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Abnormal Joint Moment Distributions and Functional Performance During Sit-to-Stand in Femoroacetabular Impingement Patients

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Abstract

Background—Femoroacetabular impingement (FAI) is a morphological abnormality of the hip joint that causes pain when performing a mechanically demanding activity of daily living such as the sit-to-stand (STS) task. Previous studies have assessed lower extremity joint mechanics during a STS task in various pathologies yet the STS task has not been studied in FAI patients.

Objective—To identify differences in joint kinetics and performance between FAI patients and healthy controls during a STS task. It is hypothesized that FAI patients will exhibit altered time needed to complete the STS task as well as altered lower extremity biomechanics when compared to healthy controls.

Design—Cross-Sectional Cohort Study

Setting—Motion capture laboratory at an institutional orthopaedic facility

Participants—Biomechanical analysis was performed in 17 FAI patients and 31 age and body mass index (BMI) matched healthy controls during the STS task.

Methods—Sagittal plane joint moments, total support moment (TSM), joint contributions to the TSM and functional measures during the STS task were compared between groups.

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No medical devices were used in this manuscript.

Main Outcome Measurements—Peak joint moments, TSM and joint contributions to the TSM were assessed during the STS task. In addition, the time to and value of the peak vertical ground reaction force (vGRF), limb symmetry index at peak vGRF, loading rate and total time needed to perform the STS task were determined.

Results—Compared to the control participants, the FAI patients exhibited worse HOOS pain and function sub-scores. No group differences were observed in peak sagittal joint moments during the STS task. However, when compared to controls, the FAI patients demonstrated reduced knee joint contributions to the TSM. In addition, the FAI patients exhibited increased time needed to perform the STS task, increased time to reach peak vGRF and reduced lower extremity loading rate during the STS task.

Conclusions—FAI patients demonstrated abnormal joint contributions to TSM and altered functional performance during the STS task. These altered movement patterns during the STS task may be compensatory mechanisms used by the FAI patients to reduce pain and improve function.

INTRODUCTION

Femoroacetabular impingement (FAI) is a morphological pathology in which abnormal joint biomechanics between the femoral head and acetabulum causes a mechanical impingement of the hip joint [1]. FAI causes significant disability, pain and altered function during activities of daily living (ADL) with a common complaint of pain when rising from a seated position [1, 2]. The repetitive impact caused by the mechanical impingement during motions involving hip flexion and internal rotation may lead to acetabular labral lesions [3]. If FAI is not properly managed or treated, the pathology may lead to degenerative effects of the hip joint with labral injury and cartilage damage eventually resulting in accelerated osteoarthritis (OA) [2, 4]. Biomechanical assessment of patients with FAI during ADL may provide researchers and clinicians with the knowledge needed to detect this pathology at an early stage and possibly reduce the adverse effects of this pathology on hip joint health and function.

Assessment of biomechanical function during the sit-to-stand (STS) task has been performed in patients with patellofemoral joint OA [5], knee joint OA [6–8], hip OA [9], following total hip arthroplasty [10] and in healthy adults [11–14] but is yet to be assessed in the FAI population. The STS task has been suggested to be the most mechanically demanding ADL [15] and is performed by adults an average of 60 times per day [11]. Also, the STS task was proven to be a sensitive performance-based measure in evaluating asymmetries due to unilateral lower extremity pathology [16–18]. Despite the previous studies [9, 10] assessing lower extremity mechanics and function during the STS task, the results of these studies are not conclusive across these patient groups and therefore suggest that further work is needed to understand the effects of pathology on lower extremity mechanics during the STS task.

An assessment of the total joint contributions during a dynamic task such as the STS may provide an understanding of any possible altered joint movement patterns that may be present in lower extremity pathologies such as FAI. One method of understanding joint movement patterns during dynamic activity is the assessment of joint contributions to the total support moment (TSM) [19]. The TSM is an assessment of the joint torque demands that are necessary to prevent collapse during dynamic activity [19, 20]. Previous studies have assessed the individual joint contributions to the total support moment, during tasks such as hopping [20] and walking [19, 21–23] yet the TSM has not been assessed in the STS task. The relative contribution of each of the lower extremity joints to body mass support during various ADL has the potential to provide unique information regarding the movement strategies required to perform complex tasks such as the STS.

Altered function in adults with FAI has been exhibited during various activities such as walking [24–27], drop-landings [28] and deep squats [29–31] yet joint mechanics and performance measures (i.e. time to completion, weight-bearing asymmetry) related to the STS task in the FAI population has yet to be reported. Therefore, the aim of the current study was to assess the effects of FAI on lower extremity joint mechanics and performance of the STS task. We hypothesized that during the STS task, the patients with FAI would demonstrate abnormal joint loading patterns and altered performance compared to healthy controls.

