-Hoc test. Significance was set at $p < 0.05$.

Results

Loading the four heads of the FDP to simulate grip resulted in flexion of both the scaphoid and lunate (Figure 4-1). The magnitudes were variable between wrist positions but in general the scaphoid flexed more than the lunate. The scaphoid flexed between -0.1° and 1.85° (average, 0.8°) across all positions, with statistical significance at 5/9 testing positions. The lunate also flexed between -0.7° and 1.3° (average, 0.4°) across all testing positions, though there was only statistical significance at 3/9 positions. Interestingly, at 10° radial deviation the lunate

extended 0.7° ($p=0.04$) and at 20° ulnar deviation the lunate extended 0.4° , but did not reach significance ($p=0.14$). Grip did not have a significant effect on the radial/ulnar deviation of the scaphoid and lunate, with the exception of 10° radial deviation where the scaphoid radially deviated 1.1° ($p<0.01$) with grip (Figure 4-2).

The effect grip had on the pronation/supination of the scaphoid and lunate was less clear than flexion/extension (Figure 4-3). From neutral to 30° there was no significant effect of grip on the scaphoid and lunate in the pronation/supination plane. At 15° , and 30° flexion the scaphoid supinated with grip an average of 0.8° , and $p<0.01$ for both positions. At 45° flexion the scaphoid similarly supinated 0.7° , but was not significant ($p=0.22$). The most significant effect of grip was seen on both the scaphoid and lunate across 10° radial deviation, 10° ulnar deviation, and 20° ulnar deviation. At 10° radial deviation the scaphoid supinated $2.5 \pm 0.5^\circ$ ($p<0.01$), while the lunate pronated $0.8 \pm 0.3^\circ$ ($p<0.01$). With the wrist in ulnar deviation the directionality of each bone was reversed. The scaphoid pronated $0.9 \pm 0.4^\circ$ and $1.5 \pm 0.3^\circ$ at 10° and 20° ulnar deviation, respectively ($p<0.01$ for both). The lunate supinated $0.8 \pm 0.1^\circ$ and $1.1 \pm 0.2^\circ$ at 10° and 20° ulnar deviation, respectively ($p<0.01$ for both).

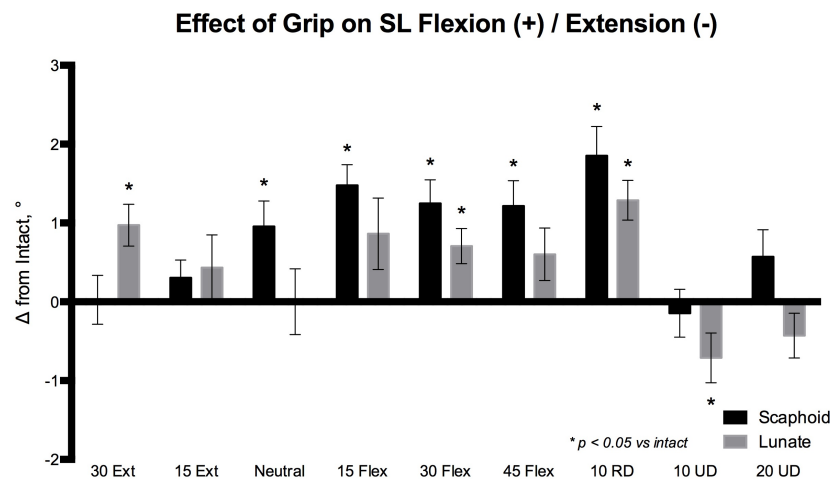


Figure 4-1. Change in flexion of the scaphoid and lunate with grip

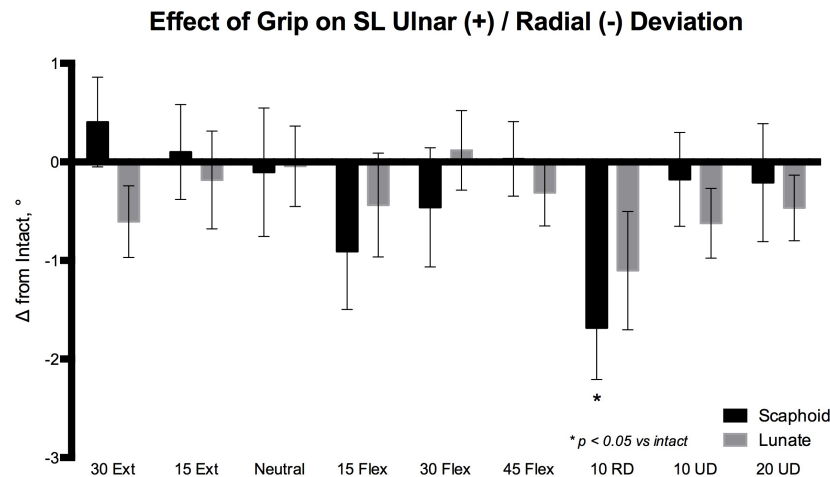


Figure 4-2. Change in the radial and ulnar deviation of the scaphoid and lunate with grip

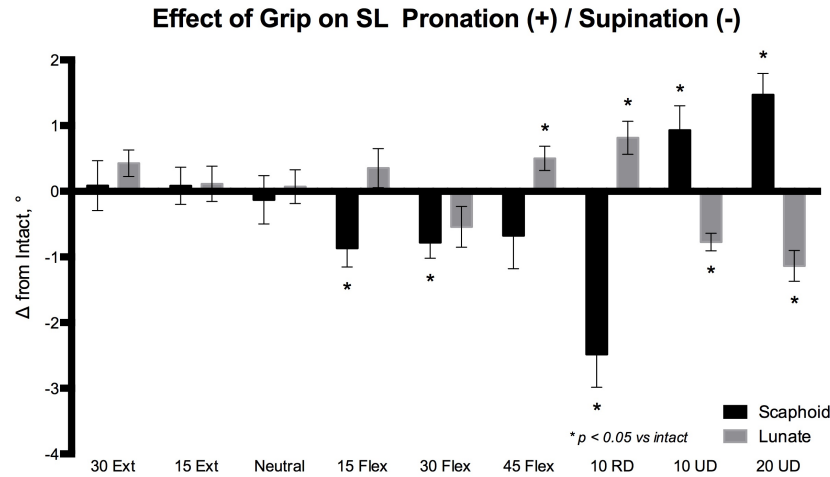


Figure 4-3. Change in the radial and ulnar deviation of the scaphoid and lunate with grip

With regards to translation, the data for scaphoid and lunate translation with grip was less significant but still promising. In the anterior/posterior axis there was a trend that grip caused posterior translation of the scaphoid with a maximum of $0.44 \pm 0.2\text{mm}$ at neutral ($p < 0.04$) and an average of 0.11 (Figure 4-4). All changes to the lunate were less than 0.3mm and there was no common directionality for the translation. In the radial/ulnar axis, both the scaphoid and lunate had positions with significant ulnar deviation (Figure 4-5). At the neutral position both the scaphoid and lunate translated ulnarly $0.6 \pm 0.3\text{ mm}$ and $0.5 \pm 0.2\text{mm}$, respectively ($p < 0.05$ for both). At 30° flexion the lunate translated $0.4 \pm 0.1\text{mm}$ ($p < 0.01$). In the proximal/distal axis there

was a trend towards proximal translation of the lunate, with one position of significance. At 15° flexion the lunate translated $0.3 \pm 0.1\text{mm}$ proximally with grip. All changes to the scaphoid in the proximal/distal axis were non significant and $< 0.2\text{mm}$ (Figure 4-6).

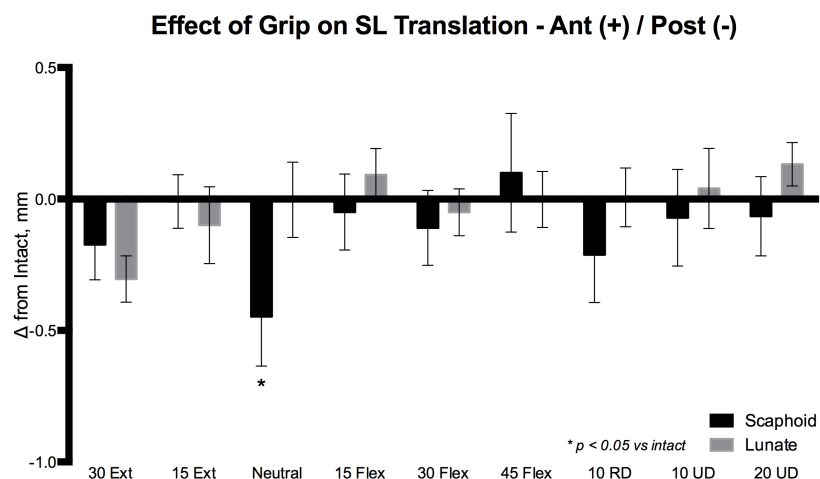


Figure 4-4. Change anterior/posterior position of the scaphoid and lunate with grip

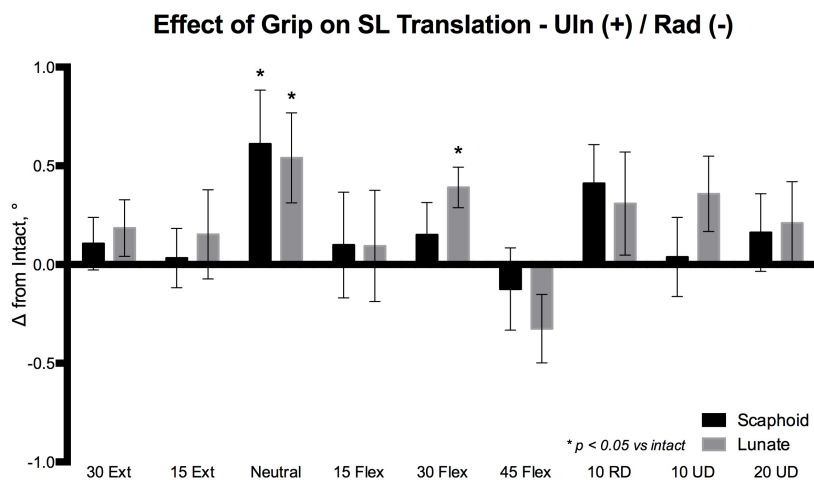


Figure 4-5. Change in the radial/ulnar position of the scaphoid and lunate with grip compared to no grip

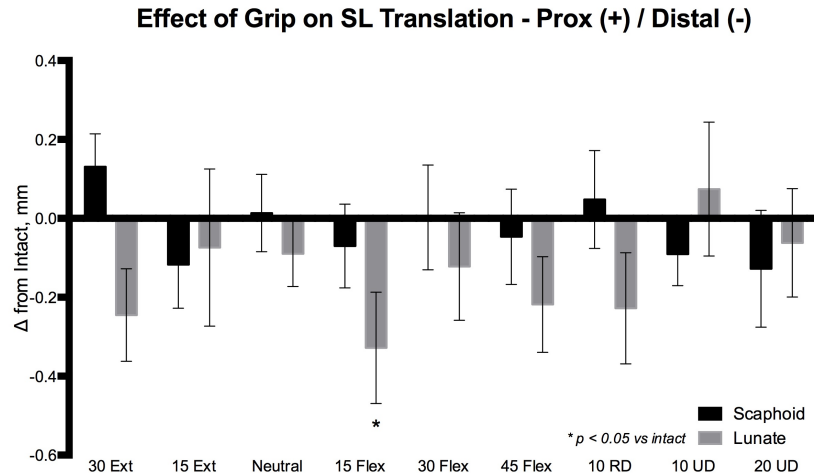


Figure 4-6. Change in the proximal/distal position of the scaphoid and lunate with grip

The loading of FDP to simulate grip did not result in significant changes to the location of the capitate head (Figure 4-7). There was a trend towards proximal translation of the capitate at 15° flexion, 10° radial deviation, 10° ulnar deviation, and 20° ulnar deviation (Average 0.3mm), but none of these reached significance. There was also a trend towards anterior translation of the capitate head across many flexion and extension position, but again this did not reach significance. Similarly grip did not have a significant effect on the distance between the scaphoid and lunate in the anterior/posterior, radial/ulnar, or proximal/distal axis. All changes were less than 0.5mm.

The distance between the scaphoid and lunate in the 3 anatomical planes, as well as 3D was significantly increased with grip (Figure 4-8). Although the data are not uniform, it does highlight some increases in the scapholunate distance at 3 testing positions. At 30° flexion and 10° ulnar deviation there was significant widening of the scapholunate joint in the radio/ulnar axis by 0.3 ± 0.1 mm at each position ($p < 0.04$). At neutral there was an increase in the scapholunate distance in the posterior/anterior axis (0.5 ± 0.1 mm, $p < 0.01$), and in the 3D distance between the two bones (0.4 ± 0.1 mm, $p < 0.03$).

