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MECHANICAL DEVIATIONS AND VERBAL-CUE ALTERED GAIT IN THE FEMOROACETABULAR IMPINGEMENT SYNDROME POPULATION

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MECHANICAL DEVIATIONS AND VERBAL-CUE ALTERED GAIT IN THE FEMOROACETABULAR IMPINGEMENT SYNDROME POPULATION

THESIS

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in the College of Education at the University of Kentucky

By

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ABSTRACT OF THESIS

MECHANICAL DEVIATIONS AND VERBAL-CUE ALTERED GAIT IN THE FEMOROACETABULAR IMPINGEMENT SYNDROME POPULATION

Femoroacetabular impingement syndrome (FAIS) is an abnormal physical hip morphology that causes functional changes and pain during gait. Mechanical gait differences in this population require further biomechanical investigation to elucidate characteristics unique to this group. Fixed speed gait trials were performed on force plates and analyzed in addition to isokinetic strength testing to find a multitude of biomechanical variables including joint moment, joint power, joint work, and peak joint angle. This work has discovered evidence of muscular deficits at the hip, specifically hip extension, as well as knee joint power contributions to gait when compared to controls. These findings suggest the FAIS population may be compensating at the knee for hip musculature deficits or disfunction. Additionally, verbal cueing may be implemented to correct altered gait patterns and assist in pain reduction during gait. When given a targeted verbal cue to promote trunk extension, the FAIS alters their ambulation entirely kinematically and maintains the kinetic profile of their standard gait. The control group, when given the cue, altered their knee joint kinematics which suggests that further research on gait retraining with cues must be designed to ensure kinetic changes occur in the intervention group when desired.

KEYWORDS: biomechanics, gait, FAIS, hip, pain, joint

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08/04/2021
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MECHANICAL DEVIATIONS AND VERBAL-CUE ALTERED GAIT IN THE FEMOROACETABULAR IMPINGEMENT SYNDROME POPULATION

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DEDICATIONS

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CHAPTER 1. INTRODUCTION

Femoroacetabular impingement syndrome (FAIS) consists of abnormal hip joint morphology and is associated with severe hip joint pain and dysfunction (Griffin et al., 2016). FAIS can be categorized into three forms: pincer, cam, and mixed. Pincer-type FAIS is denoted by over-coverage of the acetabulum on the femoral head, cam-type FAIS is classified as an osseous growth at the femoral head-neck junction while mixed type is a combination of the pincer- and cam-types. While FAIS is a unique condition that does not primarily affect a certain demographic, a main clinical concern of FAIS is that the early signs of hip joint cartilage degeneration can be observed in relatively young and active populations (Frank et al., 2015). In particular, osteochondral damage is observed within the anterior acetabulum and is thought to occur through chronic altered movement patterns at the hip in the FAIS population (Lavigne et al., 2004). Individuals requiring hip arthroscopy to surgically treat FAIS has increased 85% between 2011 and 2018, which indicates a need to identify specific biomechanical targets to effectively treat these individuals and to assist their return to normal daily function (Zusmanovich et al, 2021). FAIS is also a condition that can develop into further bone and cartilage degenerative conditions such as hip osteoarthritis (Beck et al, 2005) which suggests that early detection and prevention methods are needed. Additionally, individuals with FAIS present with lower hip extensor strength compared to control participants which highlights another avenue of possible treatment options for gait patterns (Frasson et al., 2020).

The physiological causes of FAIS symptoms have been identified, but the implications of these morphological changes with respect to short- and long-term gait patterns are still not fully understood. The primary aims of this research are to investigate the patterns of gait demonstrated by the FAIS population, kinetically and kinematically. It is also currently unclear how or to what degree neuromuscular activity of the lower limbs contribute to the gait abnormalities observed in the FAIS population. Therefore, the first aim is to compare kinematic and kinetic differences of the trunk, pelvis, and lower limbs in asymptomatic, healthy controls and patients with FAIS. Additionally, isokinetic strength of the hip and knee flexors and extensors will be evaluated between both study groups in order to provide further insight on muscular contributions to gait-related abnormalities in the FAIS population. We hypothesized that FAIS patients will exhibit weaker hip extensor musculature and will ambulate with greater hip joint loading in the surgical limb compared to asymptomatic, healthy controls.

The secondary aim of this research is to investigate the kinetic and kinematic effects of a verbal cue that is designed to alter hip joint loading to a more favorable pattern during the gait cycle. Verbal cueing is a clinical tool used to retrain or assist patients with changing their habitual movement patterns and has been shown to alter the loading of the hip in all three planes, which may be a clinical goal to reduce anterior hip pain (Lewis & Garibay, 2015). Specifically, the cue implemented in these gait trials instructed the participant to “walk upright” through their gait cycle in an effort to promote trunk extension. The implemented cue was developed with the theory that an increase in trunk extension would alter the body’s center of gravity to decrease the torque produced across the hip joints. It was hypothesized that this verbal cue would induce an increase in peak trunk extension and reduce hip joint loading.

CHAPTER 2. Mechanical Gait Differences in the FAIS Population

2.1 Introduction

Femoroacetabular impingement syndrome (FAIS) consists of abnormal hip joint morphology and is associated with severe hip joint pain and dysfunction (Griffin et al., 2016). FAIS can be categorized into three forms: pincer-, cam-, and mixed-type. Pincer-type FAIS is denoted by an over-coverage of the femoral head by the acetabulum, cam-type FAIS is classified as an osseous growth at the femoral head-neck junction while mixed type is a combination of the pincer- and cam-types. A main clinical concern of FAIS is the early signs of hip joint cartilage degeneration observed in the relatively young and active populations that seek treatment for FAIS (Frank et al., 2015). In particular, osteochondral damage is observed within the anterior acetabulum and is thought to occur through chronic altered movement patterns at the hip in the FAIS population (Lavigne et al., 2004). Individuals requiring hip arthroscopy to surgically treat FAIS has increased 85% between 2011 and 2018, which indicates a need to identify specific biomechanical targets that can be optimized and used to effectively and conservatively treat these individuals in order to assist their return to normal daily function (Zusmanovich et al, 2021). If not treated properly, FAIS can result in hip osteoarthritis (Beck et al, 2005), which suggests that early detection and prevention of hip joint degeneration in the FAIS population is needed.

Previous research has investigated both kinematic and kinetic deviations in FAIS patients from healthy, asymptomatic controls during gait, but many studies include a small number of variables of interest which may not provide a thorough understanding of the various gait deviations exhibited by patients with FAIS. Kinetic differences in gait, such as increased hip flexion moment impulse in FAIS compared to asymptomatic controls, is significantly correlated with increased hip pain, hip dysfunction, and acetabular cartilage abnormalities in FAIS (Samaan et al., 2017). In addition, knee joint biomechanics have been identified as an important marker of the initial stages of hip osteoarthritis (Ross-deVries et al., 2018) and could be a potential biomechanical target for future FAIS-related gait interventions. Joint power is a kinetic parameter that has been identified as a metric that can be used to identify altered mechanical load in the lower extremity during gait (Fickey et al., 2018). Redistribution of joint power across the lower extremity could be a clinical target for optimizing joint load and potentially decreasing hip power (Browne and Franz, 2019) and may potentially reduce hip-related symptoms in FAIS. The derivative of joint power, joint work, has been used to identify changes in hip musculature contributions during walking in the hip osteoarthritis population (Meyer et al., 2018) and in athletes with and without hip-related pain (King et al., 2021).

More specifically, no difference was observed in lower limb joint work in individuals with hip related pain (King et al., 2021), however these variables have seldom been analyzed in the FAIS population. These gait-related abnormalities may be related to hip muscle weakness observed in the FAIS population (Kierkegaard et al., 2017). Patients with FAIS exhibit hip extensor weakness compared to asymptomatic controls and remain weaker up to one-year after hip arthroscopy (Kierkegaard et al., 2017, Kierkegaard et al., 2019). Hip extensor weakness in the FAIS population may help to explain proximal segment kinematic alterations that occur during gait in the FAIS population. Patients with FAIS ambulate with decreased peak hip extension angles (Hunt et al., 2013) and ascend stairs with increased trunk flexion compared to asymptomatic controls (Hammond et al., 2017), which may be due to reduced force producing capabilities within the hip extensor musculature to support the trunk segment (Hammond et al., 2017). Increased trunk flexion during gait would lead to an increased hip joint sagittal plane loading, via an increased moment arm at the hip, and may help to explain the increased hip flexor moment impulse observed in the FAIS population (Samaan et al., 2017). Although the current FAIS population gait literature has highly assessed hip joint mechanics, an understanding of the alterations that occur in knee and ankle gait mechanics during walking in the FAIS is highly relevant and highly warranted. In addition, the role of the distal joint musculature in FAIS could provide insight into potential biomechanical and physiological targets for FAIS-related gait interventions.

2.2 Methods

Participants

Six pre-surgical patients with FAIS (6 female; mean age 31.5±10.8 years; mean body mass index [BMI] 28.0±5.85kg·m^{-2}) and 12 healthy controls from the local community (12 female; mean age 24.7±4.22 years; mean BMI 23.6±3.9 kg·m^{-2}) were sex and BMI matched for this study. FAIS patients were referred to this study by the University of Kentucky Hip Preservation Clinic. Patients with FAIS presented with both radiological (Ganz et al., 2003) and clinical signs of hip joint impingement (positive flexion, adduction, and internal rotation [FADIR]) during a physical examination (Philippon et al., 2007) by an orthopaedic surgeon. No restrictions were placed on FAIS-morphology in the healthy controls, yet all controls exhibited negative clinical signs of hip impingement (FADIR test) bilaterally. FAIS patients and healthy controls were excluded from this study if they presented with radiographic signs of hip osteoarthritis

(Kellgren Lawrence score > 1) bilaterally via anterior-posterior pelvic x-ray (Kellgren and Lawrence, 1957), lower extremity injury in the last six weeks, previous lower extremity joint replacement or surgery, movement related neurological conditions or a BMI greater than 35 $kg \cdot m^{-2}$. The primary test limb for all data collection was the surgical limb for the FAIS patients and the dominant limb for the healthy controls which was assessed by asking participants which foot they would use to a kick soccer ball the furthest (Borotikar et al., 2008). This study was approved by the University of Kentucky Office of Research Integrity (IRB #46678). Written informed consent was provided by all participants prior to any testing.