METHODS

PARTICIPANTS

A total of 17 patients with unilateral symptomatic FAI and 31 asymptomatic volunteers frequency-matched for age and BMI were included in this study. All patients with FAI were referred to this study by an orthopaedic surgeon. Patients with FAI demonstrated both radiological signs of impingement and a positive flexion adduction and internal rotation (FADIR) test as previously described in the literature [32]. All asymptomatic volunteer data were selected from a control cohort of a longitudinal study on hip biomechanics in OA [33]. Both FAI patients and control participants were excluded from the current study if they presented with: 1) contraindications to MRI, 2) total joint replacement in the lower extremity, 3) previous hip surgery on the tested limb, 4) Kellgren-Lawrence (KL) score [34] greater than one in any lower extremity joint, 5) body mass index (BMI) greater than 35 $kg \cdot m^{-2}$ and 6) neurological, spine or lower extremity conditions that would prevent the participant from performing the dynamic task assessed in the current study. The current study was approved by the University Committee on Human Research. Each participant provided written informed consent prior to testing.

RADIOLOGICAL ASSESSMENT

All participants underwent a unilateral MR-exam of the symptomatic hip and bilateral standing anterior-posterior hip radiographs. Both the MRI examination and hip radiographs were used to assess structural abnormalities supporting the diagnosis in patients with FAI and to rule out relevant abnormalities in controls. In addition, the radiographs were used to determine the test limb in the control group, by assessing the KL score for both hip joints and the hip joint with the lower KL score was used as the test limb. MRI acquisition was performed using a 3 Tesla MR scanner (GE MR750, GE Healthcare, Waukesha, WI, USA) and an eight channel cardiac coil (GE Healthcare, Waukesha, WI, USA). Participants were positioned supine in the MR-scanner and immobilized using straps in order to ensure a consistent and comfortable position. Each participant's feet were secured together in order to prevent movement during the scan. The imaging protocol used in this study has been previously described [35, 36] and is explained here briefly. Sagittal, oblique coronal and axial T_2 intermediate-weighted images were obtained using a fat suppressed, fast spin-echo sequence with a repetition time of 2400 – 3700ms, echo time of 60ms, field of view of 14 – 20cm, matrix size of 288×224 and slice thickness of 3 – 4mm.

Measurements of both the alpha and lateral center edge angles were performed by two musculoskeletal radiologists using MR-images and anterior-posterior radiographs, respectively, in order to classify patients as cam, pincer or mixed-type FAI. An alpha angle > 55° [37], as measured on the oblique axial MR-images, was used to classify patients with cam-type FAI while a lateral center edge angle ≥ 35° [38], as measured on the anterior-posterior radiograph, was used to classify patients with pincer-type FAI. Patients with the mixed-type FAI demonstrated radiological findings of both the cam and pincer-type FAI. Using these radiological criteria, a total of 8 cam, 3 pincer and 6 mixed-type FAI patients were included in this study.

In addition, the anterior-posterior weight bearing radiographs were assessed using the KL score [34], in order to assess radiographic hip OA. For the patients with FAI, the KL score of the symptomatic hip was determined. In the current study, both patients with FAI and control participants were classified as those without radiographic signs of hip OA (KL≤1).

BIOMECHANICS DATA ACQUISTION AND PROCESSING

Three dimensional position data were collected at 250Hz using a 10-camera motion capture system (VICON, Oxford, UK) and ground reaction force (GRF) data were collected synchronously at 1000Hz using two in-ground force plates (AMTI, Watertown, MA, USA). A marker set consisting of 41 retro-reflective markers was used to collect three dimensional position data. Calibration markers were placed bilaterally at the greater trochanters, medial and lateral femoral epicondyles, medial and lateral malleoli, first and fifth metatarsal heads. Pelvic tracking was performed using retro-reflective markers placed at the anterior superior iliac spines, iliac crests and L5/S1 joint. Segment tracking was performed using rigid body clusters, consisting of four markers each, placed at the lateral thighs and shanks, respectively. In addition, clusters consisting of three markers each were placed on the heel shoe counters and along with the marker at the fifth metatarsal head, were used for tracking of the foot. A one second static calibration trial was obtained and then all calibration markers, except for the markers at the fifth metatarsal heads, were removed.

Each participant was asked to perform four trials of the STS task at a self-selected speed. Each participant was seated on a box with their arms crossed over their chest, in order to prevent incidental blocking of retro-reflective markers. Box heights were adjusted to match the height of the medial femoral condyle of the test limb, in order to ensure that the participant's hip, knee and ankle joints for both legs were at approximately 90°. Participants were instructed to place one foot on each force platform and to rise up from the box upon hearing the command "stand up" without shifting their feet. A trial was deemed successful if the participant was able to fully stand up and not shift their feet during the STS task. If a trial was deemed unsuccessful, the participant was asked to perform another trial of the STS task.