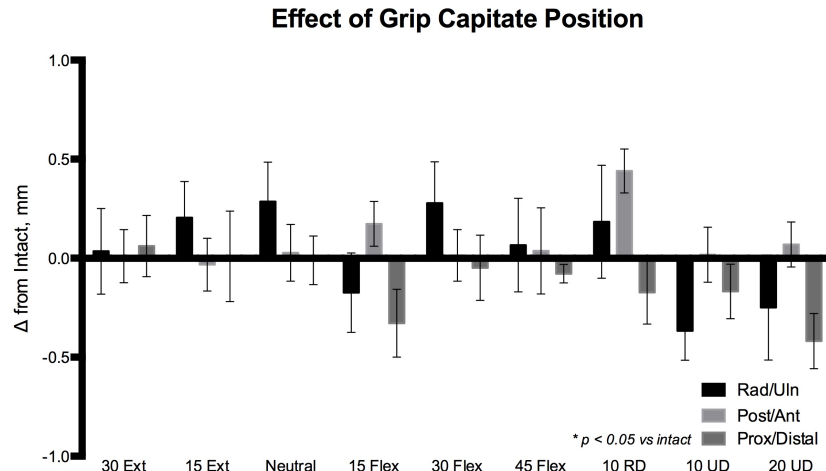


Figure 4-7. Change in the position of the head of the capitate with grip compared to without grip

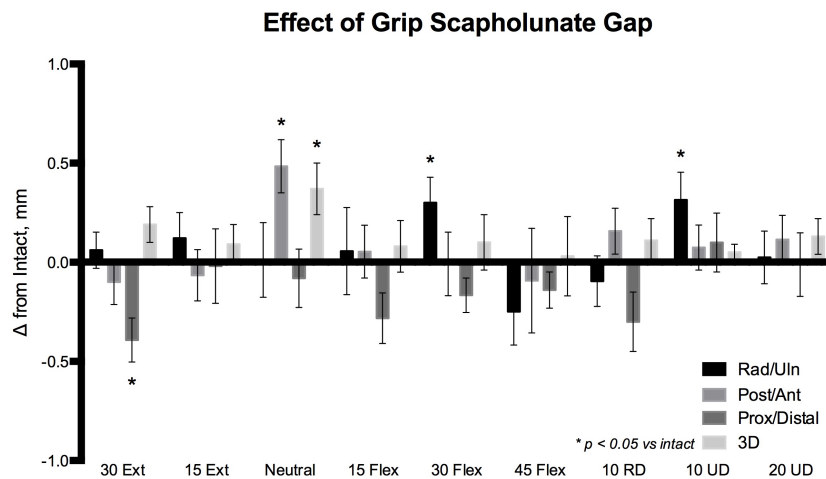


Figure 4-8. Change in the distance between the scaphoid and lunate face with grip compared to without grip

Discussion

Previous studies that have simulated grip conditions have relied upon the application of axial compression across the carpus to simulate the compression caused by grip⁶². There have been no studies to date that have evaluated the effects of simulating grip physiologically by loading the muscles tendons of FDP/FDS. Previous axial compression studies have shown flexion of the scaphoid and lunate of 5.1° and 4.2°, respectively⁶³. That study was

performed at a single testing position, and without any load applied to the wrist flexors and extensors to simulate residual muscle tension or active loading prior to axial compression of the carpus. Our study showed much smaller amounts of scaphoid and lunate flexion, (0.8° and 0.5° across all wrist positions, respectively). This difference in magnitudes can be explained by the incorporation of loading the wrist flexors and extensors prior to loading the FDP to cause grip in our study. The 100N of force applied to the wrist prior to grip should cause compression of the carpus resulting in some amount of inherent flexion of the scaphoid and lunate as compared to previous studies that applied axial compression to the unloaded wrist.

The effect of grip on pronation/supination was less consistent. The scaphoid tended to supinate when in wrist flexion and radial deviation, while pronating when in ulnar deviation. The lunate had opposite trends, pronating when in wrist radial deviation and supinating in wrist ulnar deviation. A possible boney explanation for this disparity could be the capitate sitting anteriorly in radially deviation, and axial compression with grip causing greater SL separation anterior than posteriorly, and thus causing scaphoid supination and lunate pronation. In ulnar deviation the converse would be true with the head of the capitate sitting posteriorly causing greater posterior SL separation than anterior, resulting in scaphoid pronation and lunate supination. This theory is without evidence however, and further studies are required to elucidate the true cause.

In addition to confirming the flexion of the scaphoid and lunate, the present study provided further insight into the kinematic effects grip has on the capitate and the scapholunate joint. Our hypothesis was that grip would cause proximal translation of the capitate, but the data showed that grip had no significant effect on the capitate in the intact wrist. The data regarding the scapholunate joint was more reassuring, showing that at some testing positions grip caused increased scapholunate distance in the radial/ulnar axis and total 3D distance. This has many

clinical implications. Widening of the scapholunate joint is seen after injury to the SLIL and grip has the potential to exacerbate this condition. This has been hypothesized and shown in a radiological study⁶¹, but has otherwise been previously unreported. Given that grip is a significant part of daily life, this result could provide further insight into the evolution of instability following a tear to the SLIL.

This study is not without limitations however. First, cadaveric studies have the inherent limitation of variable specimen age and tissue condition. Another limitation is the unknown amount of force that is applied by each muscle tendon in vivo. This study attempted to approximate in vivo loading conditions based on physiological cross sectional area. Additionally the testing system used applies the same muscle loading at all wrist positions. This provided consistent muscle loading conditions to be able to isolate the effect of grip, but likely does not represent an in vivo condition. Lastly grip was grossly approximated by loading the FDP, but did not incorporate loading of any of the other muscles involved in grip such as flexor digitorum superficialis, the intrinsic hand muscles, and flexor pollicis longus.

Conclusions

Grip is an important aspect of most activities of daily living, and understanding the rotational and translational effects of grip is important for injury models such as scapholunate interosseous ligament tears, and the development of osteoarthritis in the carpus. The results from this study have quantified the effect of grip on the rotational kinematics of the scaphoid and lunate, as well as the translational kinematics of the capitate and scapholunate joint. Grip caused flexion of the scaphoid and the lunate, as well as increased scapholunate distance with grip.

CHAPTER 5

Effect of Repetitive Grip after SLIL Injury

Background

Scapholunate (SL) instability is the most common form of instability in the wrist and caused by injury to the scapholunate interosseous ligament (SLIL). Injuries to the SLIL are often traumatic and caused by falling on an outstretched hand (extended and ulnarly deviated). The resultant instability following can be minor and difficult to diagnose acutely, however, when left untreated, the instability can worsen over time. Initially pain and radiographic changes may only be seen with active wrist motion, but as the instability worsens, pain and radiographic changes can be seen in the unloaded wrist. Eventually arthritis spreads throughout the articulations of the wrist thereby diminishing available treatment options and those remaining often come at a greater expense to grip strength and range of motion in order to alleviate the pain. Due to the severity of its sequelae if left untreated and its incidence, scapholunate instability has been studied extensively both in cadavers and *in vivo*.

Cadaveric sectioning studies have shown that isolated sectioning of the SLIL leads to flexion of the scaphoid and extension of the lunate⁴¹⁻⁴³. The isolated changes following injury to the SLIL alone are small, however, and sectioning of secondary stabilizers of the SL joint is necessary to cause significant changes to the rotations of the scaphoid and lunate compared to intact. Most *in vivo* studies have been performed on patients without wrist pathology in order to understand the kinematics of the intact carpus *in vivo*^{56, 65}. These studies have provided great insight into the relative motion of the carpal bones and into the anatomic axes of the wrist that minimize carpal rotation with wrist motion⁵⁰.

In spite of the significant amount of research that has been done on SL instability, there have been very few studies that have attempted to study the effect of functional stresses, such as grip, on carpal kinematics. Previous studies have been performed either in cadavers with loads applied to the wrist flexors and extensors alone⁴¹⁻⁴³ or in vivo under residual muscle tension in CT scans^{50, 56, 65-67}. The importance of altered forces transmitted across the wrist is due to the fact that the proximal row of the wrist (which the scaphoid and lunate are a part of) is an intercalated segment between the rigid distal row of the carpus and the distal radius and ulna proximally. The proximal row has no direct muscle insertions onto it, so the kinematic behavior of the bones of the proximal row is determined entirely by the forces transmitted to it distally by the distal row of the carpus and proximally by the distal radius and ulna. Any alteration in the forces transmitted across the proximal row have the potential to alter the kinematics of the proximal row and it is for this reason that functional stresses, such as grip, must be simulated in order to understand carpal kinematics under in vivo conditions.

In addition, there have been a variety of studies that have shown that altered forces across the wrist can affect carpal kinematics. It has been shown that carpal kinematics are affected by loading of the wrist flexors/extensors⁶⁸, flexion of the wrist against resistance⁶⁹, and distraction of the carpus⁷⁰. In addition, a radiographic study in cadavers evaluating multiple wrist positions and muscle loading conditions found that methods that involve alter stresses across the wrist (grip, finger traction, thumb traction, and clenched fist) were most sensitive to detecting SLIL injuries⁶¹.

Grip plays a major role in many activities of daily living and repetitive grip may also be associated with poorer clinical outcomes in patients with underlying pathology. With scapholunate instability there is also a progression in the instability from its acute injury to a

more chronic injury, and very little is known regarding the cause of this progression. By simulating repetitive grip we may begin to have an understanding as to how the carpus degenerates over the course of time from an acute injury to a chronic injury. In addition, there have been no studies to date that have evaluated the role of the head of capitate with regards to grip loading in the intact wrist or after injury to the SLIL. Clinically the head of the capitate is seen to migrate proximally with after a tear to the SLIL. Measuring the kinematics of the head of the capitate head could provide new insights into the progression of an acute SLIL injury into a chronic SLIL injury.

Methods

Experimental Design

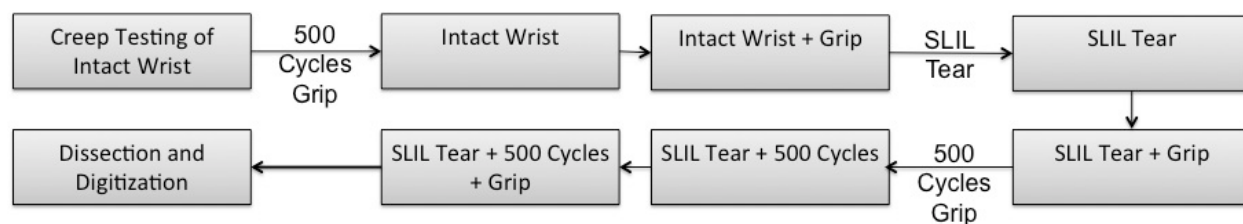


Figure 5-1. Experimental Sequence

This experiment will consist of 6 testing conditions (intact wrist, intact wrist + grip, SLIL tear, SLIL tear + grip, SLIL tear + 500 cycles, SLIL tear + 500 cycles + grip) in 10 adult upper extremities (Figure 5-1). Prior to beginning the experimental protocol, creep testing was performed on each wrist to confirm that 500 cycles of grip had no significant effect on the intact wrist. The creep testing is described in detail in the following section.

Following completion of the creep testing, the remainder of the experimental testing was begun. Testing can be broken down into three wrist conditions (intact, SLIL tear, SLIL tear +

500 cycles), each with and without grip. For each condition the same testing protocol was followed as follows. The wrist was tested at the positions of 30° of extension to 45° of flexion, in 15° increments and from 10° radial deviation to 20° of ulnar deviation, in 10° increments. At each testing position, first the FCU, FCR, ECU, and ECRB+L were loaded to their final loads (Table 2-2). Kinematic measurements are then taken by digitizing the 3 points on each tracking post in the scaphoid, lunate, capitate, and distal radius to calculate its rotation in the 3 anatomical planes of flexion/extension, radial/ulnar deviation, and pronation/supination as described in Chapter 2. Following digitization at each position with only the wrist flexors/extensors loaded, the 4 tendons of FDP were loaded to 16.2N each, per their PCSA. Loading of FDP begins with the fingers fully extended, allowing simulation of the full tendon excursion of FDP during the simulated grip. For the FDP loading all actuators are brought to a preload of 0.5 N prior to loading to their final load of 16.2 N to assure that all tendons are loaded simultaneously. Once the FDP loads are stable within +/- 0.1 N, kinematic measurements are taken by digitizing the 3 points on each tracking post in the scaphoid, lunate, capitate, and distal radius. The FDP is then unloaded fully to allow the fingers to be manually extended to full extension. A second trial is then performed of both the wrist with only the wrist flexor extensors, and with grip with Microscribe measurements repeated. The trials were compared to assure repeatability of < 1mm and the average between the two trials is used for kinematic calculations.

Specimen Preparation

10 fresh frozen cadaveric upper extremities were used for this study. The mean age was 63, with a range of 45-72. All 10 upper extremities were male, with 6 being left arms, and 4 being right arms. Specimens were dissected and prepared as described in Chapter 2. During dissection all arms were inspected for SLIL tears as well as any gross instability or degenerative

arthritis. All wrists were also passively ranged to assure they could achieve an extension of 30°, flexion of 45°, radial deviation of 10°, and ulnar deviation of 20°. During testing specimens were kept moist with normal saline with prevent desiccation.

Creep Testing

To assure that 500 cycles of grip had no significant effect on the intact wrist, creep testing was performed on each specimen prior to the experimental protocol. For the creep testing the wrist was placed at 30° extension, where the cyclic grip load would occur as described below. ECRB+L, ECU, FCR, and FCU were then loaded and kinematic measurements were taken for the intact wrist at 0 grip cycles. Two trials were performed to assure repeatability. Following kinematic measurements, the four heads of FDP were loaded to simulate grip. 25 cycles were completed with the cycle high of 16.2N and cycle low of 5N. Following 25 cycles, FDP was unloaded, along with ECRB+L, ECU, FCR, and FCU. ECRB+L, ECU, FCR, and FCU were then reloaded for repeated kinematic measurements at 25 grip cycles. Two trials were performed to assure repeatability. This process was then repeated for 500 cycles, with kinematic measurements taken at 0, 25, 50, 75, 100, 200, 300, 400, and 500 cycles.

Following completion of 500 cycles, statistical analysis was then performed for the rotation of the scaphoid and lunate in the flexion/extension, radial/ulnar deviation, and pronation/supination planes using a Repeated Measures ANOVA with Tukey Post-Hoc analysis was performed on the creep data alone. Significance was set at $p < 0.05$.

Additionally, biologic tissues are widely considered to be viscoelastic in nature, and can be modeled using the Kelvin-Voigt model, which is represented by a Hookean spring and Newtonian dashpot in parallel as seen in Figure 5-2. In order to determine if any changes were

the result of plastic deformation vs. creep, each rotation parameter underwent curve fitting using an exponential rise model.

