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Effect of increased pushoff during gait on hip joint forces

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Abstract

Anterior acetabular labral tears and anterior hip pain may result from high anteriorly directed forces from the femur on the acetabulum. While providing more pushoff is known to decrease sagittal plane hip moments, it is unknown if this gait modification also decreases hip joint forces. The purpose of this study was to determine if increasing pushoff decreases hip joint forces. Nine healthy subjects walked on an instrumented force treadmill at 1.25 m/s under two walking conditions. For the natural condition, subjects were instructed to walk as they normally would. For the increased pushoff condition, subjects were instructed to “push more with your foot when you walk”. We collected motion data of markers placed on the subjects' trunk and lower extremities to capture trunk and leg kinematics and ground reaction force data to determine joint moments. Data were processed in Visual 3D to produce the inverse kinematics and model scaling files. In OpenSim, the generic gait model (Gait2392) was scaled to the subject, and hip joint forces were calculated for the femur on the acetabulum after computing the muscle activations necessary to reproduce the experimental data. The instruction to “push more with your foot when you walk” reduced the maximum hip flexion and extension moment compared to the natural condition. The average reduction in the hip joint forces was 12.5%, 3.2% and 9.6% in the anterior, superior and medial directions respectively and 2.3% for the net resultant force. Increasing pushoff may be an effective gait modification for people with anterior hip pain.

Keywords

gait; hip pain; hip force; musculoskeletal modeling

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Conflict of interest

The authors affirm that they have no financial affiliation or involvement with any commercial organization that has direct financial interest in any matter included in this manuscript.

1. Introduction

High joint forces have been implicated in the development and progression of osteoarthritis and pain (Mavcic et al., 2004; Recnik et al., 2007). In particular, high anteriorly directed forces from the femur on the acetabulum may result in anterior hip pain, acetabular labral tears (Mason, 2001; McCarthy et al., 2001) and subtle hip instability (Shindle et al., 2006). Prior musculoskeletal simulation have demonstrated that anterior hip joint force increases with increasing hip extension during exercises (Lewis et al., 2007; Lewis et al., 2009) and during gait (Lewis et al., 2010). Anterior hip joint force also increases with decreased strength of the iliacus and psoas muscles during hip flexion and gluteal muscles during hip extension (Lewis et al., 2007; Lewis et al., 2009). Gaining a better understanding of how gait strategies affect these joint forces may improve rehabilitation outcomes (Heller et al., 2001).

Decreasing the anterior hip joint force may be particularly beneficial for patients with anterior hip pain (Lewis and Sahrmann, 2006). Clinically, we have noted that patients with anterior hip pain appear to walk with increased peak hip extension and have a delayed or decreased pushoff during gait. When these patients are instructed to decrease their hip extension and to push more with their foot when they walk, they report an immediate reduction in the hip pain. We have previously reported that walking with less hip extension reduced the anterior hip joint force (Lewis et al., 2010). We have also demonstrated that walking with increased pushoff resulted in a decrease in both the hip flexion and hip extension internal muscle moments (Lewis and Ferris, 2008). It is unknown if this alteration in gait also decreases hip joint forces. Therefore, the purpose of this study was to determine if walking with increased pushoff during gait decreases hip joint forces compared to the natural condition. The hypothesis was that increased pushoff would decrease anterior hip joint forces compared to natural pushoff.

2. Materials and methods

2.1. Subjects

Data from nine healthy subjects (3 males, 6 females) which were collected as part of a different study (Lewis and Ferris, 2008) were used in this analysis. (Table 1) All subjects agreed to participate voluntarily and provided written informed consent as approved by the Institutional Review Boards of the University of Michigan and Boston University.

2.2. Instrumentation

We used a 3-dimensional motion capture system (Motion Analysis Corp., Santa Rosa, CA, USA) at 120 Hz and reflective markers to record the position of the foot, shank, thigh and trunk. Briefly, markers were placed bilaterally on the posterior heel, 5th metatarsal head, medial and lateral malleoli, medial and lateral femoral epicondyles, and anterior superior iliac spine. A single marker was placed on the sacrum between the posterior superior iliac spines. Rigid clusters of three markers were placed on the shank and thigh bilaterally. Position data were low-pass Butterworth filtered at 6 Hz with a zero phase lag to remove artifact. Subjects walked at 1.25 m/s on an instrumented treadmill which measured vertical,

horizontal and lateral ground reaction forces and moments under each foot individually at 1200 Hz (Collins et al., 2009).