All raw marker position and GRF data were filtered using a 4th order Butterworth filter at 6Hz and 50Hz, respectively. The static calibration trial was used to form a seven segment musculoskeletal model consisting of the pelvis, bilateral femurs, shanks and feet using Visual3D (v5.00.16, C-Motion, Germantown, MD, USA). Local joint coordinate systems were created and an unweighted least squares method was used to describe segment position and orientation [39]. Joint coordinates were solved using a Cardan sequence of X-Y'-Z'', representing the medial-lateral, anterior-posterior and superior-inferior directions, respectively. Joint angles were normalized to the standing calibration trial. The stance phase of the STS task was defined from the time point where the horizontal velocity of the center of mass (COM) of the lower body exceeded $0.15 m \cdot s^{-1}$ and the time point when the maximum vertical position of the COM was achieved. The stance phase of the STS task was time normalized to 101 points.

SELF-REPORTED OUTCOMES

The hip disability and osteoarthritis outcome score (HOOS) [40] was used to obtain self-reported measures of pain and function in daily living. The HOOS sub-scores of pain and function were assessed on a 0 to 100 point scale. A score of 0 represents severe pain or functional impairment while a score of 100 represents no pain or functional impairment.

OUTCOME MEASURES

Peak sagittal hip, knee and ankle joint moments were assessed during the stance phase of the STS task. Externally applied joint moments were normalized by body mass ($Nm \cdot kg^{-1}$), where hip flexion, knee extension and ankle dorsiflexion moments were described as positive and used to assess peak joint moments. The total support moment (TSM) was calculated as the sum of the average internal hip extensor, knee extensor and ankle plantar-flexor joint moments as previously described [19]. The percent contribution of the hip (C_{Hip}), knee (C_{Knee}) and ankle (C_{Ankle}) to the TSM were calculated as the proportion of the average internal hip extensor (aM_{Hip}), knee extensor (aM_{Knee}) and ankle plantarflexor (aM_{Ankle}) moments using the following formulae:

$$C_{\mathrm{Hip}} = \left(aM_{\mathrm{Hip}} / TSM \right) \times 100$$

$$C_{\mathrm{Knee}} = \left(aM_{\mathrm{Knee}} / TSM \right) \times 100$$

$$C_{\mathrm{Ankle}} = \left(aM_{\mathrm{Ankle}} / TSM \right) \times 100$$

All GRF data were normalized by body weight (BW) and were used to determine the peak vertical GRF (vGRF) of the ipsilateral limb as well as the symmetry index (SI) [9, 41] which was used to assess weight bearing asymmetry (WBA). The SI was determined by dividing the peak vGRF of the ipsilateral limb by the vGRF of the contralateral limb. A symmetry index value of 1.00 indicates no WBA. In addition, the time to peak vGRF of the ipsilateral limb (%stance), the total time (s) needed to complete the STS task (Figure 1) and the loading rate (BW/s) of the ipsilateral limb were determined and compared between the patients with FAI and control participants. The loading rate was calculated by dividing the peak vGRF (BW) of the ipsilateral limb by the time (s) it took to reach the peak vGRF.

STATISTICAL ANALYSIS

Demographics and HOOS sub-scores were compared between patients with FAI and control participants using independent t-tests. All outcome measures were compared using one-way analysis of covariance (ANCOVA) tests, with a covariate of gender, in order to assess differences between the patients with FAI and control participants. In addition, an analysis of variance (ANOVA) was used to assess the effects of different FAI sub-types on performance of the STS task. All statistical analyses were performed using JMP Pro (v12, SAS, Cary, NC, USA) and alpha was set *a priori* at the 0.05 level.

RESULTS

There were no differences in demographics between the patients with FAI and control groups yet the patients with FAI demonstrated worse pain ($p < .001$) and function ($p < .001$) as shown in Table 1. No group differences were exhibited in external peak hip flexor, knee flexor or ankle dorsiflexor moments during the STS task (Figure 2). Both the FAI and control groups demonstrated similar TSM values ($p=0.46$) and ankle contributions ($p = .66$) yet the FAI group demonstrated a trend towards an increase (11.6%) in hip joint contributions ($p = .08$) and a significant 11.8% decrease in knee joint contributions ($p = .05$) to the TSM (Figure 3).

Peak ipsilateral vGRF ($p = .12$) and the symmetry index ($p = .37$) were similar between the FAI and control groups (Table 2). When compared to the control group, the loading rate was 37.9% lower ($p = .02$) and the peak vGRF occurred significantly later ($p = .003$) during the stance phase of the STS task in the FAI group (Figure 4). Also, the FAI patients took on average 0.6 seconds longer ($p = .005$) to perform the STS task compared to the control group. It should be noted that FAI sub-type did not demonstrate an effect on any of the dependent variables assessed in this study.