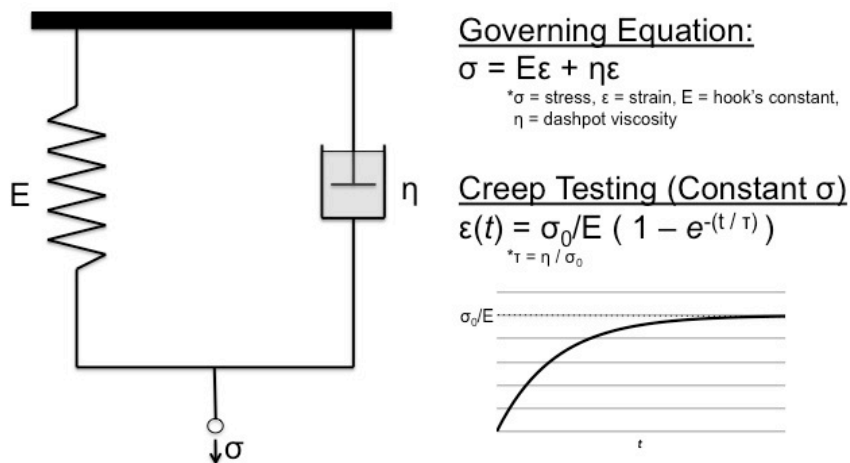


Figure 5-2. Kelvin-Voigt model for viscoelastic materials and equation for creep modeling

Sectioning of the SLIL Ligament

The SLIL ligament can be directly visualized through the dorsal capsulotomy that is created prior to testing for the tracking posts to be inserted. Prior to sectioning all muscles were unloaded to allow the wrist to be distracted to aid in sectioning the SLIL. Using a scalpel handle with an 11 blade, the dorsal and membranous portions of the SLIL are cut in the midsubstance of the ligament between the two bones (Figure 5-3). The volar portion of the ligament is then sectioned with the aid of an arthroscope. The ligament was confirmed to be fully sectioned visually with the arthroscope and also by toggling the lunate slightly to see if any of the rotation is transmitted to the scaphoid. Following completion of testing the ligament was again confirmed to be completely sectioned during post experimental dissection (Figure 5-4).

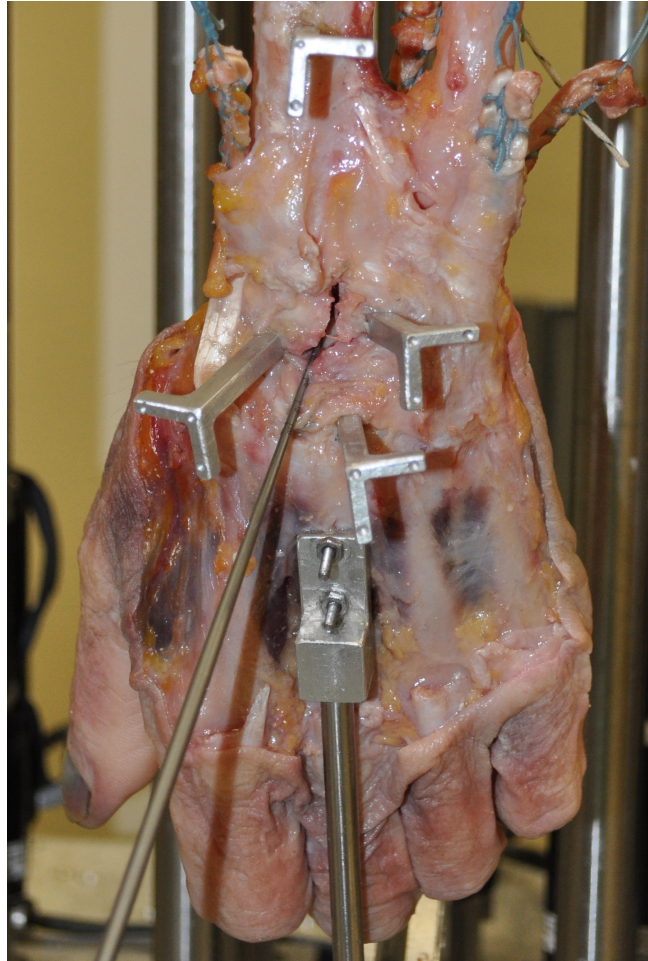


Figure 5-3. Specimen after the SLIL has been sectioned. The probe is distracting the joint to exaggerate the joint space.

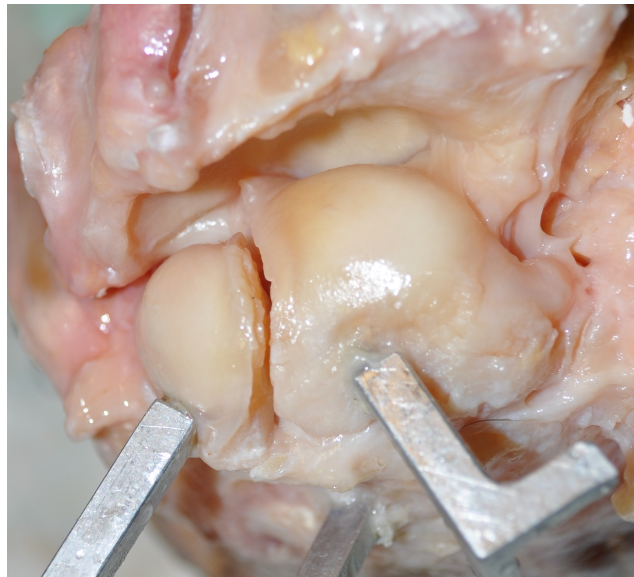


Figure 5-4. Post experimental dissection confirming complete sectioning of the SLIL. The scaphoid is on the Left, with the lunate on the right

Cyclic Grip Loading to Simulate Repetitive Use in Activities of Daily Living

Grip is a fundamental part of many activities of daily living and because many acute injuries to the SLIL go undiagnosed, many patients will continue to use their hand for grip and other activities following the injury. The purpose of the cyclic grip loading was to determine if repetitive grip was sufficient to worsen the SL instability after an acute SLIL tear. To investigate this Labview software was coded to be able to apply 500 cycles of grip load from full force (16.2 N per head) to a lower load of 5 N. The wrist was locked at 30° of extension because most grip and grasping activities occur with a slightly extend wrist of 30-35°⁵⁷. The first cycle was started with the fingers fully extended to simulate the complete excursion of the FDP tendons (Figure 5-5). The software was coded such that loading and unloading of all 4 tendons occurred together, i.e. if one tendon reached its max load prior to the others it will wait to unload until all the other tendons have reached their max force. Cycles occurred at a rate of 250 cycles per hour. During the grip cycles the specimen was kept moist with normal saline to prevent desiccation.



Figure 5-5. On the left the wrist is positioned at 30° extension prior to grip. On the right is the fully clenched hand after FDP has been loaded.

Post Experimental Dissection and Centroid Calculation

Following testing specimens were dissected free of soft tissue to isolate the scaphoid, capitate, lunate, and distal radius. Care was taken not to disturb the tracking posts in each bone. Each bone was digitized using the protocol outlined in Chapter 2. Following digitization, the centroid of the scapholunate face of the scaphoid, scapholunate face of the lunate, and head of the capitate were determined using Rhinoceros 3D modeling software. Using the relative position of the centroid for each bone to its respective tracking post coordinate transformations were made to calculate the position of the centroid for each bone at every testing condition as outline in Chapter 2. In addition to tracking the centroid of each bone, the gap between the scaphoid and lunate at the scapholunate joint was measured between the centroid of the scaphoid and lunate in 3 anatomical axes.

Data Analysis and Statistics

Data was compared for the six conditions following the creep testing (intact wrist, intact wrist + grip, SLIL tear, SLIL tear + grip, SLIL tear + 500 cycles, SLIL tear + 500 cycles + grip). All graphs are reported as the change from the intact condition. Statistical analysis was performed using a Repeated Measures ANOVA with Tukey Post-Hoc test. Significance was set at $p < 0.05$.

Results

Creep Testing

Creep testing was performed to assure that our loading protocol of 500 grip cycles did not cause irreversible changes to the carpus. In Figure 5-6 the results from the creep testing can be seen. For both the scaphoid and lunate there were no statistically significant kinematic changes caused by 500 cycles of grip in flexion/extension, radial/ulnar deviation, or pronation/supination. Most changes were less than 1° in magnitude. The lunate did not tend to have any rotational trends, with most changes being close to 0° . The scaphoid had two trends. The first being that increasing number of grip cycles caused both increased flexion and ulnar deviation, though neither of these ever reached significance. The grip cycles had little effect on the pronation/supination of the scaphoid. For the flexion/extension, and radial/ulnar deviation, an exponential rise curve fit was attempted. The radial ulnar deviation did not have a sufficient curve fit, but flexion/extension did (Figure 5-6). The curve fit showed an exponential rise in scaphoid flexion that approached 1.2° scaphoid flexion with an R^2 of 0.06. The lack of statistically significant changes confirmed that 500 grip cycles did not have any effect on the intact wrist, while the exponential rise curve fit in scaphoid flexion reassured that any changes were the result of viscoelastic creep, and not plastic deformation.

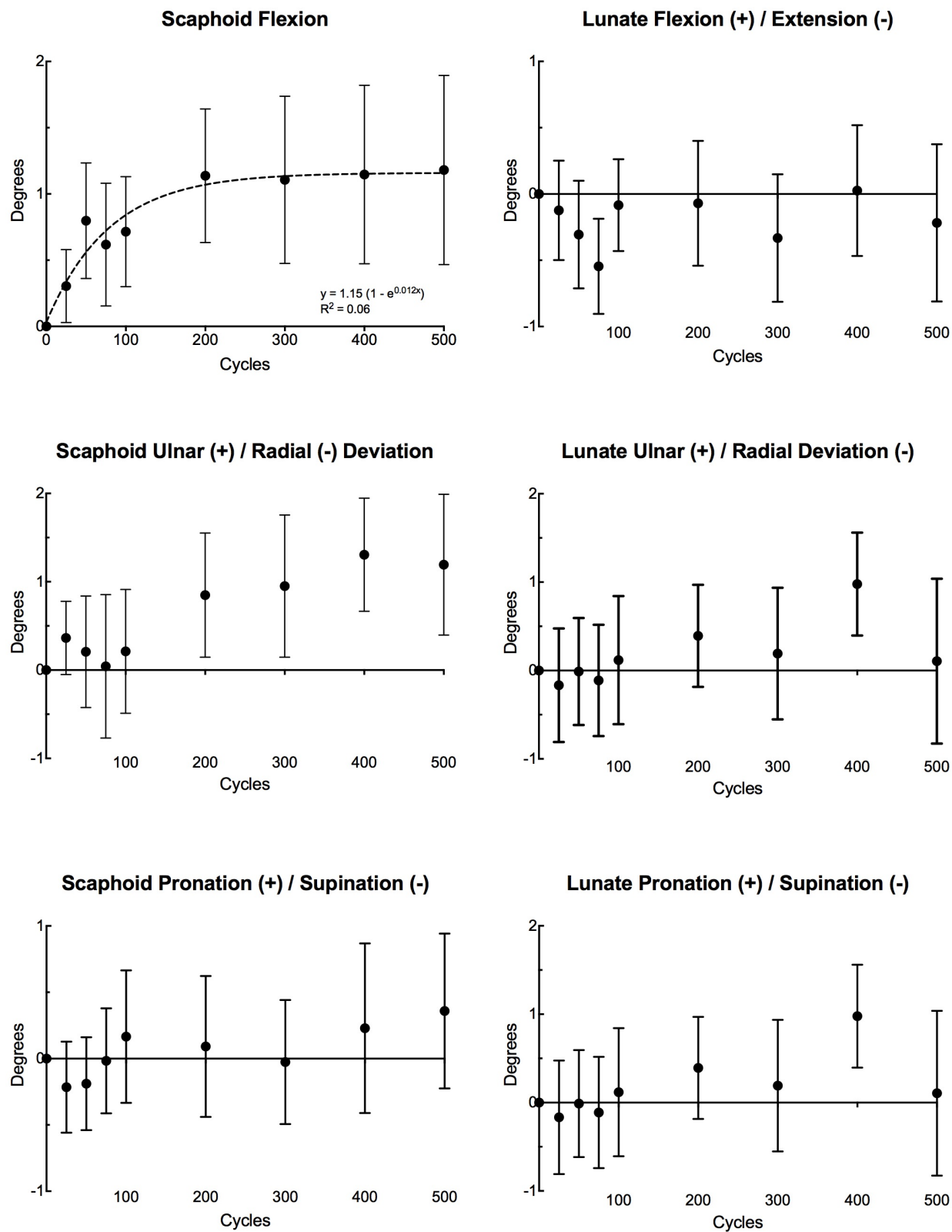


Figure 5-6. Kinematic changes after 500 cycles of grip in the intact wrist. Results for the scaphoid are on the left, with the results for the lunate on the right in each anatomical plane.

SLIL Tear

Sectioning of the SLIL resulted in significant kinematic changes to the scaphoid in both rotation and translation. On average the scaphoid flexed 6.0° (Range 0.4° - 10.4°) compared to intact across all positions, with statistical significance at 7/9 testing positions (Figure 5-7). Scaphoid flexion was more pronounced in wrist extension and ulnar deviation, with negligible changes in wrist flexion. The scaphoid also ulnarly deviated compared to intact an average of 6.3° (Range 0.4° - 10.8°) across all positions, with statistical significance at 5/9 testing positions (Figure 5-8). Again, these changes were most pronounced in wrist flexion and ulnar deviation, with very small changes in wrist extension and radial deviation. Scaphoid pronation was a fairly uniform effect of section the SLIL across all testing positions with an average change from intact of 4.8° (Range 1.8° - 6.5°) (Figure 5-9). The change in pronation was statistically significant at all positions except for 30° extension.

After sectioning the SLIL, the scaphoid translated posterior, radial, and distal, through the changes were smaller than the rotational changes. The trend continued from the rotational data that in wrist extension and radial deviation these changes were much smaller. The posterior translation compared to intact averaged 1.0mm (Range -0.1 to 1.5mm), with statistical significance at 7/9 testing positions (Figure 5-13). The radial translation compared to intact averaged 1.0mm (Range -0.2 to 2.2mm) with statistical significance at 5/9 testing positions, again showing little to minimal change in wrist extension and radial deviation (Figure 5-14). The distal translation compared to intact averaged 1.0mm (Range 0.3 to 1.8mm), and with statistical significance at 6/9 testing positions (Figure 5-15). Across all three rotational planes and three translation axes, there were no significant changes at 30° extension, 1 significant change at 15° extension, and 3 significant changes at 10° radial deviation. This is in comparison to 15° , 30° ,

45° flexion and 10°, 20° ulnar deviation, which showed a significant change in every measured parameter.