Gait Analysis

Three-dimensional marker position data were collected at 250Hz using a 15-camera motion capture system (Motion Analysis, Santa Rosa, CA). Ground-reaction force data were collected simultaneously at 1000Hz using two in-ground force plates (Bertec, Columbus, OH). A modified Cleveland Clinic marker set, consisting of 42 retroreflective markers, was used to collect 3-dimensional spatial marker position data. Four markers were placed on the torso at the sternal notch, C7, right and left acromion for the trunk segment. The CODA pelvis was used to define the pelvic system and included markers at the right and left anterior superior iliac spines, iliac crests, and posterior superior iliac spines. Markers were placed at the medial and lateral femoral epicondyles as well as the medial and lateral malleoli. Additional foot markers were placed at the calcaneus, first, second and fifth metatarsal heads. In addition, rigid body clusters consisting of four markers each were applied to each participant's thighs and shanks for segmental tracking. A one-second static calibration trial was obtained prior to the gait trials. Calibration markers at the femoral epicondyles, malleoli and first metatarsal heads were removed after the static calibration trial.

Gait data were collected at 1.35±0.7 m/s, which is the average level-ground walking speed for both males and females (Perry et al., 1992). Each participant's speed was controlled to be within 5% deviation (0.7 m/s) via two sets of electronic timing gates (Brower Timing Systems, Draper, UT). Participants completed three gait trials where they were instructed to walk in their natural manner while looking straight ahead. In order to reduce potential effects of footwear, all study participants wore standardized laboratory sneakers (New Balance MR662WSB). A gait trial was considered successful if the participant maintained the prescribed walking speed and if the entire foot of the test limb made a clean strike on at least one of the two force plates. All raw marker position and ground-reaction force data were filtered at 6 Hz and 50 Hz, respectively, using a fourth-order, low-pass Butterworth filter (Samaan et al., 2015). An eight-segment kinematic model consisting of the trunk, pelvis, bilateral thighs, shanks and feet was constructed from the static calibration trial using the Visual3D software (C-Motion, v6.01.33, Germantown, MD). All joint coordinate systems used the X-Y'-Z'' Cardan sequence, which represented the medio-lateral, anterior-posterior, and superior-inferior axes, respectively. Kinematic data were normalized to each participant's static calibration trial. Internal joint moments were normalized by body mass ($Nm \cdot kg^{-1}$). In addition, joint power ($W \cdot kg^{-1} \cdot m^{-1}$) of the hip, knee and ankle joints were computed and normalized by body mass. Trunk flexion and anterior pelvic tilt were considered positive. In addition, hip flexion, knee extension and ankle dorsiflexion angles, internal joint moments and powers were considered positive. The vertical ground-reaction force threshold indicating initial contact was 20 Newtons. The stance phase, consisting of initial contact to toe off, was analyzed for the test limb. All dependent variables were determined as the mean across three successful gait trials for each study participant.

Peak sagittal plane joint angles, internal moments and powers were computed for the trunk, pelvis, hip, knee, and ankle during the stance phase. Peak knee moments during the initial 50% of stance (loading response) were assessed. Differences in the center of gravity (COG) positions in all three planes were also calculated. Range of motion (ROM) of all segments were calculated as the maximum minus minimum sagittal joint angle values attained during stance phase except for the knee joint, where ROM was calculated from initial contact to peak knee flexion during loading response. Joint moment impulses ($N \cdot s \cdot kg^{-1}$) and work ($J \cdot kg^{-1}$) were calculated in a custom-written MATLAB script as the time-based integrals of the internal joint moments and joint powers, respectively.

Impulse, work, and power were separated into their positive and negative components at the hip, knee and ankle joints. The timing of peak joint power production, both negative and positive, were also calculated. The peak hip, knee and ankle joint positive and negative power values were summed to attain the total positive and negative powers, respectively, during each trial and were used to determine each joint's percent contribution to the net positive and negative joint powers. All moment, power and work values reported in this study are described in the internal reference frame.

Strength Testing

Lower extremity isokinetic strength data were collected using a Biodex dynamometer (Biodex Inc., Shirley, NY) at $60^{\circ} \cdot s^{-1}$. Strength data were collected on the surgical limb of FAIS patients and on the dominant limb of the healthy controls. Subjects were all verbally encouraged to maximally contract during each repetition of the strength testing. Participants performed 5 fixed range of motion maximal repetitions for the hip and knee flexors and extensors. The knee flexion/extension strength testing was performed while seated with the hip flexed at 90˚ through a 90° range of motion at the knee joint (full extension to 90° of flexion). The hip flexion/extension task was performed in a supine position with the knee flexed at 90˚ through a 30°-degree range of motion (30° of hip flexion to neutral). A minimum of 30-seconds of rest was provided between each repetition, with a minimum of two minutes of rest given to each participant between each of the two different testing positions. Peak torque values were gravity corrected and normalized by body mass ($Nm \cdot kg^{-1}$).

Strength ratios were analyzed as they can provide relevant and valuable clinical information (Calmels et al., 1997). The hip and knee extension to flexion ratio was calculated by dividing the normalized peak torque of the extensors of the given joint by the normalized peak torque of the flexors of the given joint. A hip extensor to knee flexor ratio was also calculated in the same manner to assess the interrelationship of the posterior chain musculature.

Statistical Analysis

Between group differences in age and BMI as well as all kinetic, kinematic, and strength-related parameters were compared between FAIS and control subjects using independent *t* tests. All statistical analyses were performed using the Microsoft Excel with an alpha level set at 0.05. Cohen's *d* was calculated for effect size using relevant means and standard deviations. Cohen's d values of 0 – 0.2, 0.21 – 0.5 and > 0.5 were considered small, medium and large effect sizes, respectively (Cohen, 1988).

2.3 Results

No significant differences were observed in peak gait kinematics (Table 2.2), peak joint moments (Table 2.3), joint impulses (Table 2.4), joint impulse durations (Table 2.5), peak joint power (Table 2.7) or peak joint work (Table 2.8) between the FAIS and the healthy control groups.

Table 2.1: Participant demographics.

Demographics	n	Age	BMI
Control (n=12 female)	12	26.25±8.02	23.77±3.59
FAI (n=6 female)	6	31.50±10.78	28.03±5.85

Table 2.2: All sagittal joint peak joint kinematics.

Sagittal Kinematics (degrees)	Control	FAIS	P Value	Effect Size
Peak Trunk Flexion	3.09±2.49	3.82±4.29	0.714	0.21
Peak Trunk Extension	1.64±2.69	1.35±6.12	0.918	0.06
Peak Pelvic Flexion	6.82±5.83	10.49±7.52	0.333	0.55
Peak Pelvic Extension	10.97±5.50	15.37±8.17	0.275	0.63
Peak Hip Flexion	27.87±2.66	29.25±3.55	0.434	0.44
Peak Hip Extension	10.43±4.09	7.51±2.84	0.114	0.83
Peak Knee Extension	3.99±5.87	5.92±4.94	0.544	0.36
Peak Knee Flexion	16.36±9.38	17.13±4.81	0.839	0.10
Peak Dorsiflexion	11.77±1.83	11.62±3.42	0.924	0.05
Peak Plantarflexion	14.47±6.02	18.14±6.33	0.280	0.60

Figure 2.1: Kinematic comparisons, sagittal plane.