DISCUSSION

In our study, lower extremity joint mechanics and functional performance parameters of the STS task were compared between asymptomatic controls and patients with FAI. Although both groups exhibited similar peak sagittal plane joint moments, the patients with FAI exhibited altered hip and knee joint contributions to the total support moment during the STS task. More specifically, patients with FAI used greater hip contribution and less knee contribution to complete the STS task compared to healthy controls. When performing the STS task, there were no weight bearing asymmetries or differences between groups in peak vertical GRFs achieved during the STS but the patients with FAI did demonstrate decreased loading rates and took longer to perform the STS task. These results suggest that the patients with FAI, when compared to healthy participants, use altered joint contributions and performance parameters in order to successfully perform the STS task.

The patients with FAI in our study, similar to those with hip OA [9], did not demonstrate any differences in hip or knee joint sagittal plane moments during the STS task. Also, the patients with FAI and control participants in the current study did not exhibit differences in ankle joint moments. Similar to previous studies assessing the effects of lower extremity pathologies on the TSM during hopping [20] as well as self-selected and slow walking [21], the TSM during the STS task did not differ between groups as an effect of the FAI pathology yet the relative contributions to the TSM at the hip and knee joints were altered in the patients with FAI. More specifically, the patients with FAI used increased hip and decreased knee effort to successfully perform the STS task. One might expect patients with FAI to shift the load away from the pathological hip joint, in order to reduce the demand on the hip joint, yet these patients with FAI applied a larger demand at the hip joint and reduced load at the knee joint while performing the STS task. FAI has been suggested to be a pre-cursor to hip OA [1] and the increased demand on the hip joint used by the patients with FAI during the STS task may cause increased hip joint contact forces and potentially lead to harmful long-term effects on the articular cartilage of the hip joint. Future studies that include electromyography (EMG) and musculoskeletal simulations may provide better insight into any altered muscle activity and force production that may be present during the STS task in patients with FAI.

In our study, the time to the peak vGRF occurred later during the stance phase in the patients with FAI compared to the control participants. Unlike the current study, patients with hip OA [9] did not demonstrate any differences in the time at which peak vGRF was achieved and may suggest that patients with hip OA and patients with FAI perform the STS task using different biomechanical strategies. This difference in time to peak vGRF in the patients with FAI of the current study may help explain the reduced loading rate in the patients with FAI. Since peak vGRF was similar between the patients with FAI and control participants, the longer time used to arrive at the peak vGRF helps to reduce the overall loading rate experienced by the lower extremity in the patients with FAI. The reduced loading rate in the patients with FAI may be a compensatory mechanism to reduce pain and improve function while performing the STS task. The calculation of the loading rate within the lower extremity during the STS task may be a sensitive measure in assessing hip joint function and pain in the FAI population and adds further justification to the sensitivity of the STS task in assessing unilateral lower extremity pathologies [18].

The patients with FAI in the current study performed the STS task with an increased time compared to the control participants, unlike post-THA [10] and hip OA [9] patients that did not demonstrate differences in total time needed to perform the STS task when compared to controls. Differences in the definition of the stance phase of the STS task between the current study and previous studies [9, 10] may help to explain the differences in time needed to perform the STS task between studies. More specifically, the current study used the COM of the lower body to determine the beginning and end of the STS task, while previous studies used joint position or marker velocity data to determine the beginning and end of the STS task. The use of different variables to determine the stance phase of the STS task may lead to different portions of the stance phase of the STS to be analyzed between studies, which may lead to inconclusive results between studies. A more consistent method of determining the beginning and end of the STS task should be developed and used in future studies. The patients with FAI in the current study did not demonstrate any weight bearing asymmetries (WBA) while those with hip OA demonstrated weight bearing asymmetry at the peak vertical GRF during the STS task by offloading the involved limb by 18% [9]. These results might indicate that in subjects with more advanced degenerative changes at the hip joint, time is not a sensitive enough measure of functional performance yet WBA may be sensitive enough to detect severe hip joint pathology such as OA. On the contrary, in the current study, measurement of time to perform the STS task was different between groups and can be used to assess functional performance between patients with FAI and control participants. It should be noted that both the patients and control groups in previous work [9, 10], were older then the FAI and control groups used in the current study. Despite this difference in patient age between these previous studies [9, 10] and the current study, patients in one of these previous studies were able to perform the STS task in a similar amount of time as healthy age-matched controls [10]. Therefore, it can be suggested that the increased time to complete the STS task by the patients with FAI may be due to the morphological abnormalities present at the hip joint in those with FAI. It is also possible that the increased time needed to perform the STS task by the patients with FAI may be a compensatory mechanism to reduce or manage pain.