The effect of sectioning the SLIL was less significant on the lunate, tending to only effect in a single rotational plane. Sectioning the SLIL caused an average of 6.3° of extension of the lunate compared to intact (Range 0.9°-11.0°), and this change was statistically significant in 7/9 testing positions (Figure 5-10). Again there was little change with the wrist in extension, but this time it was ulnar deviation, not radial deviation that had smaller changes as compared to what as seen in the scaphoid. There was little change in radial/ulnar deviation and pronation/supination. There was a trend towards radial deviation of the lunate with an average of 2.0°, but this was not significant at any testing positions (Figure 5-11). With pronation/supination, the lunate tended to supinate in wrist extension, and ulnar deviation, while pronating in wrist flexion (Figure 5-12).

The lunate tended to translate anterior, ulnar, and proximal, reverse of what was seen with the scaphoid. The anterior translation averaged 0.6mm (Range 0.2-1.0mm), but this was only significant at 4/9 testing positions (Figure 5-16). The lunate tended to translate ulnarly, with an average translation of 0.5mm, but this was only significant at 30° extension (Figure 5-17). The proximal translation of the lunate averaged 0.3mm (Range -0.2 – 0.8mm), but this was only significant at 4/9 testing positions (Figure 5-18).

By looking at the distance between the centroid of the face of the scaphoid and lunate at the scapholunate joint, we are able to estimate the scapholunate gap, which is clinically measured on x-ray. Clinically the widening of the SL gap in the coronal plane is looked for with SLIL injury, but we have shown changes in all 3 anatomical axes. Sectioning of the SLIL resulted in an increased distance between the scaphoid and lunate in the radial/ulnar axis compared to intact,

with an average increase of 1.4mm (Range 0.5-2.6mm) (Figure 5-19). This increase in the radial/ulnar distance compared to intact was statistically significant at 8/9 testing positions, only not being significant at 10° radial deviation. Along the anterior/poster axis, the distance increased 1.6mm on average (Range 0.1-2.5mm), with statistical significance at 8/9 wrist positions (Figure 5-20). 30° extension was the only position that was not significant. In the proximal/distal axis there was an average 1.3mm increase compared to intact (Range 0-2.5mm), which was statistically significant at 7/9 wrist positions (Figure 5-21). Lastly, the 3D distance between the two faces was analyzed. The 3D distance between the scaphoid and lunate increased 3.0mm on average (Range 0.75-4.7mm), and was statistically significant at all testing positions (Figure 5-22).

The last parameter analyzed was the location of the capitate head along the 3 anatomical axes, which showed very small changes with SLIL sectioning. In the proximal/distal axis there was a trend for proximal translation of the capitate, but this was not significant (Figure 5-23). Translation in the radial/ulnar axis showed negligible changes compared to the intact condition (Figure 5-24). The single significant finding was that the capitate translated posteriorly $1.2 \pm 0.3\text{mm}$ at 45° flexion ($p < 0.01$) (Figure 5-25). There was a trend towards posterior translation across all positions, average 0.5mm, but no other position reached significance.

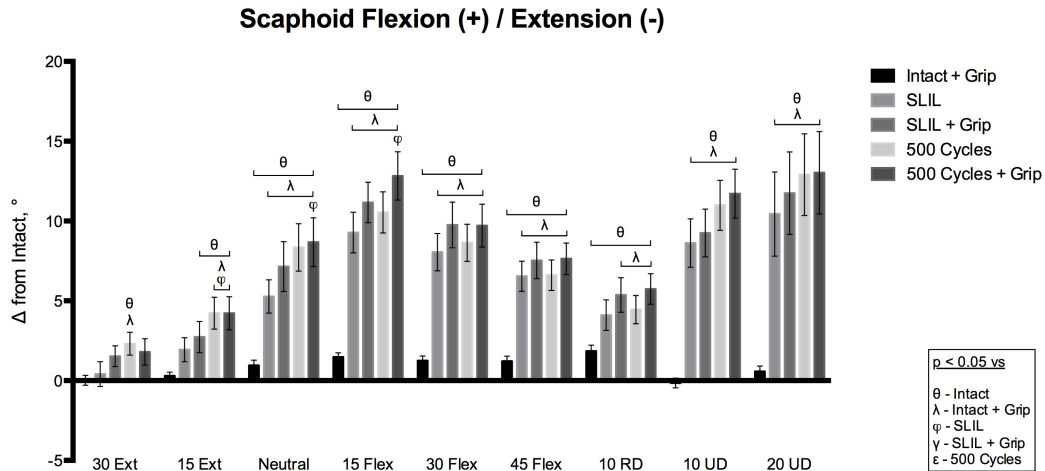


Figure 5-7. Scaphoid flexion/extension across all testing conditions

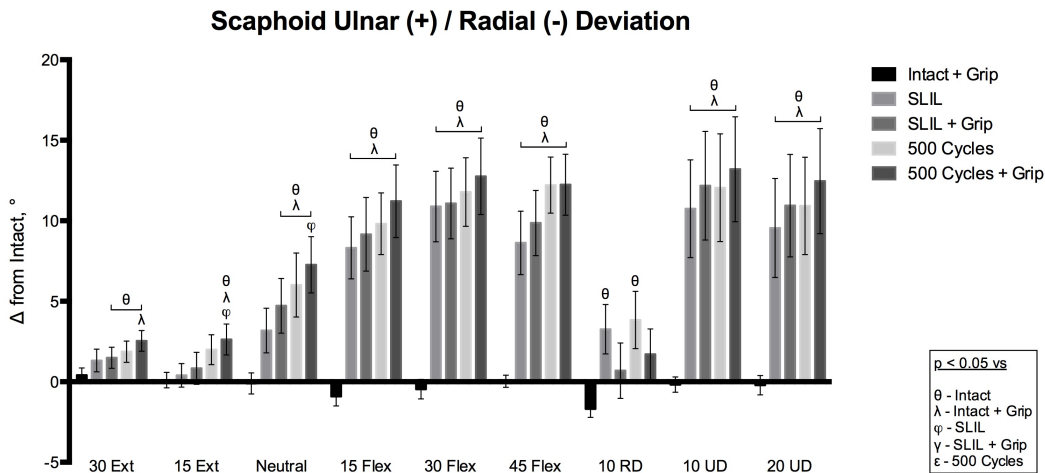


Figure 5-8. Scaphoid radial/ulnar deviation across all testing conditions

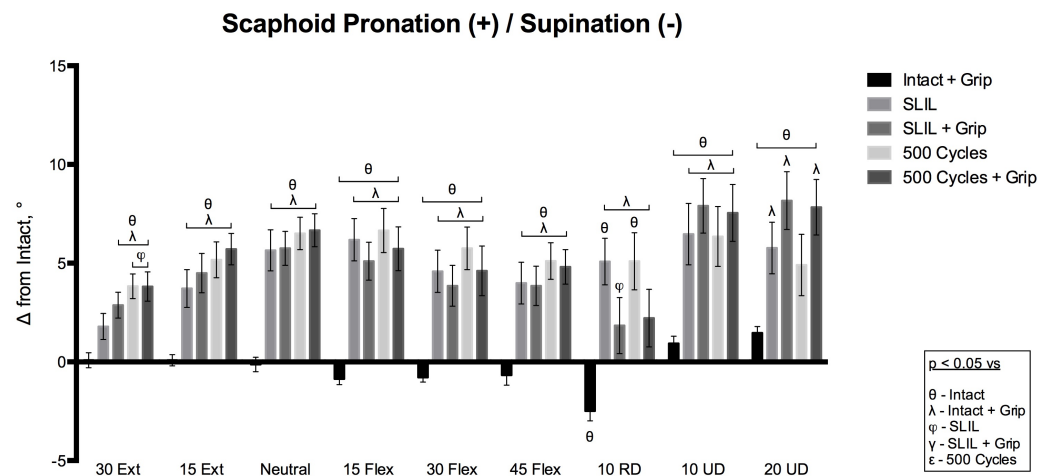
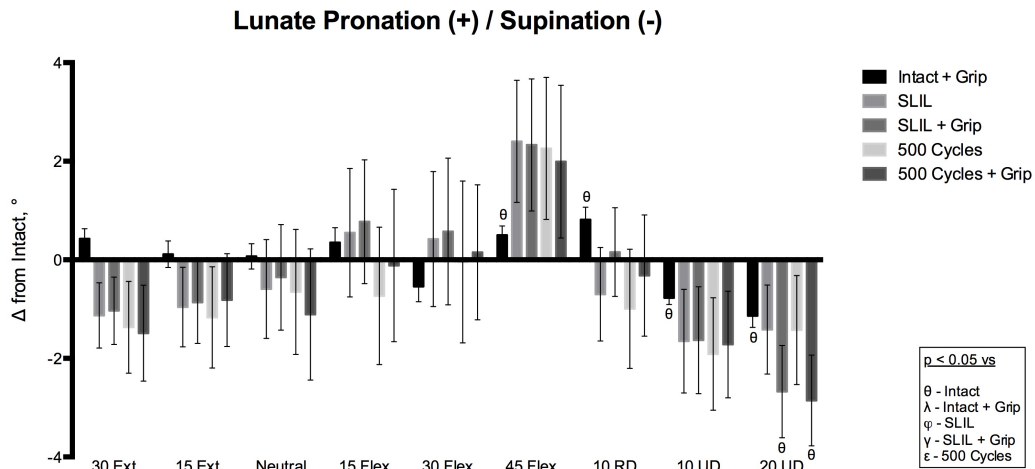
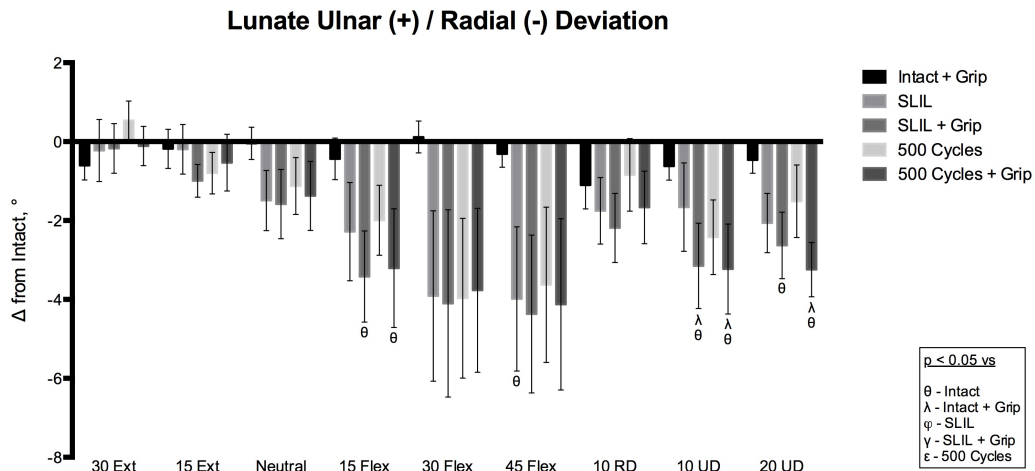
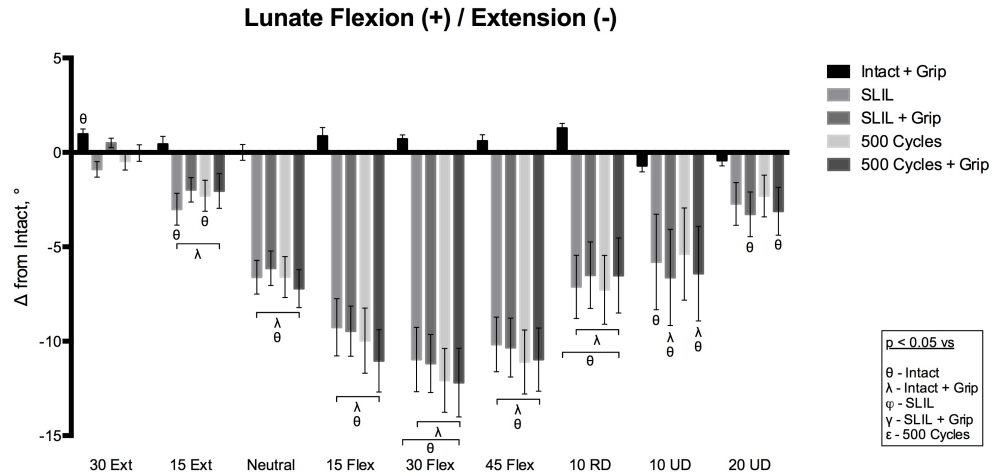


Figure 5-9. Scaphoid pronation/supination across all testing conditions



SLIL Tear with Grip

Loading the tendons of FDP to simulate grip caused subtle changes compared to the SLIL tear condition, but in general exacerbated the changes that were caused by the SLIL tear compared to the intact wrist. With grip the scaphoid flexion increased, although not significantly compared to the SLIL tear (Average 7.4° vs 6.1°). Although there were no significant increases compared to the SLIL tear, grip caused the flexion of the scaphoid at 15° extension to become significantly greater than the intact wrist ($2.7^{\circ} \pm 1.0$, $p=0.02$), making 8/9 wrist positions significantly more flexed compared to intact. Similarly there was a trend towards increased ulnar deviation compared to the SLIL tear (Average 6.8° vs. 6.3°), but these changes were not significant. At 30° extension and neutral, the scaphoid did become significantly more ulnarly deviated compared to intact, making 7/9 testing positions significant. Lastly, the pronation of the scaphoid did not show a consistent trend compared to the SLIL tear (4.9° vs 4.8°), but the scaphoid pronation at 30° extension became significant compared to intact.

Grip had less of an effect on scaphoid translation following SLIL tear compared to its effect on rotation. The scaphoid remained significantly anteriorly translated compared to intact at 7/9 positions (Average 1.1°), but there was no trend for increased or decreased translation with grip. Similarly, grip did not have an increased effect on the kinematic changes caused by the SLIL tear along the radial/ulnar axis and proximal/distal axis. All positions that had significantly changed with SLIL tear remained significant however.

The rotational kinematics of the lunate were less altered with grip compared to the scaphoid. Grip did have a tendency to slightly decrease the lunate extension caused by the SLIL tear (Average 6.1° vs 6.3°), but these changes were not significant. In the radial/ulnar deviation

plane grip caused the lunate to significantly radially deviate compared to intact at 15° flexion, 10° ulnar deviation, and 20° ulnar deviation ($3.4 \pm 1.2^\circ$, $3.1 \pm 1.1^\circ$, and $2.6 \pm 0.8^\circ$. respectively) The SLIL tear alone had not caused significant changes at these positions. Grip following the SLIL tear did not cause any change in lunate pronation/supination.