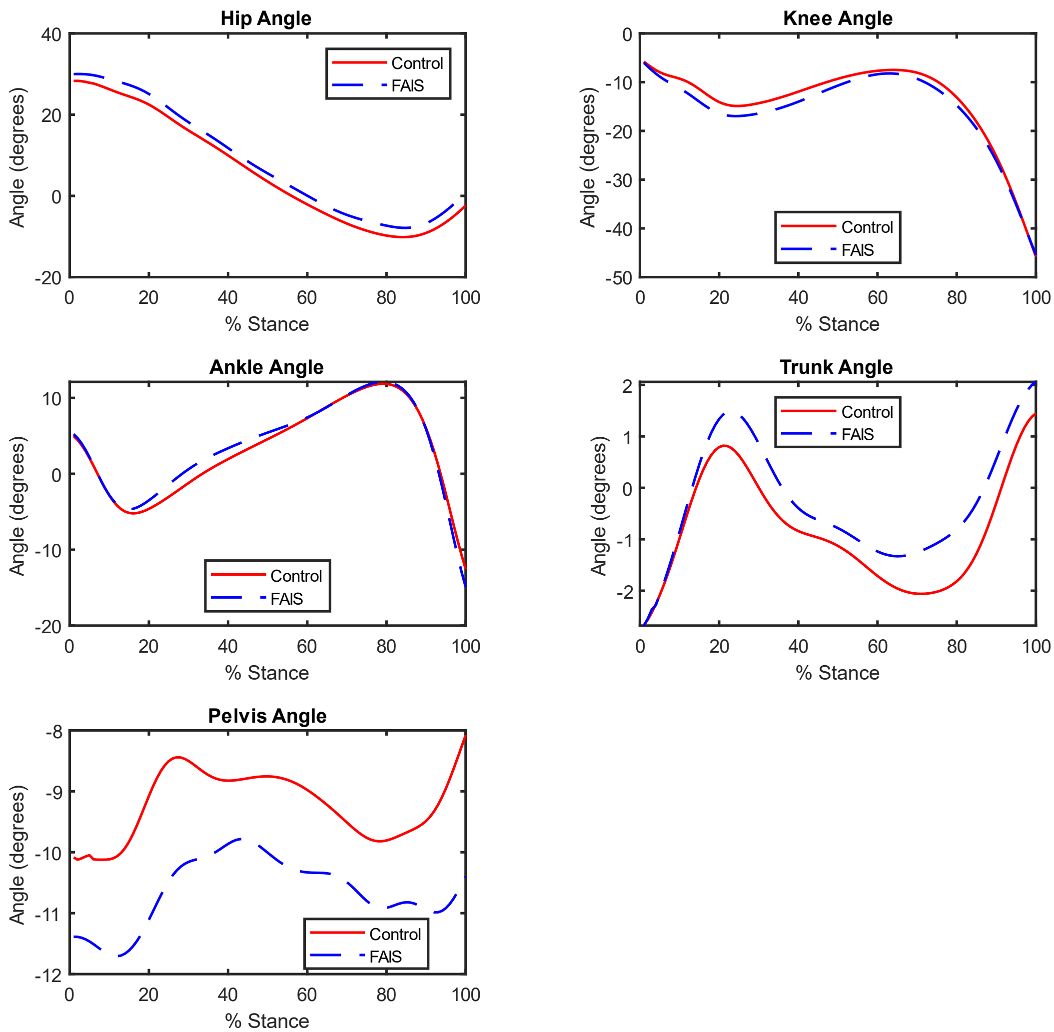


Table 2.3: Peak sagittal joint moments.

Peak Joint Moments ($Nmkg^{-1}$)	Control	FAIS	P Value	Effect Size
Hip Flexion	0.757±0.295	0.793±0.295	0.814	0.12
Hip Extension	0.698±0.417	0.550±0.227	0.375	0.44
Knee Flexion	0.373±0.248	0.537±0.240	0.239	0.67
Knee Extension	0.342±0.184	0.285±0.094	0.425	0.39
Dorsiflexion	1.120±0.656	1.248±0.570	0.699	0.21
Plantarflexion	0.216±0.123	0.201±0.085	0.781	0.14

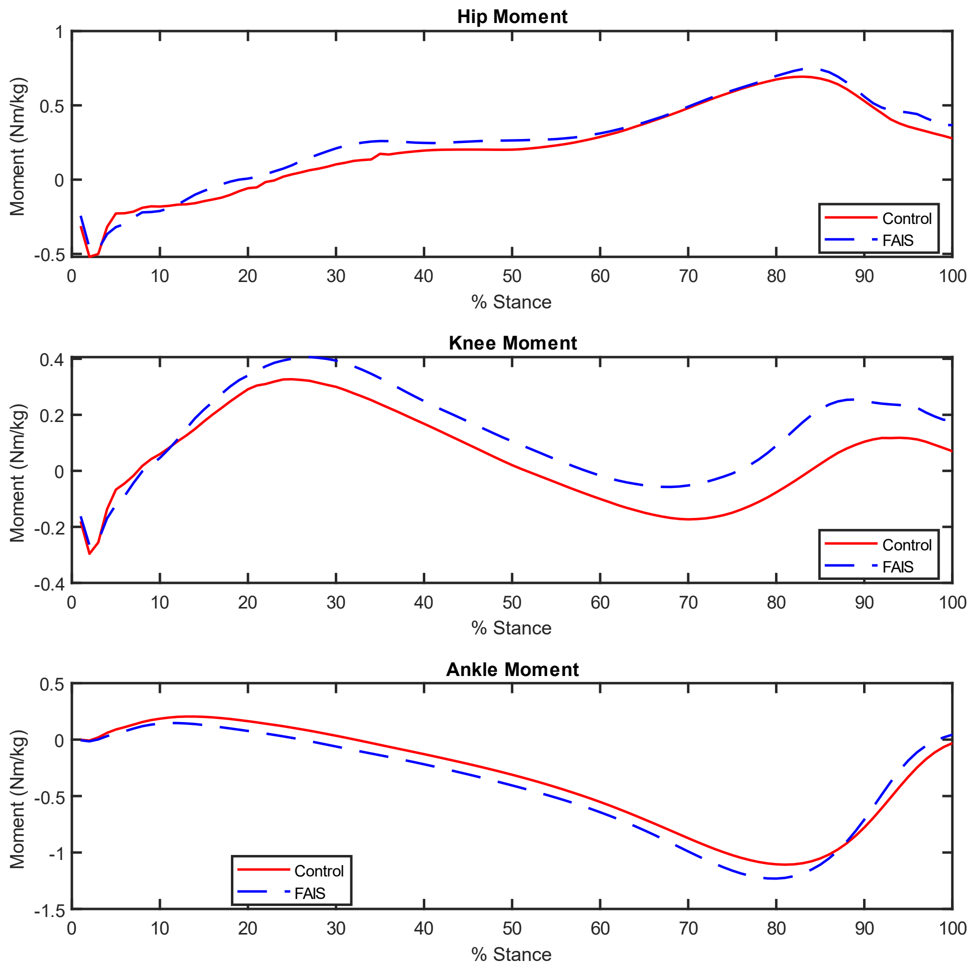
Table 2.4: Sagittal joint impulse values.

Joint Impulse (Nm*s/kg)	Control	FAIS	P Value	Effect Size
Hip Extension	0.189±0.091	0.234±0.101	0.388	0.47
Hip Flexion	0.035±0.015	0.051±0.062	0.425	0.35
Knee Extension	0.036±0.010	0.023±0.030	0.422	0.58
Knee Flexion	0.117±0.026	0.167±0.043	0.064	1.41
Plantarflexion	0.039±0.008	0.033±0.006	0.129	0.85
Dorsiflexion	0.299±0.049	0.345±0.043	0.085	1.00

Table 2.5: Sagittal joint impulse duration.

Impulse Duration (sec)	Control	FAIS	P Value	Effect Size
Hip Extension	0.488±0.021	0.478±0.015	0.920	0.55
Hip Flexion	0.156±0.020	0.160±0.039	0.958	0.13
Knee Extension	0.337±0.038	0.459±0.032	0.370	3.47
Knee Flexion	0.306±0.038	0.179±0.032	0.275	3.62
Plantarflexion	0.281±0.016	0.170±0.029	0.169	4.74
Dorsiflexion	0.363±0.022	0.467±0.031	0.293	3.87

Figure 2.2: Lower limb joint moments.



The peak positive and negative powers throughout the lower limbs were not significantly different (Figure 2.3) yet the FAIS patients ambulated with a significantly lower positive knee power contribution (p=0.03) and a significantly higher negative knee power contribution (p=0.02) compared to controls. There were no between group differences in hip, knee or ankle joint work (Table 2.8).

Table 2.6: Sagittal joint power contributions to peak lower limb power.

Joint Power Contribution (%)	Control	FAIS	P Value
Positive Hip	24.4	33.2	0.938
Positive Knee	18.0	9.6	**0.032**
Positive Ankle	57.6	57.1	0.542
Total Positive Power	100	100	
Negative Hip	51.1	29.7	0.078
Negative Knee	21.9	40.0	**0.024**
Negative Ankle	27.0	30.3	0.780
Total Negative Power	100	100	

Figure 2.3: Lower limb power curves.