For a subset of our subjects (N=3) we also collected surface electromyography (EMG) data. Surface electrodes (1.1cm diameter) with an inter-electrode distance of 2.5cm were placed over the muscle bellies of the left medial gastrocnemius, soleus and iliopsoas per recommended guidelines (Konrad, 2005). These three muscles were measured as they were expected to change with condition. The iliopsoas electrode was placed medial to the rectus femoris, lateral to the femoral pulse, and inferior to the inguinal ligament (Gottschall and Kram, 2005). Correct placement was verified with movement tests (Cram and Kasman, 1998). Data were collected at 1200 Hz, high pass filtered with a 20 Hz zero-phase lag Butterworth filter, rectified and filtered with a 10 Hz zero-phase lag low pass filtered to smooth the signal. Data were averaged over 10–12 strides for each condition.

2.3. Conditions

Each subject walked under two walking conditions. For the natural condition, subjects were instructed to walk as they normally would. For the increased pushoff condition, subjects were instructed to “push more with your foot when you walk”. Subjects were given only this simple instruction, and were not given feedback during the study. Subjects were given at least one minute to practice walking under the different conditions prior to data collection.

2.4. Data acquisition and processing

Kinematic and kinetic data were recorded for 90 seconds during walking in each condition. Data were processed in Visual3D (C-Motion, Inc, Rockville, MD) to produce the inverse kinematics and model scaling files, specifically developed to be used with OpenSim (“Comparing Visual3D and SIMM exporting to OpenSim”, 2014). Those files were then imported into OpenSim 2.0 (Delp et al., 2007), an open-source musculoskeletal modeling software. For each subject, the generic gait model (Gait2392) was scaled based on the subject’s height, weight, calibration data and segment geometry. The model of the lower extremities and trunk contains 23 degrees of freedom, which is the same as the Visual 3D model, and 92 actuators. In OpenSim, the residual reduction algorithm (RRA) was run, and the model was adjusted if indicated by adjusting maximum excitation values for residuals and re-running RRA until the simulation resulted in peak residual forces that were less than 10N and RMS differences in joint angles and translations were less than 5° or 2 cm respectively, as stated in the OpenSim software documentation (Hicks et al., 2014). We then ran the computed muscle control (CMC) algorithm (Thelen and Anderson, 2006) to determine the muscle actuation necessary to match the kinematics and force data. Hip joint forces were calculated for the femur on the acetabulum in the pelvic reference frame using the Joint Reaction analysis (Steele et al., 2012). For each subject, we created average data normalized from left heel strike to subsequent left heel strike for 10–12 strides for each condition.

To evaluate how well the calculated muscle activations reflected the measured EMG data, we qualitatively compared the data in the subset of subjects. The predicted muscle activations were generally consistent with the measured EMG and demonstrated similar

changes in muscle activation between conditions (Figure 1). Specifically, the medial gastrocnemius and soleus were activated earlier and the iliopsoas was activated less during the Increased Pushoff condition compared to the Natural Pushoff condition. The one discrepancy was that an increase in peak soleus muscle activation was not predicted by the model, but was detected in the measured EMG.

2.5. Data analysis

As we were interested in the interplay between the hip and ankle, we limited our statistical analyses to those two joints. To verify that increasing pushoff had the same effects in this subset of data as previously reported (Lewis and Ferris, 2008), we compared the peak hip and ankle joint moments and angular impulses between conditions using paired t-tests. Angular impulse was calculated separately for the corresponding positive or negative moment curve. We also compared peak hip flexion and extension angles between conditions as hip angle affects anterior joint force during walking (Lewis et al., 2010). To examine the effect of pushoff on hip joint force, we used paired t-tests to compare the maximum anterior, superior, medial and resultant (net total) joint force between the two conditions. All statistical analyses were performed in IBM SPSS Statistics version 20 (IBM Corporation, Armonk, NY) with an alpha level of 0.05.