The translation of the lunate with grip following the SLIL tear was negligible for the most part. The lunate remained significantly anteriorly translated compared to intact at Neutral through 45° wrist flexion, but grip did not increase this translation compared to SLIL tear. There was a trend towards increased proximal translation of the lunate with grip following the SLIL tear (0.5mm vs 0.3mm) but this change was not significant. With radial/ulnar deviation, grip after the SLIL tear caused increased ulnar translation compared to intact ($1.1 \pm 0.3\text{mm}$, $p<0.05$), which was not seen with the SLIL tear alone.

Grip following the SLIL tear tended to slightly increase the changes caused by the SLIL tear alone with regards to the distance between the scaphoid and lunate at the scapholunate joint in all 3 anatomical axes. These changes were not significantly different than the SLIL tear condition however. Compared to intact, grip increased the distance in the radial/ulnar axis to 1.7mm from 1.5mm for the SLIL tear, but this was not significant. There were similar small scale changes along the anterior/posterior, and proximal distal plane, but once again these changes were not significant. The average change in 3D distance compared to intact increased to 3.4mm from 3.1mm with SLIL tear, but this change was not significant. All wrist positions continued to show statistically significant increased 3D distance compared to intact.

The translation of the capitate head showed similar trends to what was seen with the SLIL tear alone, but with some small increase. The average proximal translation of the capitate

increased to 0.3mm vs 0.2mm with SLIL tear alone, both compared to intact. This did not reach significance however. With grip there began to be significant posterior translation of the capitate compared to the intact wrist. At 15° flexion, the capitate translated posteriorly $1.0 \pm 0.2\text{mm}$ ($p=0.02$) compared to intact. The remaining wrist positions had an average posterior translation of 0.5mm, but no others were statistically significant.

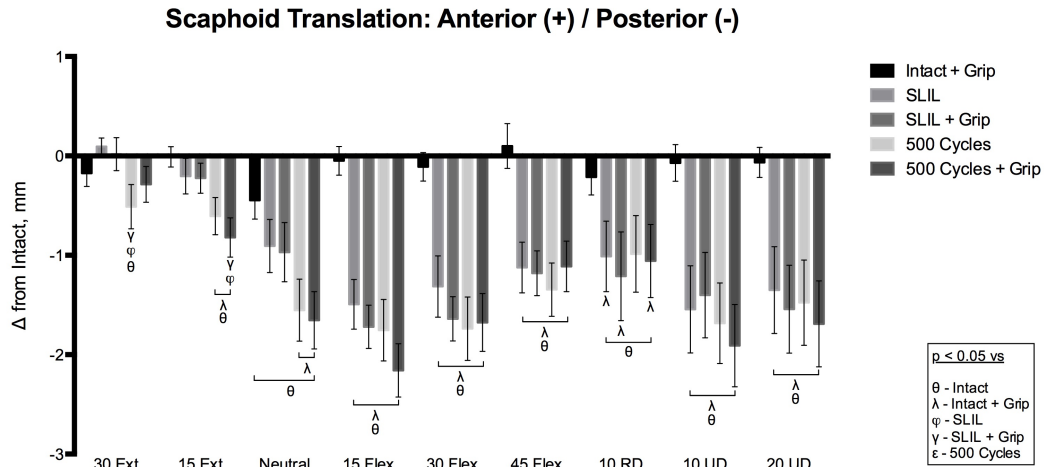


Figure 5-13. Scaphoid anterior/posterior translation across all testing conditions

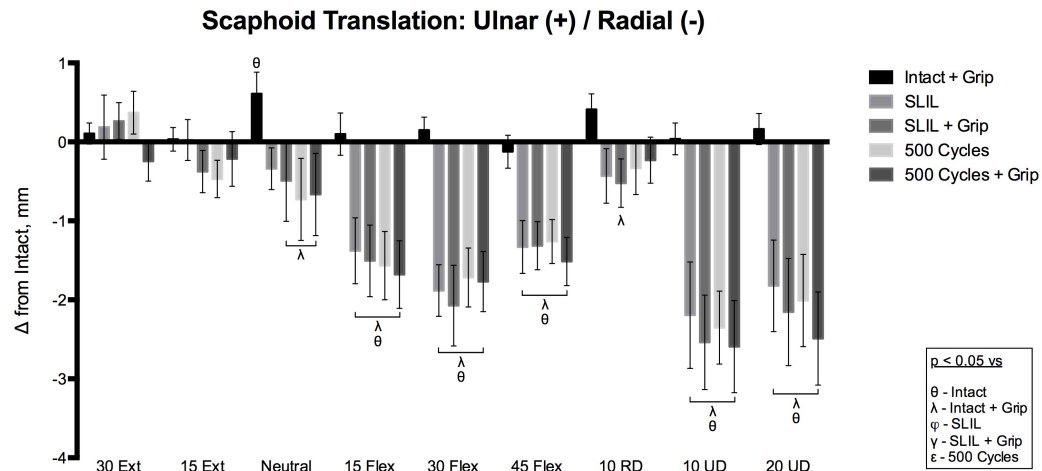


Figure 5-14. Scaphoid radial/ulnar translation across all testing conditions

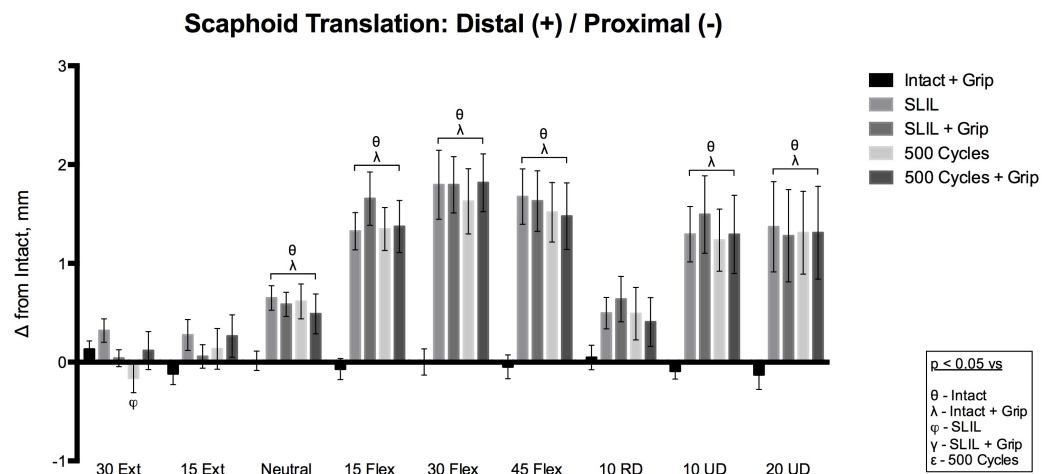


Figure 5-15. Scaphoid proximal/distal translation across all testing conditions

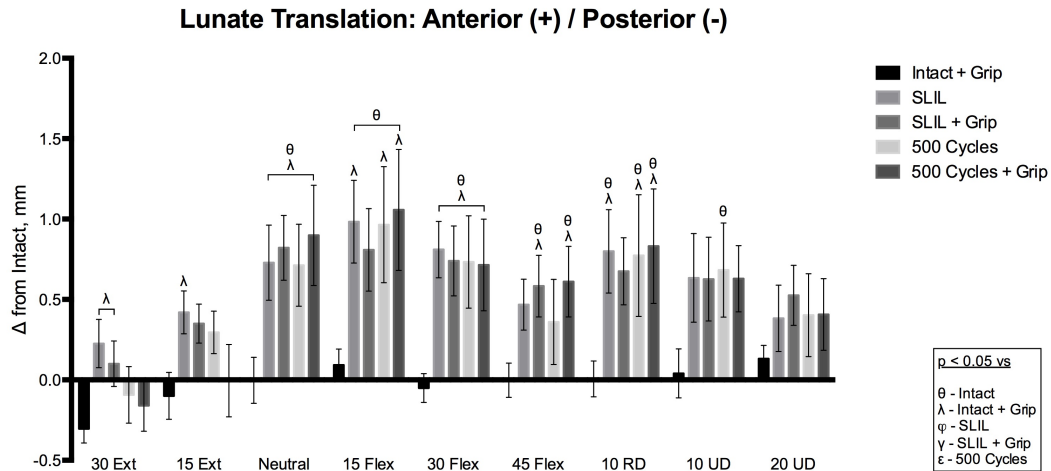


Figure 5-16. Lunate anterior/posterior translation across all testing conditions

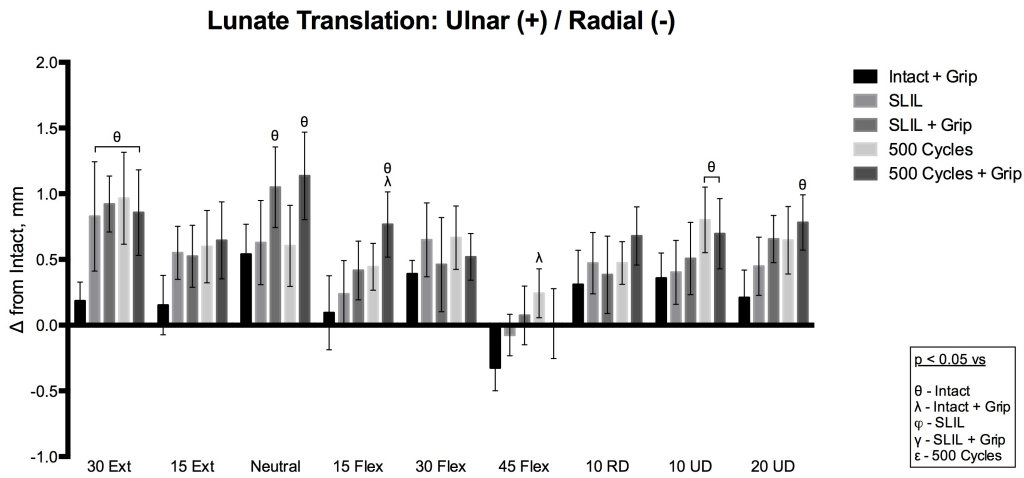


Figure 5-17. Lunate radial/ulnar translation across all testing conditions

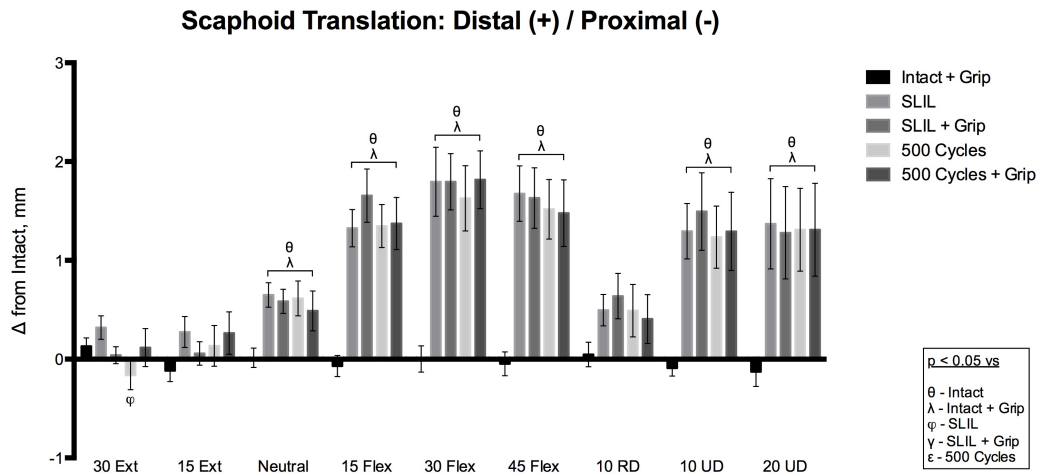


Figure 5-18. Lunate proximal/distal translation across all testing conditions

SLIL Tear Following 500 Grip Cycles

Following 500 cycles of grip loading, there were continued trends of increased flexion, ulnar deviation, and pronation. The scaphoid remained significantly flexed compared to intact and the average flexion compared to intact increased to 7.7° from 6.0° following SLIL tear alone. At 15° extension there was significantly increased scaphoid flexion compared to SLIL tear ($4.2 \pm 1.0^\circ$ vs $1.9 \pm 0.8^\circ$, $p < 0.05$), representing the continued trend of the collapse of the scaphoid in flexion. In addition, the scaphoid flexion at 30° wrist extension became statistically significant compared to intact. Similarly the ulnar deviation of the scaphoid remained significant compared to intact across 7/9 testing positions, and increased to 7.8° from 6.3° following the SLIL tear compared to intact. This change between the SLIL tear and following 500 grip cycles was not significant however. In addition to remaining significantly pronated compared to intact across all testing positions, the 500 grip cycles caused a significant increase in scaphoid pronation at 30° compared to the SLIL tear condition (3.8° vs 1.8° , $p < 0.05$). This definitively showed the 500 cycles of grip had a significant effect on the scaphoid rotational kinematics.

The posterior translation of the scaphoid after 500 grip cycles became significant at all wrist positions, with an average posterior translation of 1.3mm. In addition, at 30° extension the posterior translation was statistically significant compared to the SLIL tear condition (0.0 vs 0.5mm, $p = 0.02$). This further represented significant kinematic alterations to the carpus caused by the 500 grip cycles. The scaphoid remained translated significantly radially and distally compared to intact at 5/9 and 6/9 testing positions, respectively, but the 500 grip cycles did not cause any further kinematics changes along these axes.

The rotational kinematics of the lunate were largely unaltered following the 500 grip cycles compared to the SLIL tear. The lunate remained significantly extended compared to intact at 7/9 positions, but did not show a strong trend towards further extension after 500 cycles. Like previous conditions there was a trend towards radial deviation, that was not significant, and there was little effect on pronation/supination of the lunate.

After 500 cycles the lunate remained significantly anteriorly translated compared to intact, increasing to 5/9 positions from 4/9 positions after SLIL tear. The lunate also was proximally translated at 5/9 wrist positions, up from 4/9 after SLIL tear. The ulnar translation of the lunate compared to intact became significant at 2/9 positions, compared to 1/9 for SLIL tear. For all 3 anatomical axes, there were no significant changes compared to SLIL tear.