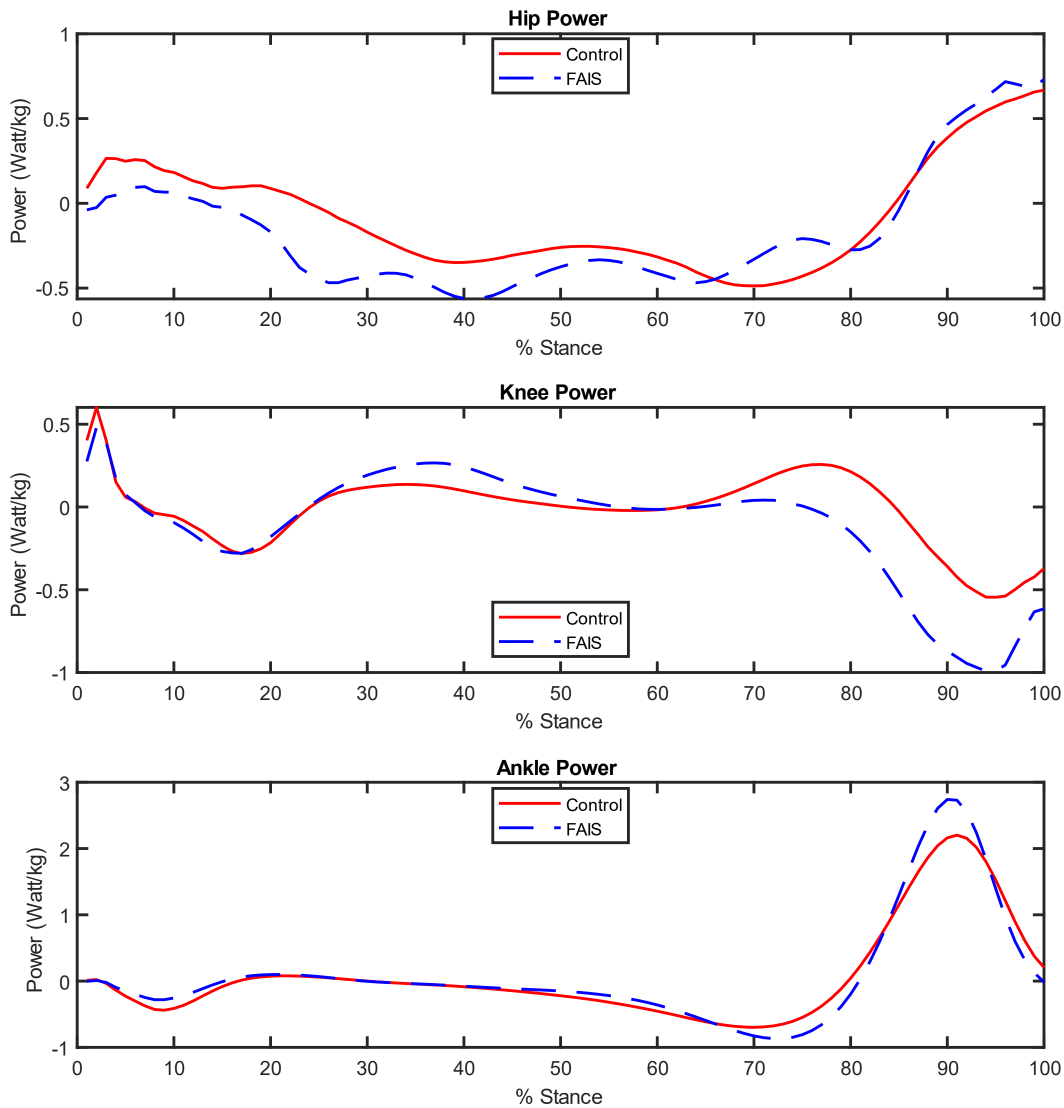


Table 2.7: Internal peak joint powers.

Peak Joint Power (Watt·kg^{-1})	Control	FAIS	P Value	Effect Size
Hip Extension	0.698±0.222	0.732±0.223	0.433	0.15
Hip Flexion	0.487±0.301	0.564±0.436	0.412	0.21
Knee Extension	0.545±0.388	0.991±0.498	0.077	1.00
Knee Flexion	0.602±0.625	0.482±0.319	0.353	0.24
Dorsiflexion	0.697±0.537	0.867±0.556	0.950	0.31
Plantarflexion	2.202±1.594	2.740±1.916	0.391	0.31

Table 2.8: Internal joint work.

Joint Work (Joule·kg^{-1})	Control	FAIS	P Value	Effect Size
Hip Extension	0.043±0.013	0.059±0.054	0.525	0.41
Hip Flexion	0.069±0.041	0.078±0.064	0.755	0.17
Knee Extension	0.068±0.046	0.141±0.074	0.062	1.18
Knee Flexion	0.049±0.034	0.056±0.041	0.745	0.19
Dorsiflexion	0.140±0.094	0.151±0.110	0.848	0.11
Plantarflexion	0.178±0.134	0.199±0.114	0.742	0.17

Patients with FAIS exhibited significantly weaker hip extensor strength (Table 2.9) compared to healthy controls (p=0.04). The knee extensor to knee flexor strength ratio was significantly lower in the FAIS group compared to healthy controls (p=0.005). Patients with FAIS also exhibited a lower hip extensor to knee flexor strength ratio compared to controls (p=0.006).

Table 2.9: Peak isokinetic strength values and strength ratio.

Peak Isokinetic Torque (Nm/kg)	Control	FAIS	P Value	Effect Size
Hip Flexion	1.108±0.225	0.756±0.387	0.161	1.11
Hip Extension	1.229±0.459	0.731±0.353	**0.036**	1.22
Knee Flexion	0.727±0.272	1.098±0.431	0.125	1.03
Knee Extension	1.668±0.527	1.486±0.233	0.390	0.45
Strength Ratios (%)				
Hip Ext/Hip Flex	110.91±27.1	96.71±36.0	0.424	0.45
Knee Ext/Knee Flex	245.62±62.2	151.72±42.4	**0.005**	1.76
Hip Ext/Knee Flex	198.16±111	65.76±26.5	**0.006**	1.64

2.4 Discussion

This study evaluated the sagittal plane kinematic and kinetic changes at the trunk, pelvis and lower extremity joints during walking as well as hip and knee strength in patients with FAIS and healthy controls. Patients with FAIS exhibited weaker hip extensors, a lower knee extensor to knee flexor strength ratio, and a lower hip extensor to knee flexor strength ratio than asymptomatic controls. Kinetically, FAIS patients ambulated with a lower positive knee power contribution and higher negative knee power contribution to the knee joint positive and negative powers, respectively.

The results of the current study did not demonstrate any differences in sagittal plane trunk, pelvis or lower extremity joint kinematic- or moment-based parameters between the FAIS and control groups. Previous work has shown the differences in gait parameters within the FAIS population are greater hip flexion moment impulse, hip flexion moment, decreased sagittal ROM, and decreased peak knee flexion moment (Hammond et al., 2017, Samaan et al., 2017). The reason for differences in our results compared to previous studies may be due to the fixed walking speed used in this study compared to a self-selected walking speed. In addition, the FAIS patients enrolled in this study may be at an earlier stage of disease compared to the FAIS population examined in these previous studies. This may suggest that the alterations in gait kinematics and moments may occur at a later stage of disease and were not exhibited by our FAIS cohort.

Despite the lack of differences in peak joint power, the FAIS patients in our study exhibited smaller and larger contribution of positive and negative knee powers, respectively, to the overall positive and negative knee joint power produced during walking. Previous research regarding joint work and joint power have found no significant differences in walking trials between controls and individuals with hip related pain (King et al., 2021). The power contribution differences at the knee between control and FAIS groups determined by our study suggest alterations in knee flexor and extensor activity during walking in the FAIS group. Although the joint power does not allow for assumptions of exact muscular activity during dynamic motion it does provide an approximation of concentric and eccentric movement dominance during the stance phase of gait. The internal positive knee power contribution in the FAIS group was half of the value exhibited by healthy controls which indicates lower eccentric knee extensor activity during loading response in FAIS. This finding suggests that FAIS patients walk with less eccentric muscular activity of the quadriceps. The internal negative knee power contribution in the FAIS group was higher than controls, specifying greater concentric knee flexor activity during the first half of the stance phase. Through joint power analysis, it is possible to determine which portions of the gait cycle demonstrate prominent differences and therefore may be optimal clinical targets for rehabilitation specialists or biomechanical research regarding the FAIS population.

Similar to previous work, the FAIS patients in our study exhibited lower hip extensor strength compared to asymptomatic controls (Frasson et al., 2020, Kierkegaard et al. 2017). More specifically, the FAIS patients in our study exhibited a 41% reduction in peak hip extensor strength compared to controls. This lower hip extensor strength may lead to increased reliance on the hamstrings as a secondary hip extensor. Although not statistically significant, the FAIS patients exhibited approximately a 34% higher peak knee flexor torque compared to the control group. The weaker hip extensor and relatively strong knee flexor musculature would lead to the significantly lower hip extensor to knee extensor strength ratio observed in the FAIS group. This lower hip extensor to knee flexor strength ratio may help to explain the higher contribution of the peak negative knee joint power to the overall eccentric activity observed across the lower extremity in the FAIS group. If the posterior chain of the FAIS participants is weaker, composed of the hip extensors and knee flexors, then this would lead to an increase in the negative knee joint power contribution needed to counteract the repetitive concentric quadricep demands during walking in FAIS. The main finding in regard to strength between control and FAIS participants is that the lower limb sagittal agonist/antagonist muscle pairing strength ratios are significantly different. As a result, FAIS patients are demonstrating increased joint power contribution of the knee.

Therefore, assessment of the ratio of hip extensor to knee flexor strength would serve as an ideal measure of lower extremity limb strength in the FAIS population. The severely lower ratio of hip extension to knee flexion strength in FAIS, may be due to a lack of hip extension strength as opposed to knee flexion strength deficits. It can be asserted from these findings that FAIS patients engage in more hamstring engagement at the knee either as a compensation for hip extensor weakness. The long-term effects of this gait pattern on the knee and hip are not understood and cannot be extrapolated from this study. However, evidence from this study suggests a higher level of knee flexor activity and may need to be investigated for long term outcomes in FAIS. If a strength training protocol were enacted to adjust the knee flexor and extensor strength ratio, concentric training would be recommended as it has been shown to be effective in improving functional scoring outcomes in the knee osteoarthritis population (Vincent & Vincent, 2020).

This study is not without its limitations and the results should be interpreted with these limitations in mind. The small sample size and strictly female cohorts limit the study power are limitations to this current study. A second limitation is the use of a fixed walking speed as opposed to a self-selected walking speed, which may result in different gait mechanics compared to the fixed walking speed. In addition, the use of walking may not be mechanically demanding enough to demonstrate differences in hip joint loading in the FAIS population and a more demanding task (stair ascent, squat, etc.) should be investigated in the future.

2.5 Conclusion

The findings of this cross-sectional study show some similarities to the body of literature regarding the FAIS population and gait, but do not closely replicate results from similar studies. While some differences were exhibited in knee joint power contributions between the two groups, no kinematic changes were found. The results of this study do indicate a need for further investigation into the lower extremity strength of FAIS patients with a more clinical perspective to evaluate the long-term consequences of strength deficits on joint health and function in the FAIS population. This study does provide clinicians such as physical therapists with a target for strength training and possible gait retraining to optimize the strength ratio discrepancy seen in the posterior chain functionality of the FAIS participants. Although it is unclear what the root cause of this muscular strength difference is, there is evidence that indicates a need for further research into this neuromuscular alteration.