3. Results

The simple instruction to “push more with your foot when you walk” reduced the maximum hip flexion and extension peak moment and angular impulse ($p < 0.025$) without changing the peak hip angles ($p > 0.219$) compared to the natural condition (Table 2, Figure 2). At the ankle, the plantar flexion angular impulse was increased in the Increased Pushoff condition compared to the Natural Pushoff condition ($p < 0.001$) indicating that subjects were able to increase pushoff.

The effect of pushoff on hip joint force, however, was less consistent. The average reductions in the peak hip joint forces were 12.5%, 3.2% and 9.6% in the anterior, superior and medial directions respectively and 2.3% for the net resultant force (Table 2, Figure 3). Of this, only the reduction in the peak anterior hip joint force was significant ($p = 0.042$). Despite average decreases in joint forces, the result was not consistent. One subject had higher anterior forces in the increased pushoff condition compared to the natural condition.

4. Discussion

The results of this study support the hypothesis that increasing ankle pushoff during gait decreases the peak anterior hip joint force. We had previously demonstrated that increasing ankle pushoff decreases both the hip flexion and hip extension peak moments and angular impulses (Lewis and Ferris, 2008). As the peak anterior hip joint force occurs temporally near to the peak hip flexion moment during late stance, we surmise that the reduction in the anterior hip joint force is attributable to the reduction in the hip flexion moment. This explanation is consistent with the finding that forces at the hip are primarily due to muscle activation (Bassey et al., 1997; Correa et al., 2010; Lewis et al., 2010). Furthermore, the production of a hip flexion moment in a position of hip extension, such as during late stance,

results in an anterior hip joint force (Lewis et al., 2007) due to the directional pull of the hip flexor muscles.

Despite the average decrease in the anterior joint force, there was one subject with an increase in peak anterior joint force. This finding indicates that the gait modification is not always effective in reducing the anterior joint force. Additionally, there were not significant reductions in the superior, medial or resultant force indicating that gait modifications should be tailored to the particular goal for the individual patient. For example, for a patient with hip osteoarthritis, it might be more important to reduce the superiorly directed or net resultant joint force than the anterior joint force as higher peak joint stresses have been associated with disease progression (Mavcic et al., 2004; Recnik et al., 2007).

Modification of gait to reduce joint forces is a powerful non-invasive treatment tool. Strategies of gait modification have been tested for knee osteoarthritis and demonstrate a potential benefit (Fregly et al., 2007; Fregly et al., 2009; Hunt et al., 2011; Kinney et al., 2013). One previous study evaluated the benefit of shifting the trunk laterally and demonstrated an improvement in pain in adults with hip pain (Schroter et al., 1999). Our study is the first to test a modification at the ankle to reduce hip joint forces. Walking with increased pushoff has been recommended for patients with anterior hip pain or an acetabular labral tear (Lewis and Sahrmann, 2006). The results of this study indicate that simple cues to increase ankle pushoff decrease the anterior hip joint force, and therefore, may be clinically beneficial. Based on these results, the logical next steps would be to determine whether increased pushoff can lead to a clinically beneficial effect and if long-term gait modifications can be maintained in the clinical populations at risk of hip pain and / or injury.

Anterior hip joint force increases with increasing hip extension angle (Lewis et al., 2010). When walking with increased pushoff, subjects did not decrease the hip extension angle. The combined cues to decrease hip extension angle and increase pushoff may result in a greater and more consistent reduction in anterior hip joint force. This combined approach could be tested in a future study.

The hip joint forces calculated in this study, while higher than those measured by instrumented hip prostheses (Bergmann et al., 1993; Bergmann et al., 2001; Lu et al., 1998), are consistent with estimated forces for young healthy subjects (Valente et al., 2013). Joint forces can only be measured in vivo through the use of instrumented prostheses, which changes the environment of the biological hip, and therefore may not accurately depict the forces in younger healthy adults. This is a particularly important difference as the majority of hip joint force comes from muscle activation (Bassey et al., 1997; Correa et al., 2010; Lewis et al., 2010).