There are a few limitations in our study that need to be discussed. We did not obtain hip joint muscle strength or EMG data in the FAI or control groups. It has been demonstrated that patients with FAI exhibit reduced hip muscle strength and altered EMG activity of hip musculature [42] yet this previous study was performed using isometric contractions and not an isokinetic or more dynamic activity such as the STS task. Future studies involving biomechanical assessment of patients with FAI should include lower extremity EMG and strength measurements as these EMG and strength data will provide a better understanding of the functional alterations that occur during dynamic activity in the FAI population. In addition, future studies assessing the effects of FAI in the STS task should analyze trunk and pelvis segment biomechanics as patients with FAI may demonstrate altered trunk and pelvic mechanics in order to compensate for the altered mechanics at the hip joint. As mentioned earlier, a more consistent method of determining the beginning and end of the STS task should be determined so that results can be more easily compared between studies. The current study did not use an instrumented seat to assess the time point of buttocks lift-off, which may affect the determination of the actual start of the STS task. In a rehabilitation facility or clinic, the visual cue of buttocks lift-off and maximal hip extension can be used to determine the start and stop of the STS task. Future longitudinal studies should be performed in order to assess whether surgical interventions (i.e. hip arthroscopy) restores normal hip joint mechanics in the FAI cohort during various ADL such as the STS task. Also, larger cohorts of FAI patients should be enrolled in future biomechanical studies in order to assess the effects of gender and FAI sub- type on biomechanical performance during the STS task.

CONCLUSION

In conclusion, the STS task may prove to be a useful tool in assessing lower extremity joint mechanics and functional performance in patients with FAI. The results of the current study suggest that the patients with FAI use increased hip and reduced knee joint effort to successfully perform the STS task during the early stages of the pathology. In addition, the results of this study may help clinicians develop better rehabilitation programs and surgical interventions for the FAI cohort, in order to improve lower extremity joint mechanics and functional performance during an ADL such as the STS task.

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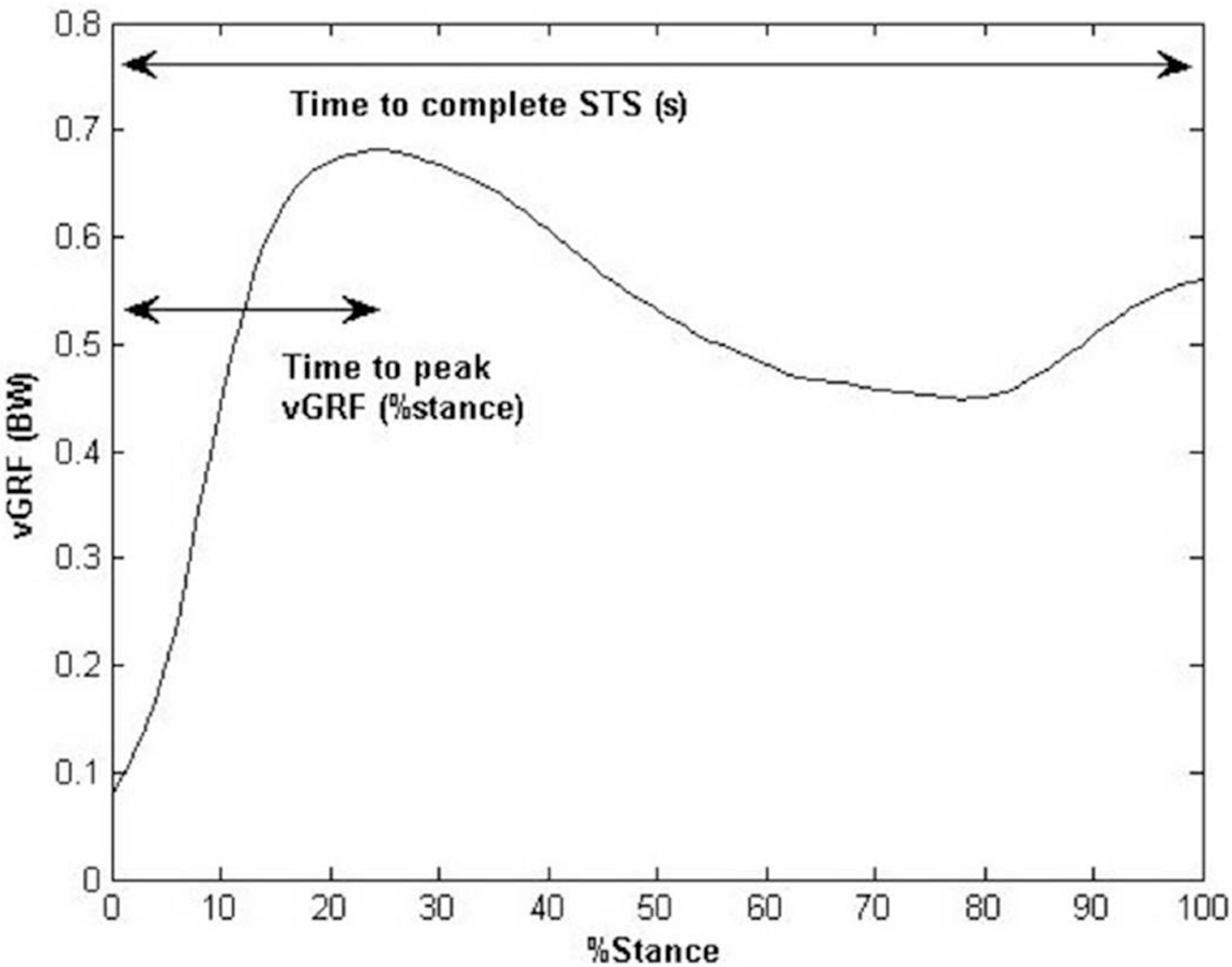