CHAPTER 3. Implementing Verbal Gait Cues to Reduce Hip Joint Loading

3.1 Introduction

Surgical intervention to treat both structural- and clinical-symptoms in the femoroacetabular impingement syndrome (FAIS) population has risen by 85% over the last decade (Zusmanovich et al, 2021). FAIS is specifically defined as a hip joint morphology syndrome that can be classified into three types: pincer-, cam-, and mixed-type. Pincer-type FAIS is characterized as osseous over-coverage of the femoral head by the acetabulum, cam-type FAIS is typified by femoral head-neck junction osseous growth and mixed-type FAIS is an amalgamation of the cam and pincer-type morphologies (Griffin et al., 2016). These bone growth abnormalities cause physiological impingement of the hip joint, resulting primarily in anterior acetabular pain and gait abnormalities that may be deleterious to cartilage health over time (Lavigne et al., 2004). Of note, previous research findings suggest that hip pain in the FAIS population is correlated with increased trunk flexion, external hip flexion moments and decreased peak external knee flexion moments (Hammond et al., 2017).

Surgical intervention is a pathway to symptom treatment for FAIS, however, there is evidence to suggest that surgical intervention in the cam-type FAIS population does not change lower extremity mechanics when comparing pre and postoperative gait (Catelli et al., 2019). This finding suggests a need for alternative or additional methods of retraining FAIS-related gait patterns to have more favorable long-term outcomes related to cartilage health and hip-related symptoms. It may be possible to alleviate problematic symptoms without needing surgical intervention to correct the abnormal hip joint morphology in the FAIS population. Providing verbal cue adjustments to patients before gait trials is seldom researched but verbal cues have been shown to be effective in altering lower body joint loading and changing muscular activity during gait (Lewis & Garibay, 2015). Verbal cuing has been shown to reduce hip joint contact forces in all three planes of motion, which may lead to a decrease in anterior hip pain (Lewis & Garibay, 2015). Verbal cueing is a commonly used method of gait retraining in physical therapy clinics and has been shown to increase volitional lower limb muscular activity as well as promote favorable gait kinematics in the stroke population (Moore et al., 2019, Ploughman et al., 2018). While lower extremity mechanics have been investigated in the FAIS population (Catelli et al., 2017, Liao et al., 2019, Samaan et al., 2017), to our knowledge, adjustments to the natural gait patterns via verbal-based cue has not been implemented in the FAIS population. Auditory and physical cueing are commonplace in rehabilitation clinics for individuals with neurological conditions such as Parkinson's or post stroke patients. Specifically, targeted verbal cues have been shown to be effective in changing spatiotemporal gait parameters in the post stroke population (Parker et al., 2021). Verbal-based cues to alter habitual gait patterns within the FAIS population have not been evaluated as a method to optimize lower extremity joint mechanics and to reduce hip pain and cartilage degeneration in the FAIS population.

Therefore, the purpose of this study was to conduct a cross-sectional, evaluation of the kinematic and kinetic differences of the trunk, pelvis, and lower limbs in asymptomatic, healthy controls and FAIS patients during gait with and without a verbal cue to adjust trunk position. This cue was designed specifically to promote trunk extension in effort to reduce pain correlated with the increased trunk flexion and increased external hip flexion moment impulse observed in the FAIS population (Hammond et al., 2017, Samaan et al., 2017).

3.2 Methods

Participants

Six pre-surgical patients with symptomatic FAIS (6 female; mean age 31.5±10.78 years; mean body mass index [BMI] 28.0±5.85kg·m^{-2}) and 12 healthy controls (12 female; mean age 24.7±4.22 years; mean BMI 23.6±3.9 kg·m^{-2}) were sex and BMI matched for this study. FAIS patients were referred to this study by the University of Kentucky Hip Preservation Clinic while healthy controls were recruited from the local community. Patients with FAIS presented with both radiological (Ganz et al., 2003) and clinical signs of hip joint impingement (positive flexion, adduction, and internal rotation [FADIR]) (Philippon et al., 2007) as determined by an orthopaedic surgeon. FAIS patients and healthy controls were excluded from this study if they presented with radiographic signs of hip osteoarthritis (Kellgren Lawrence score > 1) bilaterally via anterior-posterior pelvic x-ray (Kellgren and Lawrence, 1957), lower extremity injury in the last six weeks, previous lower extremity joint replacement or surgery, movement related neurological conditions or a BMI greater than 35 kg·m^{-2}. No restrictions were placed on FAIS-morphology in the healthy controls yet all controls exhibited negative clinical signs of hip impingement (FADIR test). The primary test limb for all data collection was the surgical limb for FAIS patients and the dominant limb for the healthy controls which was assessed by asking participants which foot they would kick a soccer ball with (Borotikar et al., 2008). This study was approved by the University of Kentucky

Office of Research Integrity (IRB #46678). Written informed consent was provided by all participants prior to any testing.

Gait Analysis

Three-dimensional marker position data were collected at 250Hz using a 15-camera Cortex system (Motion Analysis, Santa Rosa, CA). Ground-reaction force data were collected simultaneously at 1000Hz using two in-ground force plates (Bertec, Columbus, OH). A modified Cleveland Clinic marker set, consisting of 42 retroreflective markers, was used to collect 3-dimensional spatial marker position data. Four markers were placed on the torso at the sternal notch, C7, right and left acromion for the trunk segment. The CODA pelvis was used to define the pelvic system and included markers at the right and left anterior superior iliac spines, iliac crests, and posterior superior iliac spines. Markers were placed at the medial and lateral femoral epicondyles as well as the medial and lateral malleoli. Additional foot markers on standardized shoes were placed at the calcaneus, first, second and fifth metatarsal heads. In addition, rigid body clusters consisting of four markers each were applied to each participant's thighs and shanks for segmental tracking. A one-second static calibration trial was obtained prior to the gait trials. Calibration markers at the femoral epicondyles, malleoli and first metatarsal heads were removed after the static calibration trial.

Gait data were collected at 1.35±0.7 m/s, which is the average level-ground walking speed for both males and females (Perry et al., 1992). Each participant's speed was controlled to be within 5% deviation (0.7 m/s) via two sets of electronic timing gates (Brower Timing Systems, Draper, UT). Participants completed three unaltered gait trials followed by three cue-based gait trials with the instruction to "walk upright" prior to each trial. The verbal cue was given to the individual before each of their cue-based gait trials and it was not disclosed to the individual what the hypothesized purpose of the cue was. In order to reduce potential effects of footwear, all study participants wore standardized laboratory sneakers (New Balance MR662WSB). A gait trial was considered successful if the participant maintained the prescribed walking speed and if the entire foot of the test limb made a clean strike on one of the two force plates. All raw marker position and ground-reaction force data were filtered using a 6 Hz and 50 Hz, respectively, fourth-order low-pass Butterworth filter (Samaan et al., 2015). An eight-segment kinematic model consisting of the trunk, pelvis, bilateral thighs, shanks, and feet was constructed from the static calibration trial using the Visual3D software (C-Motion, v6.01.33). The vertical ground-reaction force threshold indicating initial contact was 20 Newtons. All joint coordinate systems used the X-Y'-Z'' Cardan sequence which represented the medio-lateral, anterior-posterior, and superior-inferior axes, respectively. Kinematic data were normalized to each participant's static calibration trial. Internal joint moments were normalized by body mass ($Nm \cdot kg^{-1}$). In addition, joint power of the hip, knee and ankle joints were computed and normalized by body mass ($W \cdot kg^{-1}$). Hip flexion, knee extension and ankle dorsiflexion angles, internal moments and powers were considered positive. Data were analyzed from heel strike to toe off (stance phase) across three trials for standard (no verbal cue) gait and three trials for the verbal cue-based gait.

Peak sagittal plane joint angles were computed for the trunk, pelvis, hip, knee, and ankle. Internal joint moment, joint power, and joint work were also computed for the hip, knee, and ankle joints. Peak knee flexion angle and moments were obtained during loading response. Changes in the center of gravity (COG) positions in all three planes were also calculated. Joint moment impulses ($Nm \cdot s \cdot kg^{-1}$) and work ($J \cdot kg^{-1} \cdot m^{-1}$) were calculated in a custom-written MATLAB script using trapezoidal numerical integration from the internal joint moments and joint powers, respectively. Impulse, work, and power were separated into their positive and negative components at each lower extremity joint (hip, knee, ankle). The timing of peak joint power production, both negative and positive, were calculated. The peak hip, knee and ankle joint positive and negative power values were summed to attain the total positive and negative powers, respectively, during each trial and used to determine each joint's percent contribution to the net positive and negative joint powers. All moment, power and work values reported in this study are in the internal reference frame.

Statistical Analysis

Biomechanical parameters were compared within groups to assess the difference in the participant's gait and cue-altered gait using paired *t* tests. All statistical analyses were performed using the Microsoft Excel Data Analysis Tool Pack with an alpha level set at 0.05. Cohen's *d* was calculated for effect size using relevant means and standard deviations. Cohen's d values of 0 – 0.2, 0.21 – 0.5 and > 0.5 were considered small, medium and large effect sizes, respectively (Cohen, 1988).

3.3 Results

When comparing standard and cue-altered gait within the control group (Table 3.2), the peak trunk extension angle increased by approximately 5.4 degrees (P=0.001) and the peak trunk flexion angle decreased by approximately 4.9 degrees (P=0.002). No significant differences were found in peak joint power (Table 3.5). The peak knee flexion moment (Table 3.3) during loading response between control gait conditions increased by approximately 12.9% ($P<0.05$) and the negative ankle work (Table 3.5) changed from -0.14 J·kg to -0.12 J·kg ($P=0.014$) during stance.

Table 3.1: Participant demographics.

Demographics	n	Age	BMI
Control (n=12 female)	12	26.25±8.02	23.77±3.59
FAI (n=6 female)	6	31.50±10.78	28.03±5.85

Figure 3.1: Sagittal kinematics for the control group.