The distance between the scaphoid and lunate remained significantly increased in all 3 anatomical axes compared to intact, but the 500 grip cycles did not significantly increase any of these measurements. The radial/ulnar distance increased to 1.7mm from 1.5 after SLIL tear ($p>0.05$). The anterior/posterior distance increased to 1.8mm from 1.6mm after SLIL tear ($p>0.05$). The proximal/distal distance increased to 1.4mm from 1.3mm after SLIL tear ($p>0.05$). The 3D distance increased to 3.4mm from 3.0mm after SLIL tear ($p>0.05$).

Following 500 cycles of grip, there began to be significant changes to the translation of the capitate head. On average the capitate translated 0.6mm proximally compared to intact (Range 0.2-1.2mm), and this was statistically significant at 4/9 testing positions. Also, at 15° extension the proximal translation was statistically significant compared to SLIL tear ($0.6 \pm 0.1\text{mm}$ vs $0.1 \pm 0.1\text{mm}$, $p=0.03$). Similarly, the anterior translation of the capitate began significant at 3/9 testing positions compared to intact, averaging 0.7mm (Range 0.1-1.5mm).

There was also no significant change compared to SLIL tear. There was no change in the radial/ulnar translation of the capitate compared to intact across all positions.

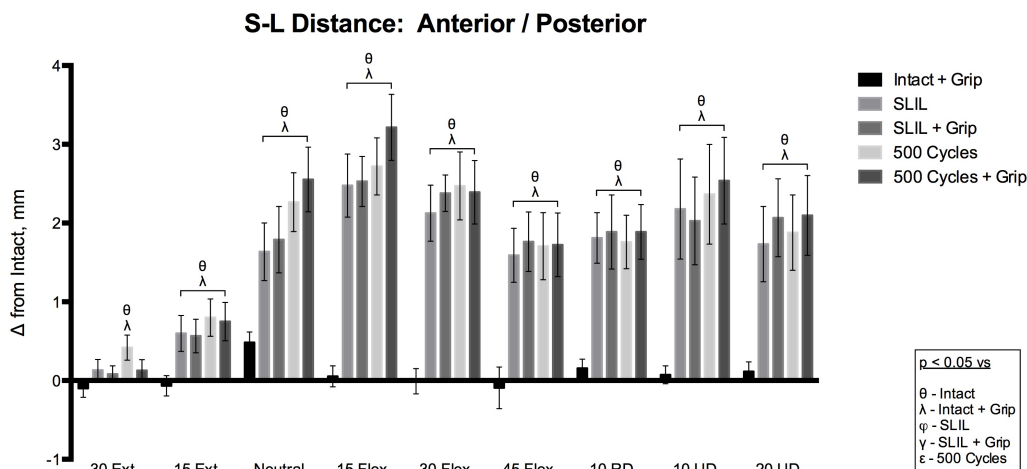


Figure 5-19. Scapholunate gap in anterior/posterior axis across all testing conditions

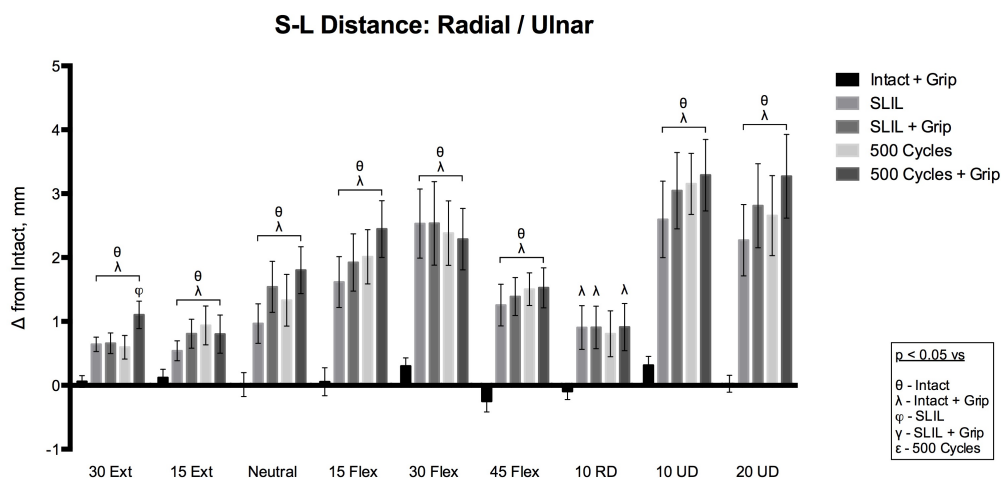
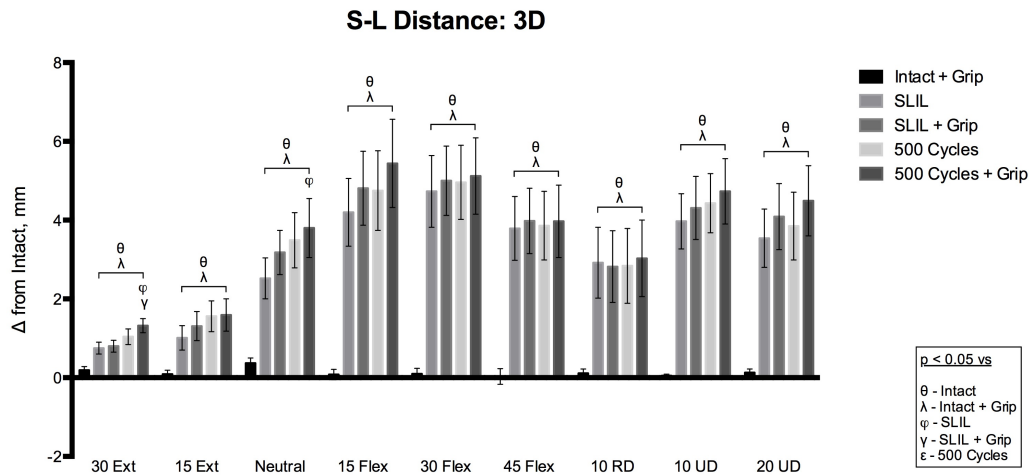
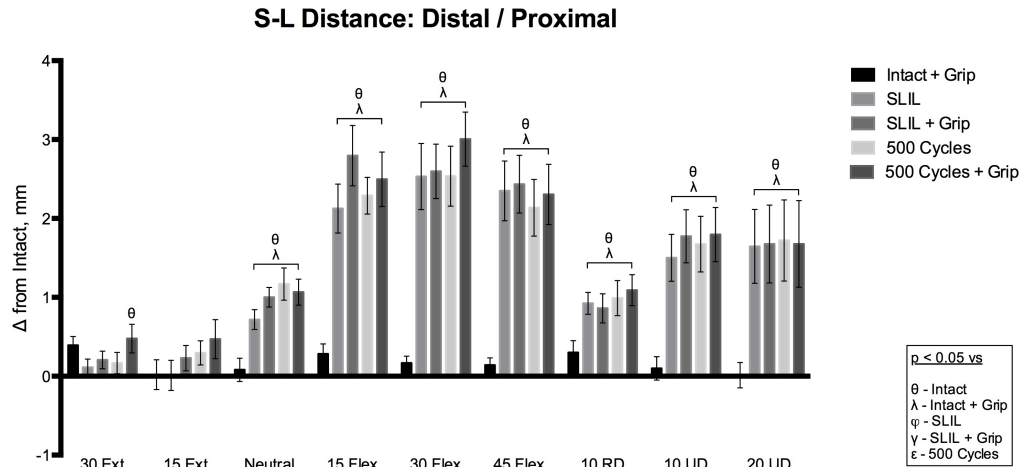


Figure 5-20. Scapholunate gap in radial/ulnar axis across all testing conditions



SLIL Tear Following 500 Grip Cycles with Grip

After applying grip, following the 500 cycles the scaphoid began to show significant kinematic changes compared to the SLIL tear condition. With grip the scaphoid remained significantly flexed compared to intact at 8/9 testing positions (Average 8.4°), but also had increased flexion compared to the SLIL tear condition at 15° extension, neutral, and 15° flexion. At 15° extension the scaphoid flexion was $4.2 \pm 1.0^\circ$ compared to $1.9 \pm 0.8^\circ$ after SLIL tear ($p=0.04$). At neutral the scaphoid flexion was $8.6 \pm 1.5^\circ$ compared to $5.3 \pm 1.0^\circ$ after SLIL tear

($p=0.04$). At 15° flexion the scaphoid flexion was $12.8 \pm 1.5^\circ$ compared to $9.3 \pm 1.3^\circ$ after SLIL tear ($p=0.01$). The scaphoid also remained significantly ulnarly deviated compared to intact at 8/9 testing positions (Average 8.5°), and showed increased ulnar deviation compared to the SLIL tear condition at 15° extension and neutral. At 15° extension the scaphoid ulnar deviation was $2.6 \pm 1.0^\circ$ compared to $0.4 \pm 0.7^\circ$ after SLIL tear ($p=0.03$). At neutral the scaphoid flexion was $7.3 \pm 1.8^\circ$ compared to $3.2 \pm 1.4^\circ$ after SLIL tear ($p=0.03$). Lastly, the scaphoid remained significantly pronated compared to intact at all testing positions (Average 5.4°), and showed increased pronation compared to SLIL tear at 30° extension (3.8° vs 1.8° , $p<0.05$). All these significant kinematic changes compared to SLIL tear represent continued carpal collapse caused by repetitive grip.

The translation of the scaphoid in all 3 anatomical axes was mostly unchanged by applying grip following 500 grip cycles. The only exception was an increase in posterior translation of the scaphoid at 15° extension compared to SLIL tear ($0.8 \pm 0.2\text{mm}$ vs. $0.2 \pm 0.2\text{mm}$, $p=0.03$). In general the scaphoid remained significantly translated posteriorly, radially, and distally compared to the intact condition.

The rotational and translational kinematics of the lunate were unchanged by applying grip following 500 grip cycles. Compared to intact, the lunate rotation remained significantly extended, and radially deviated as was seen in the 500 cycle condition. The lunate also remained significantly translated anteriorly, and proximally as was seen in the 500 cycle condition. There were no kinematics changes of the lunate that were significantly different compared to the SLIL tear condition.

The distance between the scaphoid and lunate had some significant changes with grip following the 500 cycles. At 30° extension the radial/ulnar distance between the scaphoid and lunate was increased compared to the SLIL tear condition ($1.1 \pm 0.2\text{mm}$ vs $0.6 \pm 0.1\text{mm}$, $p=0.02$). The 3D distance also increased significantly compared to SLIL tear at 30° extension ($1.3 \pm 0.2\text{mm}$ vs $0.8 \pm 0.2\text{mm}$, $p<0.01$) and neutral ($3.8 \pm 0.8\text{mm}$ vs $2.5 \pm 0.5\text{mm}$, $p<0.05$). These changes show the continued displacement between the scaphoid and lunate that occurs following the SLIL tear with repetitive grip loading.

Lastly, the capitate also had significant translational changes with grip following 500 grip cycles. The capitate translated proximally 0.8mm on average (Range 0.4-1.1mm) across all testing positions, and was statistically significant at 6/9 testing conditions, compared to only 3/9 positions after the previous 500 cycles condition. In addition, the proximal translation was statistically significant compared to SLIL at 15° extension ($0.5 \pm 0.2\text{mm}$ vs $0.1 \pm 0.1\text{mm}$, $p<0.05$) and neutral ($0.8 \pm 0.1\text{mm}$ vs $0.1 \pm 0.1\text{mm}$, $p<0.01$). The capitate remained posteriorly translated as seen in previous conditions, but there was no significant increase.

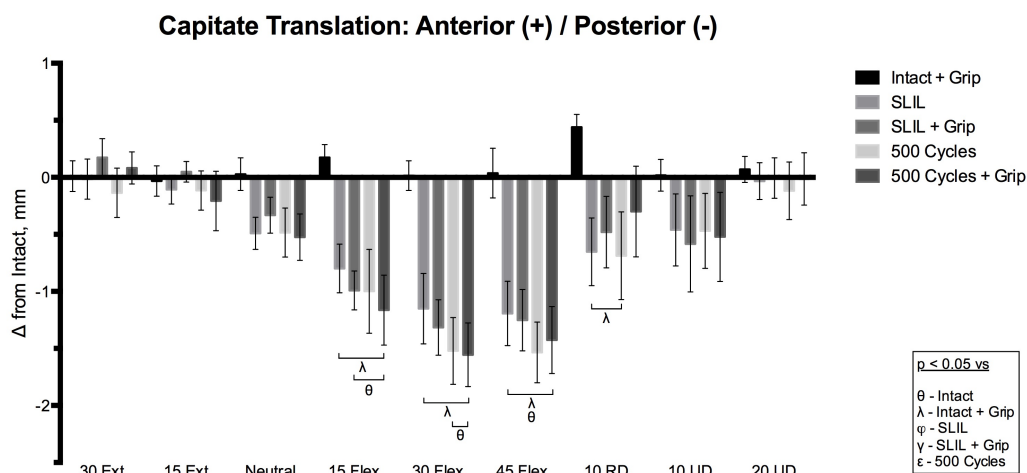
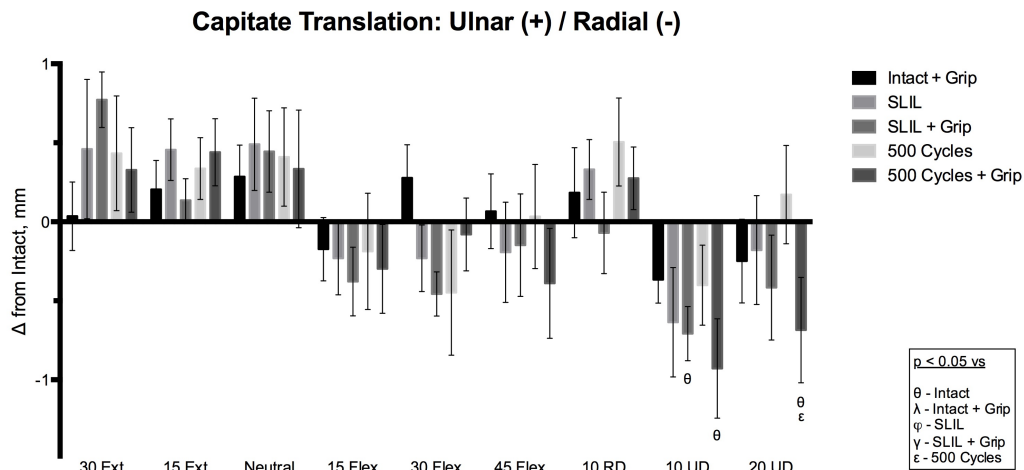
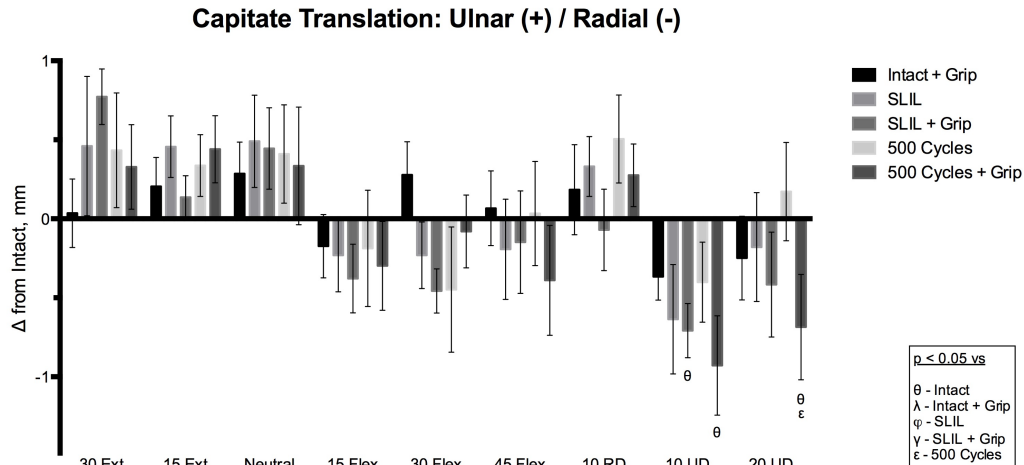