Figure 1.
A representation of the vertical ground reaction force (vGRF) profile, normalized by body weight (BW), of a study participant across the stance phase of the sit-to-stand (STS) task. The time to peak vGRF of the STS task was measured as a percentage of stance (%stance) while the time to complete the STS task was measured in seconds(s).

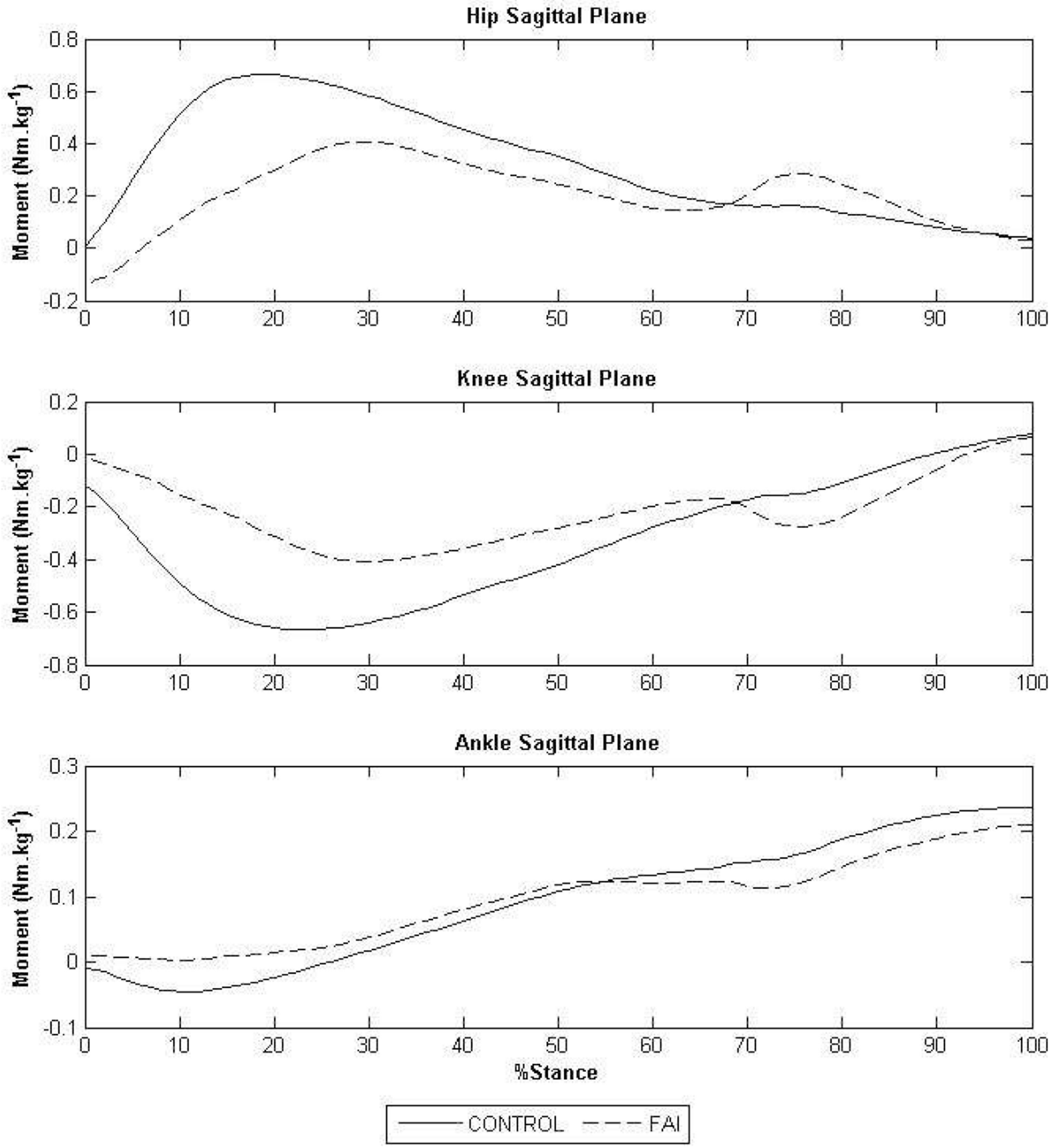

Figure 2.
External sagittal plane joint moments, normalized by body mass (Nm·kg^{-1}), during the stance phase of the sit-to-stand task for the control participants and femoroacetabular (FAI) patients are shown with the solid and dashed lines, respectively. Positive joint moments represent hip flexion, knee extension and ankle dorsiflexion.