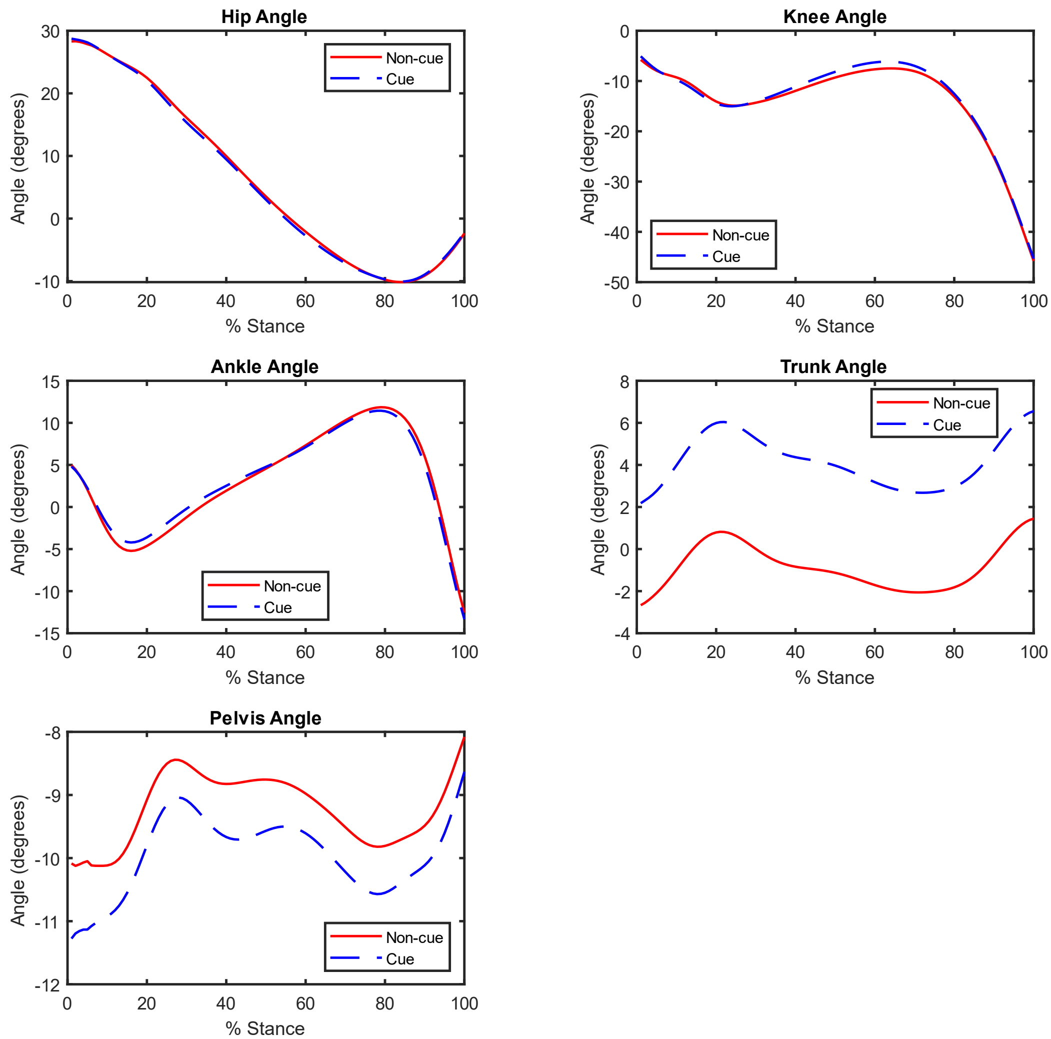


Figure 3.2: Sagittal kinematics for the FAIS group.

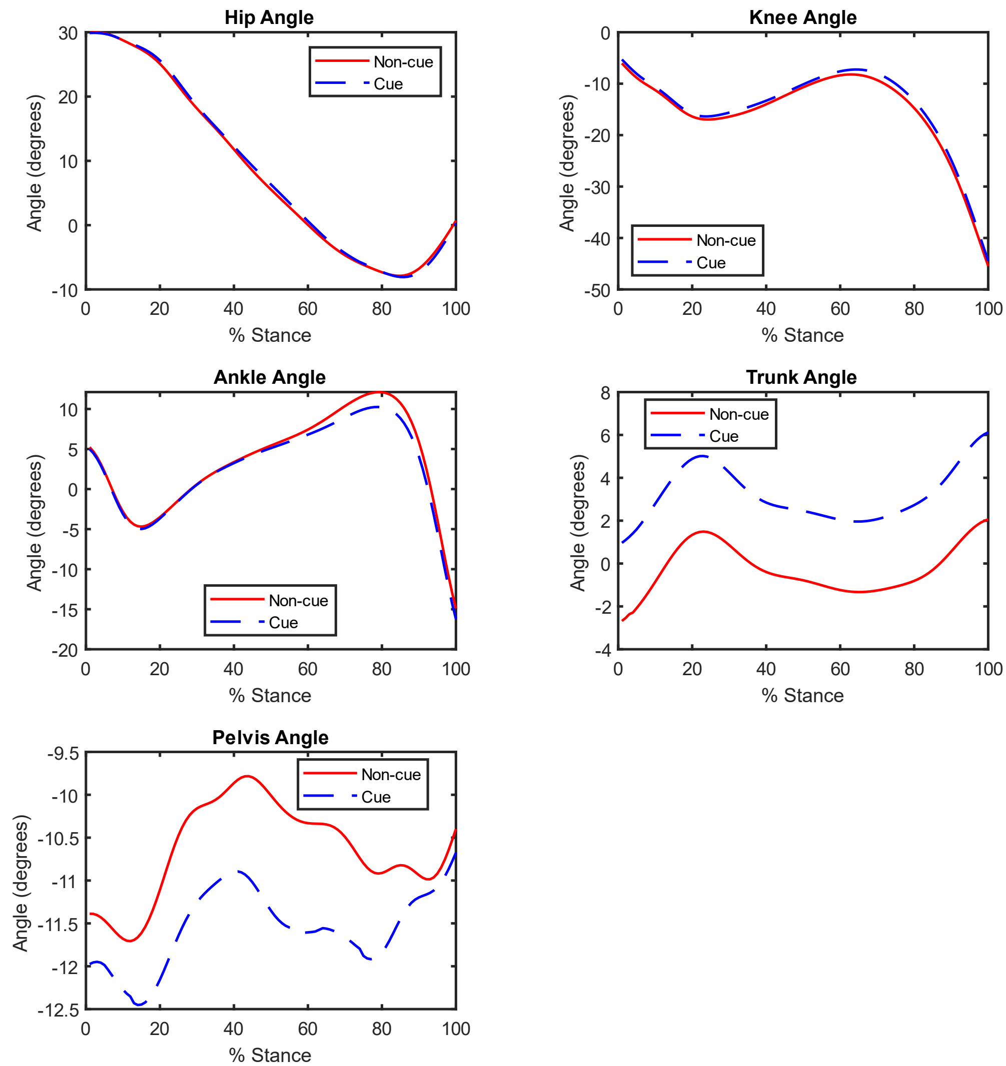


Table 3.2: Sagittal control kinematics.

	CONTROL			
Sagittal Kinematics (deg)	*Unaltered*	*Cue-altered*	*P Value*	*Effect Size*
Peak Trunk Flexion	3.09±2.49	1.85±4.91	**0.002**	0.32
Peak Trunk Extension	1.64±2.69	7.06±5.28	**0.001**	1.53
Peak Pelvic Flexion	6.82±5.83	7.35±4.22	0.615	0.10
Peak Pelvic Extension	10.97±5.50	11.77±4.12	0.473	0.17
Peak Hip Flexion	27.87±2.66	28.48±3.22	0.545	0.21
Peak Hip Extension	10.42±4.09	10.43±3.00	0.994	0.003
Peak Knee Extension	3.99±5.88	3.87±4.04	0.956	0.02
Peak Knee Flexion	16.36±9.38	15.58±6.79	0.825	0.10
Peak Dorsiflexion	11.77±1.83	11.35±2.00	0.368	0.22
Peak Plantarflexion	14.47±6.02	15.35±6.36	0.232	0.14

Table 3.3: Sagittal FAIS kinematics.

	FAIS			
Sagittal Kinematics (deg)	*Unaltered*	*Cue-altered*	*P Value*	*Effect Size*
Peak Trunk Flexion	3.82±4.29	0.76±6.08	**0.043**	0.58
Peak Trunk Extension	1.35±6.12	5.26±6.77	**0.000**	0.61
Peak Pelvic Flexion	10.49±7.52	11.24±7.47	0.094	0.10
Peak Pelvic Extension	15.37±8.17	16.69±9.93	0.263	0.15
Peak Hip Flexion	29.25±3.55	30.07±3.30	0.421	0.24
Peak Hip Extension	7.51±2.84	7.68±2.86	0.771	0.06
Peak Knee Extension	5.92±4.94	5.30±4.40	0.856	0.13
Peak Knee Flexion	17.13±4.81	16.50±4.65	0.855	0.13
Peak Dorsiflexion	11.62±3.42	10.16±3.15	**0.026**	0.44
Peak Plantarflexion	18.14±6.33	19.69±6.87	**0.045**	0.24

Table 3.4: Control internal sagittal peak joint moments.

	CONTROL			
Peak Joint Moments ($Nm \cdot kg^{-1}$)	*Unaltered*	*Cue-altered*	*P Value*	*Effect Size*
Hip Flexion	0.757±0.295	0.795±0.307	0.057	0.13
Hip Extension	0.698±0.417	0.670±0.421	0.670	0.07
Knee Flexion	0.327±0.259	0.343±0.192	**0.045**	0.07
Knee Extension	0.296±0.263	0.290±0.202	0.772	0.03
Dorsiflexion	0.204±0.119	0.193±0.693	0.401	0.22
Plantarflexion	1.108±0.128	1.111±0.686	0.746	0.006

Table 3.5: FAIS internal sagittal peak joint moments.