Figure 5-23. Capitate anterior/posterior translation across all testing conditions



Association between Capitate Proximal Translation and SL Gap

Two significant translational findings were observed in this experiment with SLIL injury and rep: an increase in the distance between the scaphoid and lunate, and proximal translation. A linear regression model was used to see if there was any correlation between the proximal capitate translation and the scapholunate distance in the radial/ulnar axis or 3D distance. The plot was composed of the scapholunate distance and proximal capitate translation for every specimen, testing position, and testing condition. The results are shown in Figure 5-26. Both plots showed a modest correlation between the scapholunate distance and capitate proximal translation. The

correlation coefficients for radial/ulnar and 3D scapholunate distance vs. capitate proximal translation were -0.83 and -1.10, respectively. The R^2 , or goodness of fit, for both models was still fairly low, with both being approximately 0.1.

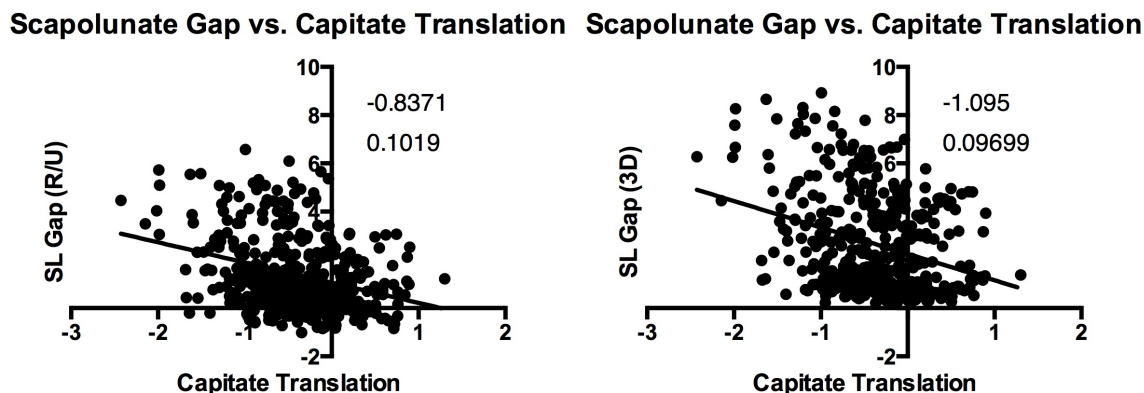


Figure 5-26. Linear regression models analyzing proximal capitate translation vs. scapholunate gap (R/U on left, 3D on Right)

Summary of Significant Findings

Below in Table 5-1 is a summary of the number of testing positions each significant finding was found for each testing condition.

Significant Finding	SLIL Tear	SLIL + Grip	500 Cycles	500 Cycles + Grip
Scaphoid Flexion c/t Intact	7/9	8/9	9/9	8/9
Scaphoid Pronation c/t Intact	8/9	9/9	9/9	9/9
Scaphoid UD c/t Intact	5/9	7/9	8/9	8/9
Scaphoid Flexion c/t SLIL	-	-	1/9	2/9
Scaphoid Pronation c/t SLIL	-	-	1/9	1/9
Scaphoid UD c/t SLIL	-	-	-	2/9
Lunate Extension c/t Intact	6/9	7/9	6/9	7/9
Lunate Extension c/t SLIL	-	-	-	-
SL R/U Distance c/t Intact	8/9	8/9	8/9	8/9
SL R/U Distance c/t SLIL	-	-	-	1/9
SL 3D Distance c/t Intact	9/9	9/9	9/9	9/9
SL 3D Distance c/t SLIL	-	-	-	2/9
Capitate Prox Trans c/t Intact	-	-	3/9	6/9
Capitate Prox Trans c/t SLIL	-	-	1/9	2/9

Table 5-1. Number of testing positions each significant finding was observed for each condition. c/t = compared to

Discussion

The purpose of this study was to evaluate the effect of sectioning the SLIL on the kinematics of the carpus and to further understand the effect repetitive grip had following a SLIL injury. Current research postulates that injury to the SLIL alone is not sufficient to cause kinematic alterations to the carpus; but that injury to secondary stabilizers is required to cause abnormal kinematics⁴¹. Further studies have shown significant kinematic alterations with sectioning of the SLIL alone, particular with scaphoid flexion and lunate extension, however⁴²,⁴³. In addition to reporting the isolated effects of a SLIL tear using a new wrist testing system, this study sought to investigate whether functional stresses from grip, a vital part of activities of daily living, had the ability to exacerbate any kinematic alterations seen with SLIL sectioning.

Acute SLIL Tear

Our study showed that sectioning of the SLIL caused significant kinematic changes to the scaphoid and lunate. The scaphoid flexed, ulnarly deviated, and pronated across most testing positions. This flexion and ulnar deviation is in line with what has been shown previously^{42, 43}, but this is the first study to report significant pronation of the scaphoid following SLIL sectioning. The magnitudes of our changes are similar what has been previously reported. The scaphoid flexed an average of 6.0° while ulnarly deviating an average of 6.3°. Similar to what has previously been reported the kinematic changes were much smaller and even non significant with the wrist in extension. The primary effect of SLIL sectioning on the lunate was significant extension across most wrist positions, averaging 6.3°.

The SLIL tear also caused significant scaphoid and lunate translation. Isolated sectioning of the SLIL caused radial and posterior translation of the scaphoid, while causing anterior and ulnar translation of the lunate. The radial translation of the scaphoid and ulnar translation of the lunate has been shown previously in a single study⁴⁷ and is confirmed again in this study. The report of scaphoid posterior translation and lunate anterior translation is, however, the first report of this phenomenon. The scaphoid translated, on average, 1.0mm radially and 1.0mm posterior, in line with the previous study. The lunate translated, on average, 0.6mm ulnarly and 0.5mm anteriorly. The translation of the scaphoid and lunate in opposite directions after an isolated tear give insight into the clinical observation of a widened scapholunate joint following injury. The small magnitudes of change also correlate with the fact that in the acute setting a change cannot be seen on x-ray.

Our system was designed to measure the distance between the centroid of the face of the scaphoid and lunate at the scapholunate joint as well in order to quantify the change in size of the gap along all 3 anatomical axes. The SLIL tear caused a significant increase in the R/U, A/P, and P/D width of the SL distance. The SL distance increased, on average, 1.4mm along the R/U axis, 1.6 along the A/P axis, and 1.3mm along the P/D axis. Looking at the change in 3D distance between the scaphoid and lunate, it increased 3.0mm on average. This data suggests that although on clinical x-rays there often is no detectable change to width of the scapholunate joint, the initial injury does cause an increased SL distance in all 3 anatomical axes. The lack of finding on x-rays may also be attributed to the lack of a solid comparison as the contralateral wrist has often shown to be unreliable^{71, 72}.

The head of the capitate translated dorsally following sectioning of the SLIL. The average translation was 0.5mm, but was only significant at a single testing position. The isolated injury to the SLIL did not seem to have a significant effect on the capitate.

Effect of Grip after an acute SLIL Tear

The effect of grip on a wrist with an acute SLIL tear is important to quantify for two reasons. The first being that because often times these acute injuries can go undiagnosed, patients will continue to use their wrist/hand for activities of daily living such as grip. Understanding how grip affects the wrist after there is a tear to the SLIL may aid in understanding how the injury progresses and help develop more effective surgical treatments to prevent progression. Additionally, it is valuable to study as many stress radiographs that are used to diagnose SLIL tears involve grip⁶¹. Simulating grip after an injury to the SLIL has also never been done in the literature.

In general grip caused an exacerbation of the kinematic alterations seen with sectioning of the SLIL alone. The changes were not statistically significant compared to the SLIL condition, but grip did cause an increase in the number of testing positions where a significant change from intact was seen with previously described kinematic changes. The flexion of the scaphoid became significant at 8/9 positions, its pronation significant at all testing positions, and its ulnar deviation became significant at 7/9 testing positions. The extension of the lunate also became significant compared to intact at 7/9 of testing positions. There were no further changes to the translational kinematics of the scaphoid, lunate, capitate, or SL distance however.

These results have important clinical implications. First of all, it shows that there is an exacerbation of the kinematic abnormalities with grip. This data confirms the clinical practice of taking stress radiographs with grip in order to more sensitively diagnose SLIL tears by exaggerating the symptoms. Furthermore, this data can give us an idea of how the injury can progress following an acute tear when the wrist and hand are still used for grip activities.

Effect of 500 Cycles of Grip Loading after SLIL Tear

After seeing that grip after an acute tear can worsen the kinematic abnormalities of the scaphoid and lunate, the next goal was to test the effect of repetitive grip loading to see if permanent alterations to the carpus without grip were created or if grip only caused changes that were reversible. The repetitive grip loading also simulates the clinical condition of a patient that continues to use their hand and wrist for grip and other activities of daily living after having torn the SLIL. Clinically the chronic injury to the SLIL results in the development of a SLAC wrist where it has been described that the scaphoid is flexed, lunate is extended, scapholunate distance is significantly increased, and the head of the capitate is translated anteriorly into the SL joint^{73, 74}. Previously it has been shown that 1000 cycles of wrist circumduction were sufficient to increase scaphoid flexion, lunate extension, and SL distance⁴¹⁻⁴³. This study seeks to build upon that data by simulating a more realistic functional stress, grip, which has previously been shown to predispose to SL repair failures³⁶.

After 500 cycles of grip loading the kinematic changes seen with SLIL tear compared to intact were present at a greater wrist range of motion, and there were additional kinematic changes seen compared to the SLIL tear condition. Compared to intact the flexion and pronation

of the scaphoid were significant at all wrist positions, while its ulnar deviation was significant at 8/9 testing positions. There was no further change seen with the lunate extension, or SL distance.

The most significant findings were those kinematic changes that were statistically significant compared to the SLIL tear condition. 500 cycles of grip caused a significant increase in the flexion and pronation of at the scaphoid at a single position each. While only seen at a single position each, it shows the gradual progression of carpal collapse with repetitive grip. In addition, at 3/9 testing positions it was shown that the capitate had translated proximally compared to the intact wrist, and at a single position this change was significant compared to the SLIL tear condition. The proximal translation of the capitate has never been quantified before, except for grossly on x-rays on SLAC wrists.

The Effect of Grip after SLIL tear and 500 Cycles of Grip Loading

The last condition tested was the effect of grip after 500 cycles to look at how the carpus behaves with grip after a chronic SLIL tear. With grip in the acute tear condition we saw exacerbation of the kinematic alterations caused by the SLIL alone. Grip following the 500 cycles showed similar results. With grip even more kinematic changes were seen that were significant compared to the SLIL condition. The flexion of the scaphoid was now significant at 2/9 wrist positions, and its ulnar deviation became significant at 2/9 positions. In addition, the SL distance in both the R/U axis and 3D distance increased compare to the SLIL tear. Lastly, the proximal translation of the capitate became significant at 2/9 testing positions.

The effect of repetitive grip on the lunate was something we were very interested in because the normal effect of grip is to flex the lunate, however in a wrist with a chronic SLIL

tear, the lunate sits extended^{73, 74}. This led us to wonder if grip alone could lead to an increase in the extension of the scaphoid as is seen clinically in a wrist with a chronic SLIL tear. Although there was a trend towards increased lunate extension following 500 cycles and then with grip, this did not reach significance. Further studies in this area should be conducted however, as the data was promising.

Limitations

This study is not without limitations however. First, cadaveric studies have the inherent limitation of variable specimen age and tissue condition. Another limitation is the unknown amount of force that is applied by each muscle tendon in vivo. This study attempted to approximate in vivo loading conditions based on physiological cross sectional area. Additionally the testing system used applies the same muscle loading at all wrist positions. This provided consistent muscle loading conditions to be able to isolate the effect of grip, but likely does not represent an in vivo condition. Lastly grip was grossly approximated by loading the FDP, but did not incorporate loading of any of the other muscles involved in grip such as flexor digitorum superficialis, the intrinsic hand muscles, and flexor pollicis longus.

Summary

The combination between increased scaphoid flexion, increased lunate extension, increased SL gap, and proximal migration of the head of the capitate all points to the fact that our repetitive grip loading is sufficient to create a chronic SLIL injury. The summary of kinematic changes is seen in Table 5-2 In Figure 5-27 you can see a 3D reconstruction of the wrist with an intact SLIL on the left and after a SLIL tear and 500 cycles of grip loading on the right. It is clear

that there is a widening of the SL Gap, proximal migration of the head of the capitate, and collapse of the proximal row of the carpus. Figures 5-28, 5-29, and 5-30 show overlays of the position of the scaphoid, lunate, and capitate in both the intact condition, and following a SLIL tear with 500 grip cycles. This model has potential applications for better testing surgical treatments to treat the chronically injured wrist as compared to a wrist that has just had an acute injury.