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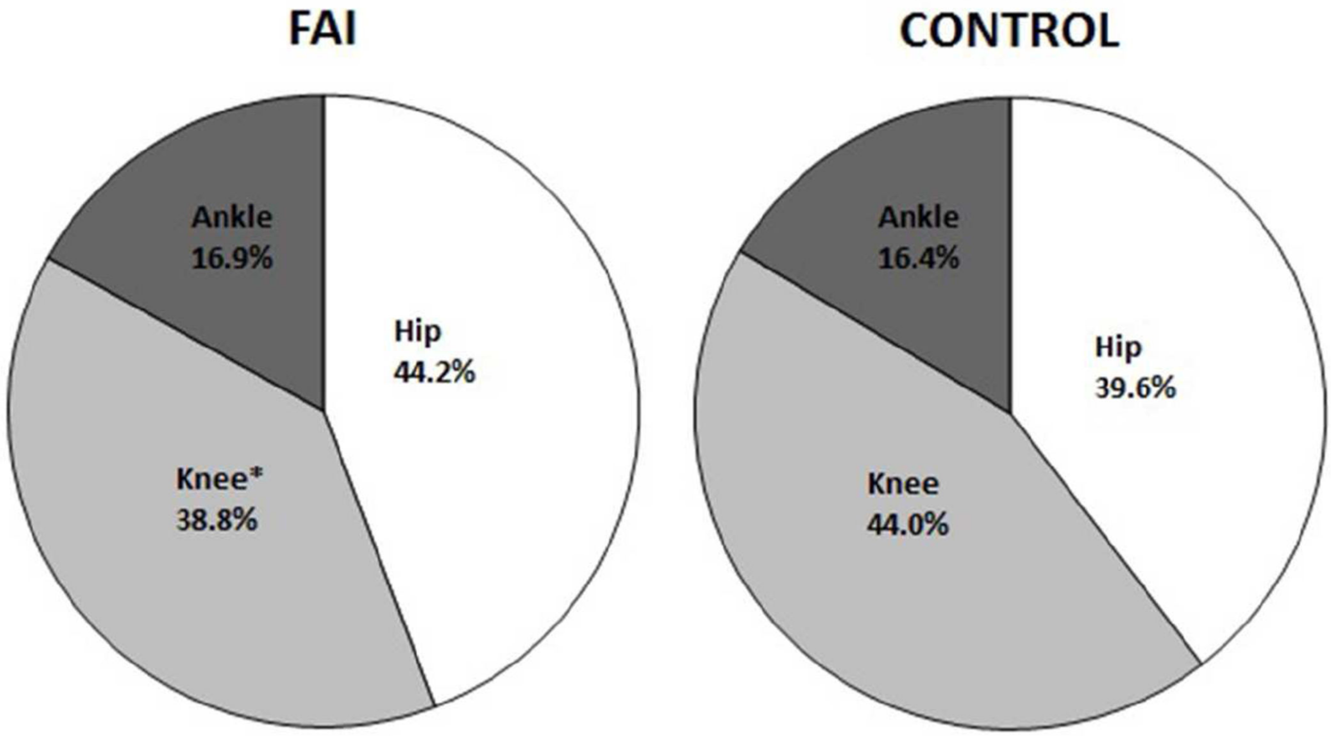

Figure 3.
Hip, knee and ankle joint contributions to the total support moment for the femoroacetabular (FAI) and control groups. An * indicates a statistically significant difference ($p \leq 0.05$) between groups.