	FAIS			
Peak Joint Moments (Nm·kg-1)	Unaltered	Cue-altered	P Value	Effect Size
Hip Flexion	0.793±0.295	0.796±0.315	0.836	0.01
Hip Extension	0.550±0.227	0.552±0.204	0.970	0.01
Knee Flexion	0.327±0.263	0.343±0.103	0.663	0.08
Knee Extension	0.296±0.260	0.209±0.101	0.965	0.44
Dorsiflexion	0.204±0.094	0.193±0.624	0.797	0.03
Plantarflexion	1.108±0.094	1.112±0.588	0.292	0.01

Figure 3.3: Control group sagittal joint moments.

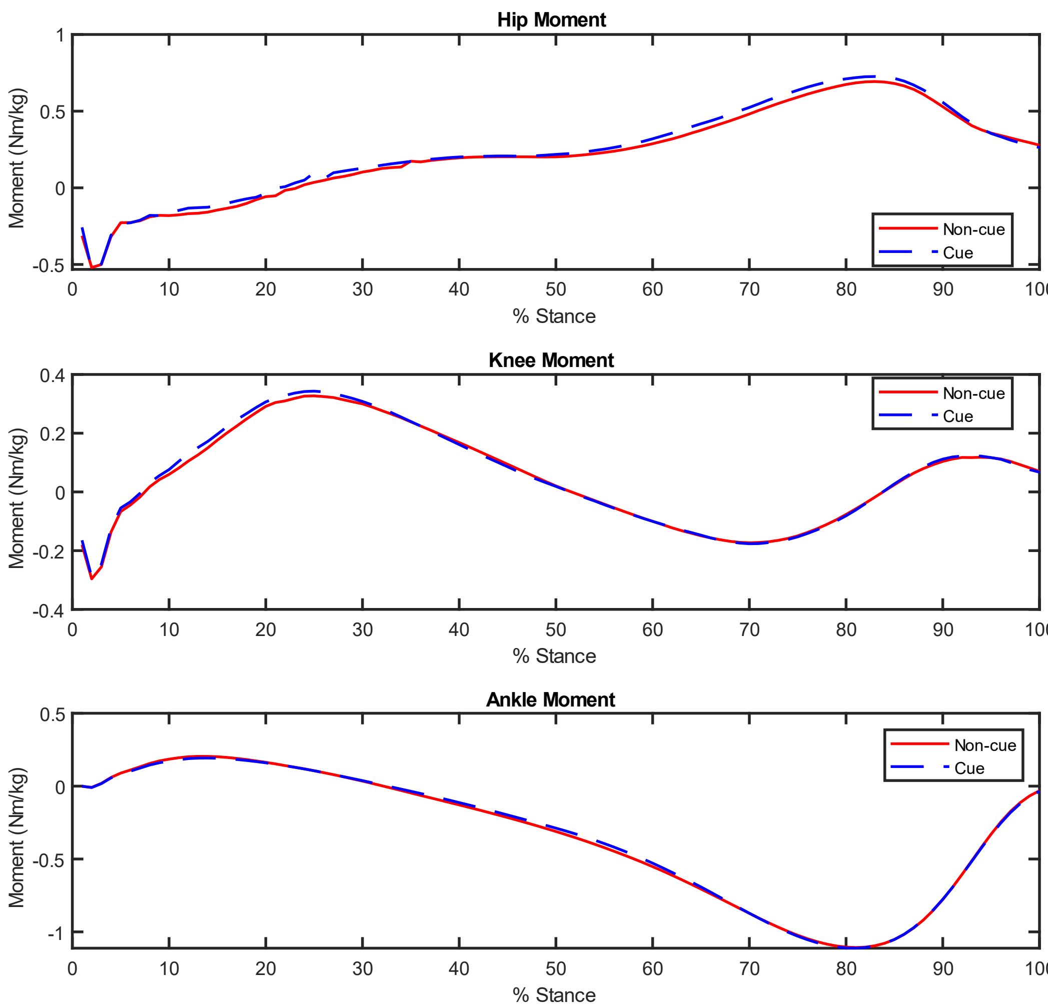


Figure 3.4: FAIS group sagittal joint moments.

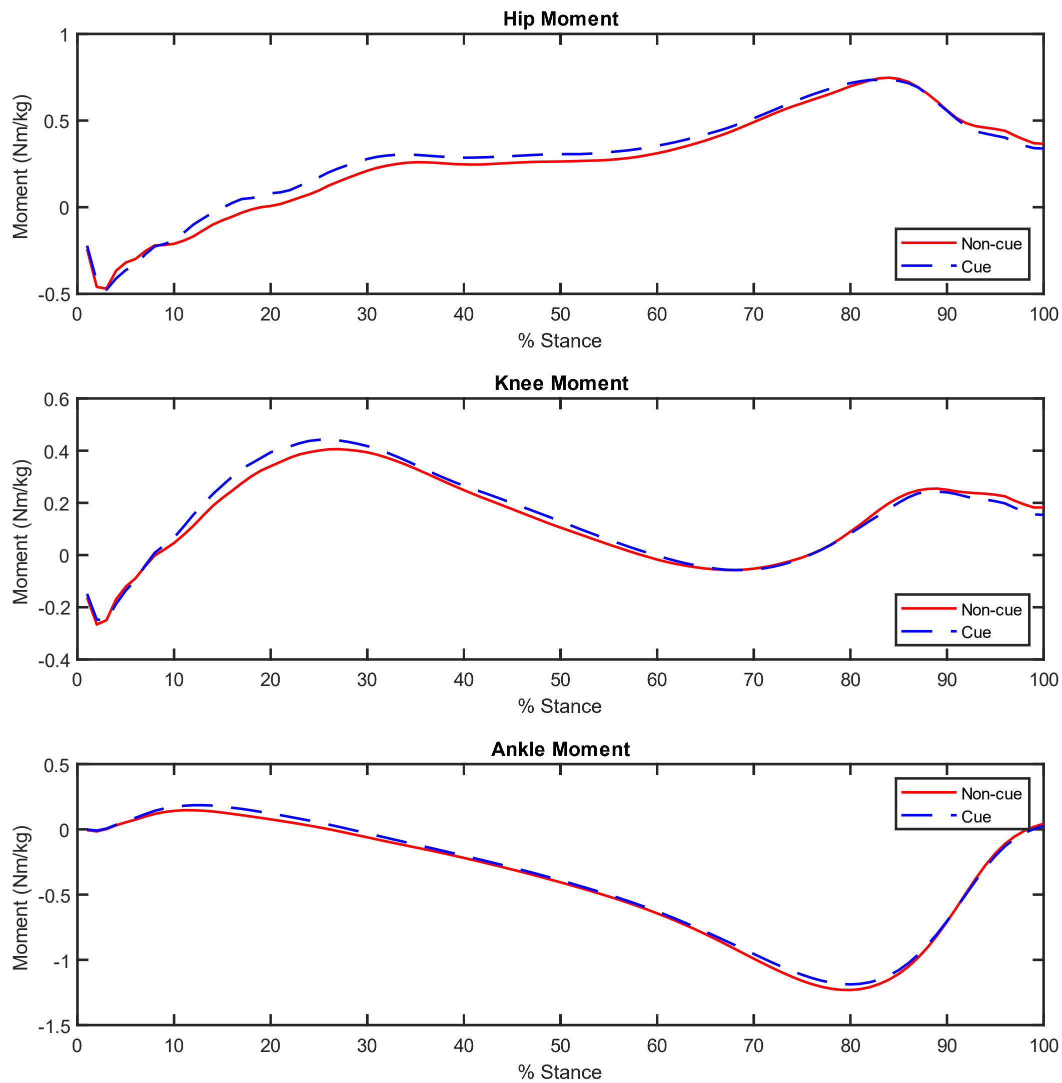


Figure 3.5: Control sagittal joint powers.

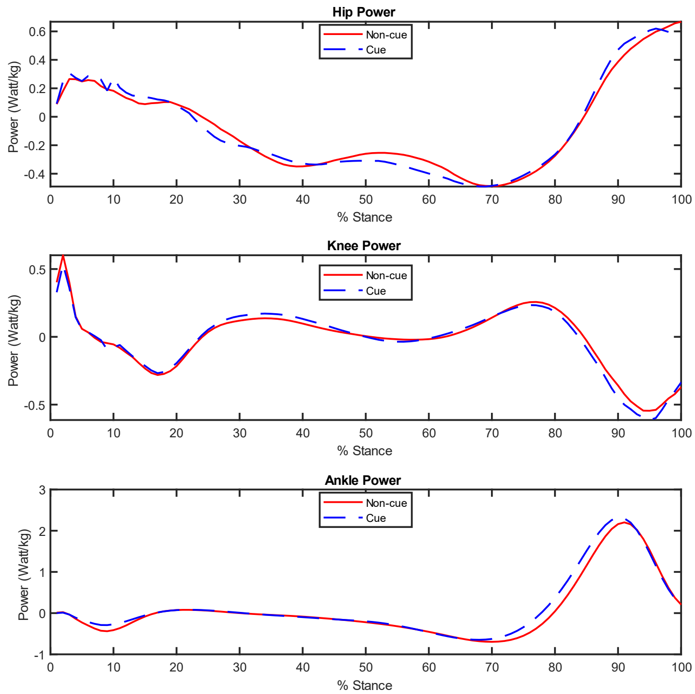


Figure 3.6: FAIS sagittal joint powers.