Significant Finding	SLIL Tear	SLIL + Grip	500 Cycles	500 Cycles + Grip
Scaphoid Flexion	6.1°*	7.4°*	7.7°*#	8.4°*#
Scaphoid Pronation	4.8°*	4.9°*	5.5°*#	5.4°*#
Scaphoid UD	6.3°*	6.8°*	7.8°*	8.5°*#
Lunate Extension	6.3°*	6.1°*	6.4°*	6.6°*
SL R/U Distance	1.5mm*	1.7mm*	1.7mm*	1.9mm*#
SL 3D Distance	3.0mm*	3.4mm*	3.4mm*	3.7mm*#
Capitate Prox Trans	0.2mm	0.3mm	0.6mm*#	0.8mm*#

Table 5-2. Average significant rotations and translations across all testing positions for each condition compared to intact. c/t = compared to. *at least one position with $p < 0.05$ vs intact. #at least one position with $p < 0.05$ vs SLIL

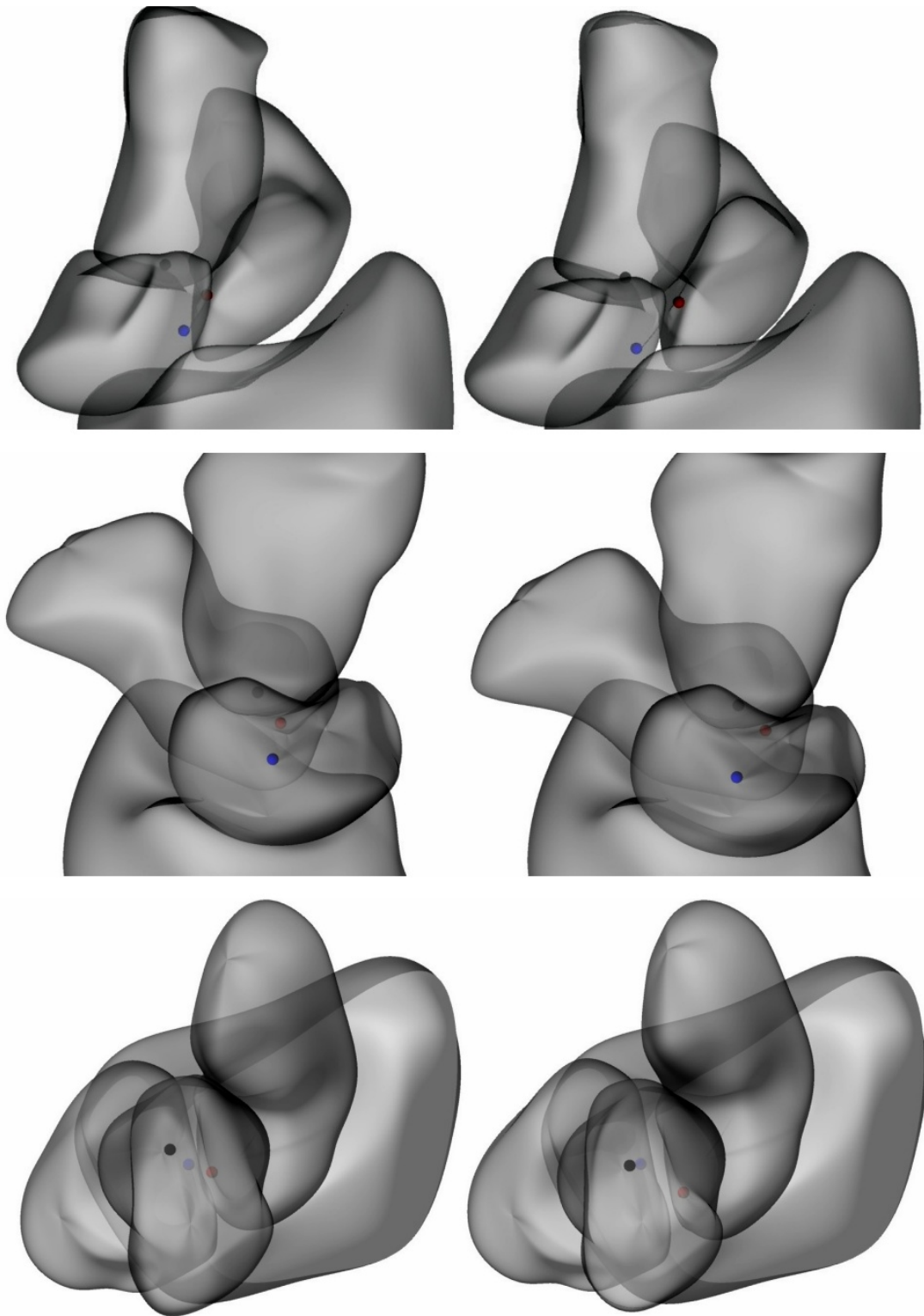


Figure 5-27. On the left is the intact carpus and on the right is the carpus after sectioning the SLIL and 500 cycles of grip loading. The scaphoid collapses in flexion and pronation while the lunate extends and supinates. The scaphoid and lunate are seen to spread apart and the head of the capitate migrates proximally

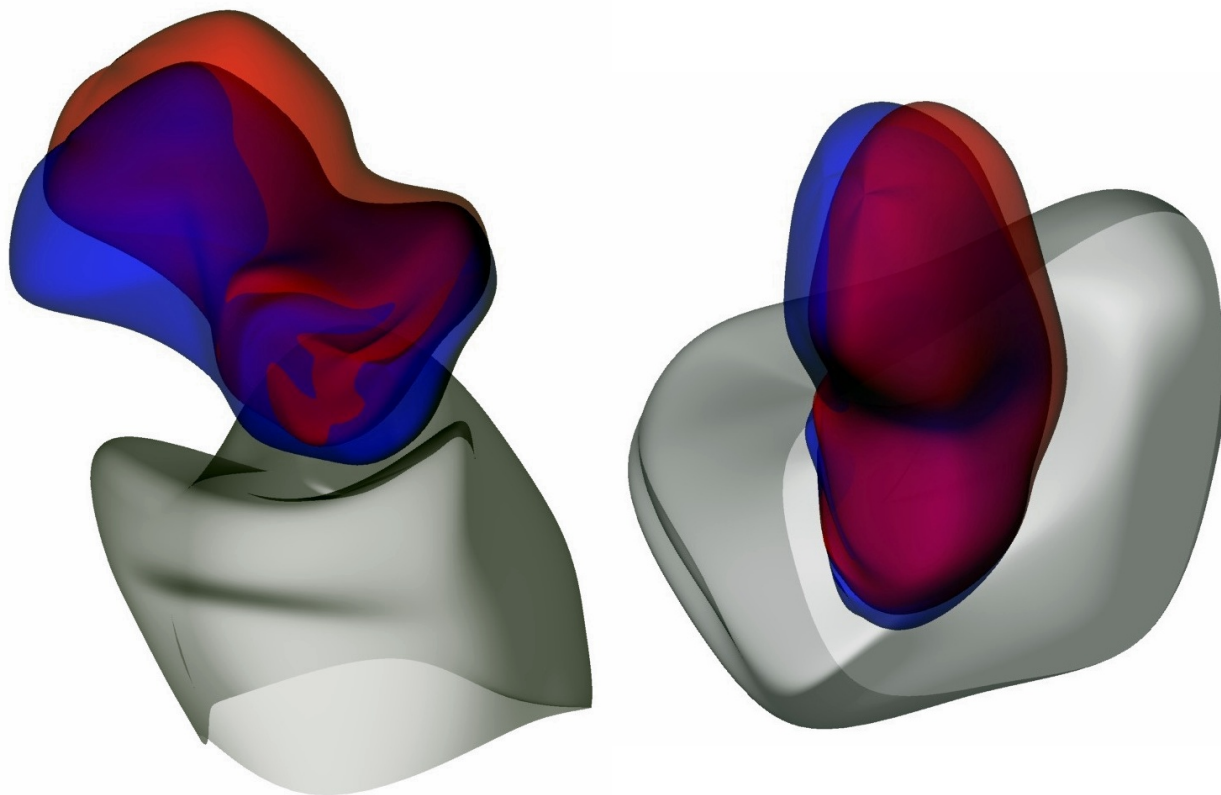


Figure 5-28. The kinematic changes of the scaphoid from Intact (red) to SLIL and 500 grip cycles (blue). Significant flexion and pronation of the scaphoid are seen.

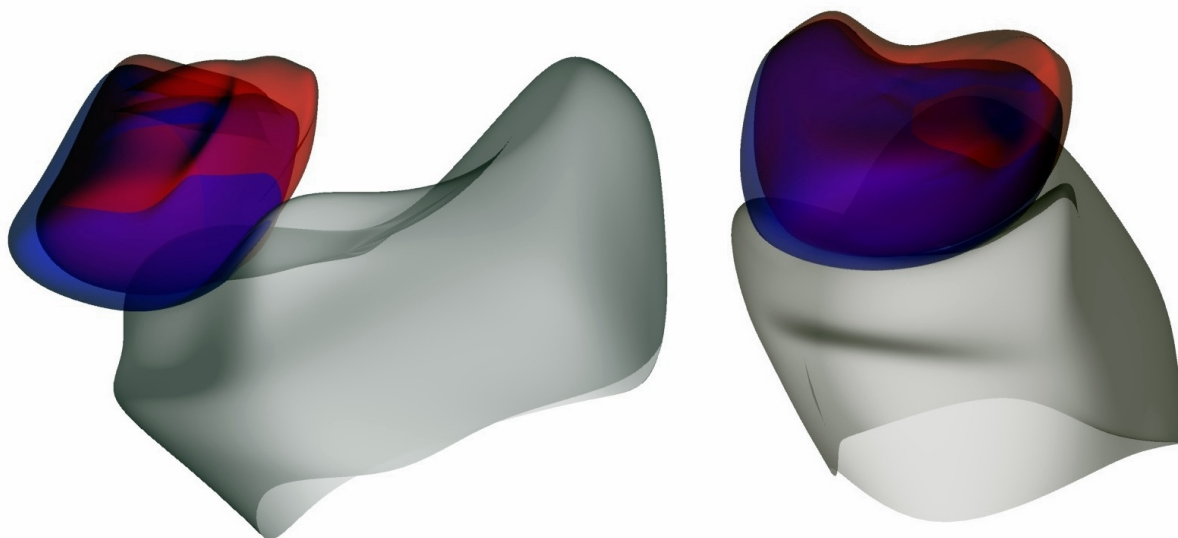


Figure 5-29. The kinematic changes of the lunate from Intact (red) to SLIL and 500 grip cycles (blue). Significant extension, supination, and ulnar translation of the scaphoid are seen.

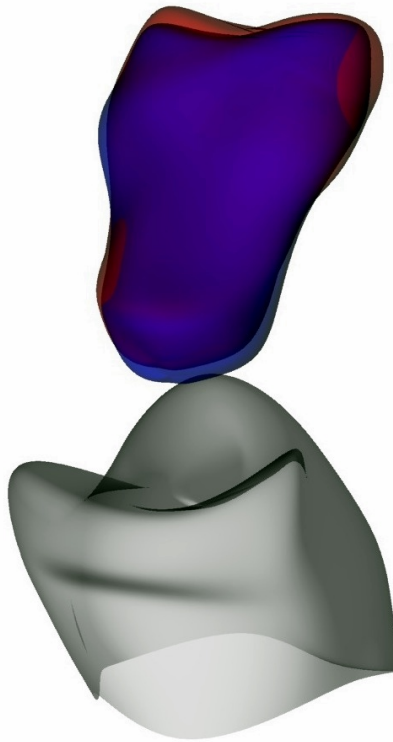


Figure 5-29. The kinematic changes of the capitate from Intact (red) to SLIL and 500 grip cycles (blue). Significant proximal translation of the capitate is seen.

Conclusions

This study has shown that isolated injury to the scapholunate interosseous ligament is not without consequence as it causes significant rotational and translational changes to the carpus. Furthermore, this study showed that repetitive grip leads to many of the kinematic alterations seen in a wrist with a chronic SLIL injury or in a SLAC wrist. Lastly, this study is the first to date that has quantified the role of the proximal translation of the capitate following an SLIL injury. This proximal migration of the capitate may be the cause of further carpal collapse following the acute injury. Future studies are warranted to further investigate the role of the head of the capitate with grip and after an SLIL tear.

CHAPTER 6

Summary and Conclusions

Summary

In this dissertation a new actuator driven cadaveric wrist testing simulator has been developed capable of applying customizable loading protocols and measuring the rotational and translational kinematics of the carpus. This testing system has been validated by comparing the rotational kinematics of the intact carpus to numerous previously published studies. The effect of grip was studied in the intact wrist, leading to further insight to the effect of grip on the flexion of the proximal carpal row and widening of the scapholunate joint. Lastly, this system has been used to understand the kinematic consequences of an acute scapholunate interosseous ligament tear and a chronic tear by applying 500 cycles of repetitive grip. Our chronic tear model closely mimics what has been reported clinically of scaphoid flexion, lunate extension, widening of the scapholunate joint, and proximal translation of the capitate. This study is the first to document quantitatively the proximal translation of the head of the capitate in a chronic SLIL injury model. Future studies can be performed to use this chronic injury model to develop improved repair and reconstruction techniques.

Conclusions

A newly developed and validated cadaveric wrist testing system has been developed. It is capable of measuring the rotational and translational kinematics of the carpus, as well as generating post experimental 3D models of every testing position. The system is based on custom Labview software to design loading protocols for multitudes of conditions and repositionable linear actuators to suit the needs of the experiment at hand. It has been used thus far to develop a greater understanding of the effect of grip on the carpus, but future studies are limitless. The system has intentionally been designed with the flexibility and customizability to investigate many hypotheses in wrist kinematics in the future. So while a significant amount of knowledge has been added to the field of carpal kinematics with grip and scapholunate interosseous ligament tears, the true development of this dissertation is a tool that can be used for years to come to investigate any aspect of cadaveric carpal research.

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