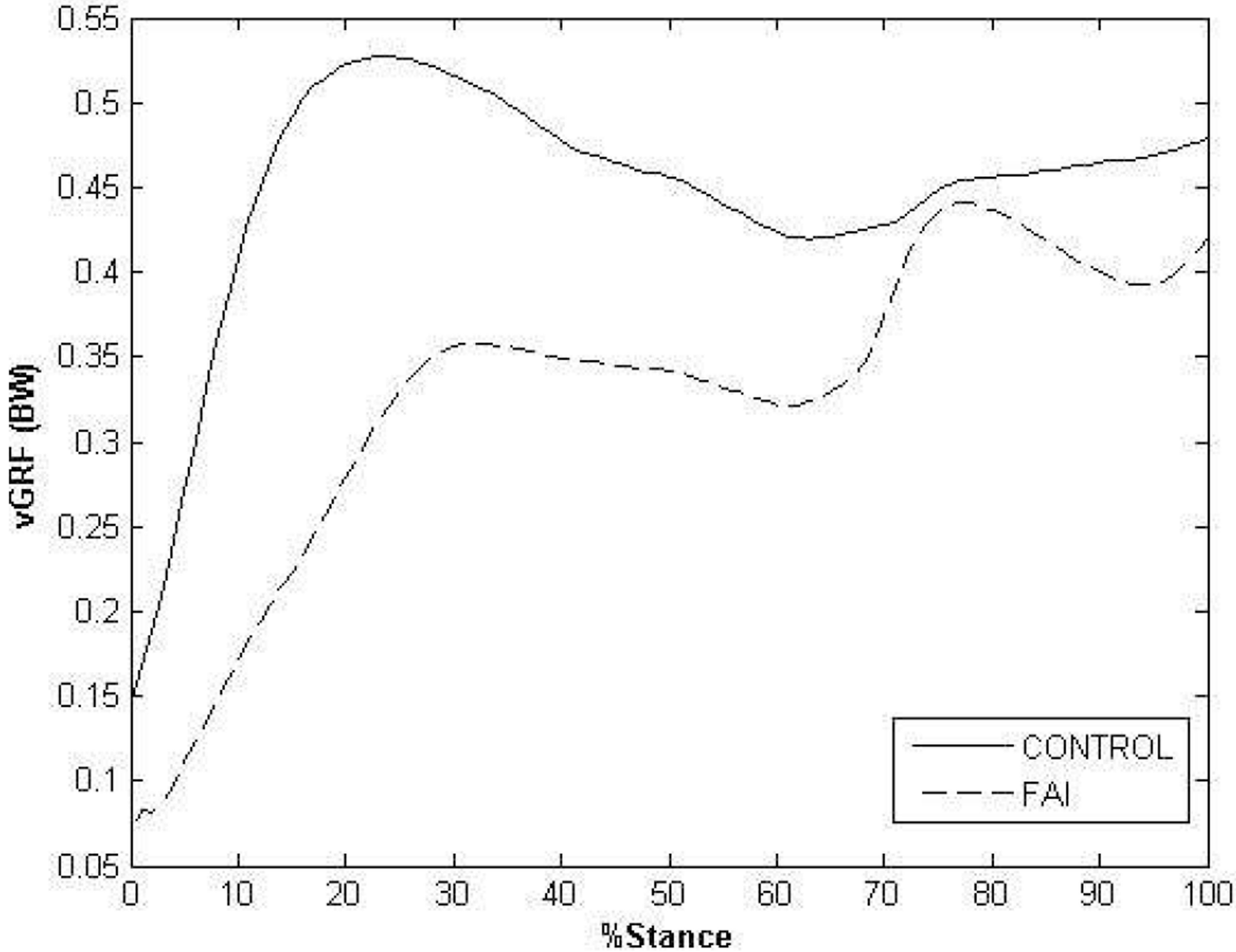

Figure 4.

Vertical ground reaction force (GRF) profiles, normalized by body weight (BW), during the stance phase of the sit-to-stand task for the ipsilateral limb of the control participants and femoroacetabular (FAI) patients are shown with the solid and dashed lines, respectively.

Table 1

Demographics, hip disability and osteoarthritis outcome (HOOS) sub-scores, for the femoroacetabular (FAI) and control (CONT) groups are reported as the mean±standard deviation.

	FAI (N=17)	CONT (N=31)	P-Value
Age (years)	40.1±7.2	41.4±12.6	.70
Gender (M:F)	13:4	17:14	.14
BMI($kg \cdot m^{-2}$)	24.8±3.6	24.0±3.6	.45
HOOS Pain	67.2±18.8	96.4±7.74	< .001 *
HOOS Function	69.4±21.5	97.1±6.71	< .001 *

An * indicates a statistically significant difference (P ≤ .05).

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Table 2

Biomechanical and performance based outcomes for the femoroacetabular (FAI) and control (CONT) groups during the sit-to-stand (STS) task are presented. Results are reported as the mean±standard deviation. Positive external joint moments represent hip flexion, knee extension and ankle dorsiflexion.

	FAI	CONT	p-value
Peak Joint Moments (Nm·kg^{-1})			
Hip Sagittal Plane	0.85±0.19	0.86±0.26	.93
Knee Sagittal Plane	−0.85±0.15	−0.84±0.24	.87
Ankle Sagittal Plane	0.28±0.11	0.26±0.09	.40
Total Support Moment (Nm·kg^{-1})	0.84±0.20	0.93±0.28	.46
Time to peak vGRF (%stance)	48.6±20.5	31.9±16.5	.003 *
Peak ipsilateral vGRF (BW)	0.60±0.05	0.62±0.07	.12
Symmetry Index	1.01±0.19	1.06±0.10	.37
Total time to perform STS (s)	1.99±0.65	1.39±0.70	.005 *
Loading Rate (BW/s)	4.28±2.57	6.89±3.66	.02 *

An * indicates a statistically significant difference ($P \leq .05$).

Abbreviations: body weight (BW: Newtons/Newtons), seconds (s), vertical ground reaction force (vGRF).