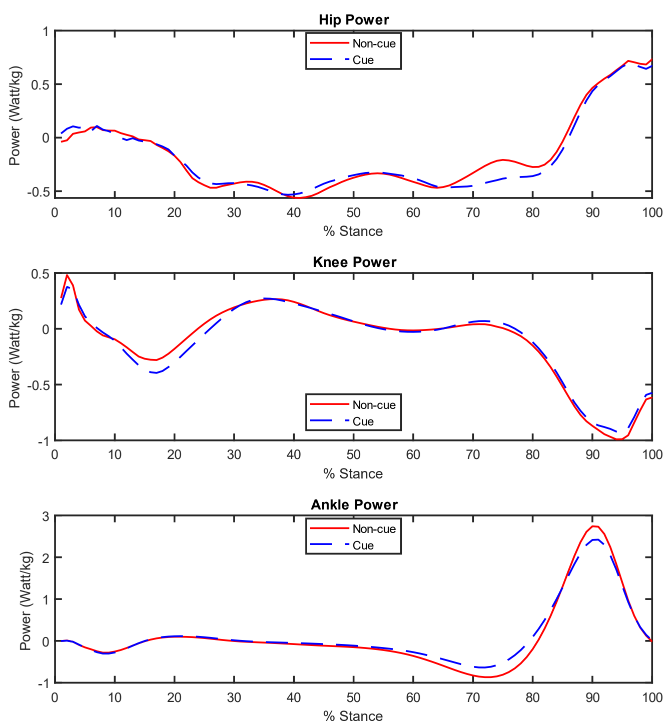


Table 3.6: Control internal sagittal peak joint powers.

	CONTROL			
Peak Joint Power (Watt·kg^{-1})	*Unaltered*	*Cue-altered*	*P Value*	*Effect Size*
Hip Extension	0.942±0.479	0.990±0.528	0.497	0.09
Hip Flexion	1.565±0.256	1.313±0.178	0.386	1.14
Knee Extension	0.670±0.379	0.697±0.422	0.601	0.07
Knee Flexion	0.696±0.551	0.781±0.733	0.519	0.13
Dorsiflexion	0.827±0.542	0.754±0.516	0.394	0.14
Plantarflexion	2.221±1.561	2.219±1.606	0.988	0.001

Table 3.7: FAIS internal sagittal peak joint powers.

	FAIS			
Peak Joint Power (Watt·kg^{-1})	*Unaltered*	*Cue-altered*	*P Value*	Effect Size
Hip Extension	1.722±2.211	1.426±1.396	0.428	0.16
Hip Flexion	0.824±0.433	1.567±2.038	0.348	0.50
Knee Extension	1.113±0.450	1.029±0.389	0.530	0.20
Knee Flexion	0.499±0.240	0.463±0.310	0.602	0.05
Dorsiflexion	0.842±0.406	0.702±0.342	0.144	0.37
Plantarflexion	2.959±1.578	2.969±1.542	0.880	0.006

Table 3.8: Control internal sagittal joint work.

	CONTROL			
Joint Work (Joule·kg^{-1})	*Unaltered*	*Cue-altered*	*P Value*	*Effect Size*
Hip Extension	0.043±0.013	0.042±0.023	0.800	0.05
Hip Flexion	0.069±0.041	0.078±0.047	0.072	0.20
Knee Extension	0.068±0.043	0.070±0.048	0.719	0.04
Knee Flexion	0.049±0.032	0.057±0.035	0.066	0.24
Dorsiflexion	0.140±0.090	0.122±0.080	**0.014**	0.21
Plantarflexion	0.178±0.128	0.186±0.136	0.108	0.06

Table 3.9: FAIS internal sagittal joint work.

	FAIS			
Joint Work (Joule·kg^{-1})	*Unaltered*	*Cue-altered*	*P Value*	*Effect Size*
Hip Extension	0.058±0.054	0.049±0.030	0.402	0.21
Hip Flexion	0.078±0.064	0.086±0.060	0.199	0.13
Knee Extension	0.141±0.073	0.130±0.063	0.110	0.16
Knee Flexion	0.056±0.041	0.044±0.029	0.326	0.34
Dorsiflexion	0.151±0.110	0.129±0.086	0.258	0.22
Plantarflexion	0.199±0.114	0.202±0.116	0.430	0.03

When comparing the gait conditions within the FAIS group, no kinetic changes were found to be significantly different ($P>0.05$). The peak trunk extension angle increased by approximately 3.9 degrees ($P<0.001$) and the peak trunk flexion angle decreased by approximately 4.5 degrees ($P=0.04$). The peak ankle dorsiflexion angle decreased by approximately 1.4 degrees ($P=0.03$) and the peak ankle plantarflexion angle increased by approximately 1.5 degrees.

No center of gravity, power contribution, moment impulses or moment duration changes at any joint analyzed were found to be significantly different within the control or FAIS groups ($P>0.05$).

3.4 Discussion

The current study investigated the effects of a verbal cue to modify gait mechanics in patients with FAIS. The implemented cue of “walk upright” was a predominately passive cue that required no active, conscious changes to the lower body from the individual during their natural gait. Significant differences seen in the control subjects with the implementation of this cue included overall increased trunk extension, increased peak knee flexion moment, and increased negative ankle work. FAIS participants demonstrated increased trunk extension, and increased ankle plantarflexion. Although the verbal cue led to increased trunk extension during gait in both groups, there were differing joint kinematic and kinetic alterations within each group. Only kinetic changes at the knee and ankle joints occurred within the control group, while only joint kinematic changes occurred within the FAIS group between gait conditions. Also, neither group demonstrated any changes in hip joint kinematics or kinetics when provided with the verbal cue. This finding suggests that the FAIS population were able to selectively alter their gait pattern in a way that differs from asymptomatic controls and that strictly affects their gait-related kinematics without altering lower extremity joint loading.

Previous work in the FAIS population demonstrated increased trunk flexion during stair ambulation (Hammond et al., 2017). The verbal cue used in this study was effective in significantly decreasing trunk flexion during gait in both healthy controls and FAIS patients. Although both controls and FAIS patients ambulated with a more extended trunk when provided with the verbal cue, there were no corresponding changes in the total body COG. Neither the control nor FAIS group demonstrated any changes in pelvic kinematics after being provided the verbal cue, which may help to explain the lack of changes in the total body COG within groups. In addition, neither the control or FAIS groups demonstrated any changes in hip joint kinematics or kinetics when provided with this verbal cue. This suggests that this verbal cue may not be effective in altering hip joint loading patterns associated with hip pain in the FAIS population (Samaan et al., 2017).

When provided with the verbal cue, the control group ambulated with increased peak knee flexion moment during loading response and increased negative ankle work without any corresponding changes in knee or ankle joint kinematics. On the other hand, after being provided with the verbal cue, the FAIS group ambulated with increased ankle plantarflexion angle during loading response without any corresponding changes in lower extremity joint kinetics. The increased plantarflexion seen with the utilization of this cue may be an effective, initial measure to reduce anterior hip pain during gait as seen in another cue-related biomechanical gait study (Lewis & Garibay, 2015). These findings suggest that the verbal cue used in this study primarily alters ankle joint kinematics instead of hip mechanics during gait. The ankle work findings in the control group correlate with greater concentric activity by the ankle plantar-flexors that occur prior to toe off. Both the increased peak knee flexion moment and increased negative ankle joint work occur during loading response in the control group when provided with the verbal cue which suggests a coupled interaction between knee and ankle joint loading in healthy controls when asked to "walk upright". Also, evidence of increased knee loading suggests that the cue used in this study may be inadvisable for individuals with knee osteoarthritis where increasing knee loading is not a desirable outcome.

Within both groups, the peak trunk flexion and extension changed to show that the cue was promoting the intended changes at the trunk. Therefore, the hip seems to be unaffected by this specific cue and shows it is likely not effective in reducing anterior hip pain via a reduction in hip joint loading. The range of motion at the trunk within both groups was also consistent between unaltered and altered gait conditions which shows that the cue did promote a decrease in trunk flexion throughout the entire stance phase. This means that participants walked with similar sagittal trunk excursion as opposed to displaying a greater overall movement of the trunk, which was not desired. While this adjustment was hypothesized to decrease anterior hip pain, the cue was acute and only three trials were performed, making it impossible to determine if a favorable pain change would occur if this cue were to be done chronically. In the future, it may be worthwhile to develop gait retraining protocols that are designed around chronically used cues instead of short-term, acute cues. Future studies regarding verbal cueing should consider implementing longer walking periods or having participants complete multiple visits during a gait retraining program focused on chronically implemented cues.

This study is not without its limitations and the results of this study should be interpreted with caution. First, this study incorporated a small sample size with only female subjects, which may reduce the overall power in this study. Second, the verbal cue used in this study was used to assess acute changes in gait mechanics and should be studied after implementation of this verbal cue into a gait retraining program. Next, the use of a fixed walking speed as opposed to a self-selected walking speed may not provide us with an accurate understanding of the changes in gait mechanics that occur during natural gait after being provided with this verbal cue in the FAIS population.

3.5 Conclusion

This study provides evidence to suggest that the FAIS population are able to selectively alter their sagittal plane gait kinematics while maintaining similar lower extremity joint loading during walking. The findings from this study suggest that acute, verbal cues are indeed effective at changing specific kinematic parameters in the FAIS population, but attention should be given to designing a cue that will also augment the joint kinetics. This study provides a base to design further biomechanical research into a cueing strategy for reducing hip pain and joint loading in the FAIS population. Verbal cues could be an integral part of gait retraining or rehabilitation programs for populations with unique or challenging gait characteristics such as FAIS, but more research should be conducted to ensure that the cues target desired joints or segments while minimizing unwanted effects on gait mechanics. Currently, cues are predominately used to assist in neuromuscular or neurological rehabilitation, but as the literature around gait and cue implementation develops it is likely that this field can also provide beneficial clinical methods for reducing hip pain and joint degeneration in the FAIS population.

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