This study also differs slightly in how hip joint forces are presented. Unlike most other studies (Bergmann et al., 1993; Bergmann et al., 2001; Heller et al., 2001; Valente et al., 2013), we selected a pelvic reference frame. This selection allowed us to evaluate the walking conditions in terms of the effect of the femur on the acetabulum. This subtle difference maintained our focus on forces experienced by the acetabulum and its surrounding structures such as the labrum.

A limitation of the current study is that the subjects did not have hip pain and therefore may not respond in the same way as subjects with hip pain. We sought to test the concept of using pushoff to decrease hip joint forces before testing the clinical application. We are in the process of testing gait modifications in patients with hip pain.

Conclusion

Subjects in this study were able to reduce the anterior hip joint force substantially (by 12.0%) with the simple cue “push more with your foot when you walk”. The observed decrease in anterior hip joint force suggests that this gait modification would be beneficial for people with anterior hip pain and an acetabular labral tear. The use of subject-specific gait data and musculoskeletal modeling may help determine appropriate gait modifications for other patient populations to reduce hip joint forces.

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Figure 1.

Comparison of recorded EMG (top row) to muscle force calculated with OpenSim (bottom row) for the subjects with EMG data (N=3), mean and standard deviation (shaded area).

Figure 2.

Ankle, knee and hip joint kinematic and kinetic mean and standard deviation (shaded region) data for all subjects. Ankle dorsiflexion, knee flexion, and hip flexion are positive.

Figure 3.

Calculated hip joint forces in the three directions and resultant (net total), mean and standard deviation (shaded region) of all subjects. The anterior joint force was significantly less in the Increased Pushoff condition compared to the Natural Pushoff condition.

Table 1

Demographic data for the 9 subjects included in this study.

Subject Demographics (N=9)	Mean	SD
Age (years)	26.7	6.7
Height (m)	1.70	0.09
Weight (kg)	65.0	10.4

Table 2

Mean and standard deviation (SD) of the peak kinematic, kinetic and joint force data from all subjects ($N=9$). Percent change is from the Natural to the Increased Pushoff condition with positive indicating an increase and negative indicating a decrease. Bold text indicates significant differences ($p<0.05$) for the paired t-test between the Natural and Increased Pushoff conditions.

Condition	Natural Pushoff		Increased Pushoff		Percent Change (%)		Statistical Analysis		
Angle (degrees)	Mean	SD	Mean	SD	Mean	SD	<i>t</i>	<i>df</i>	<i>p</i>
Hip Flexion	24.6	3.5	25.7	2.9	5.3	9.4	-1.33	8.00	0.219
Hip Extension	-19.1	5.3	-19.0	6.8	3.1	16.4	-0.19	8.00	0.851
Joint Moment (Nm)									
Hip Flexion	48.6	10.2	37.1	11.4	-24.6	9.3	8.34	8.00	<0.001
Hip Extension	-50.2	9.9	-42.8	6.9	-13.7	11.0	-3.43	8.00	0.009
Ankle Dorsiflexion	12.9	4.6	14.9	3.8	22.0	30.3	1.26	8.00	0.242
Ankle Plantar flexion	-96.4	24.5	-99.6	20.1	4.7	8.5	-2.02	8.00	0.078
Angular Impulse (Nms)									
Hip Flexion	10.2	2.7	7.4	4.0	-30.3	18.1	5.11	8.00	0.001
Hip Extension	-8.6	2.9	-7.4	2.4	-12.5	11.0	-2.74	8.00	0.025
Ankle Dorsiflexion	1.3	0.7	1.3	0.5	22.9	36.8	-0.54	8.00	0.603
Ankle Plantar flexion	-25.6	7.8	-32.2	8.8	26.8	9.1	10.51	8.00	<0.001
Hip Joint Force (N)									
Anterior	1787.7	389.2	1579.5	491.3	-12.5	16.8	2.41	8.00	0.042
Superior	3006.9	372.3	2892.5	524.4	-3.2	15.4	0.73	8.00	0.488
Medial	1033.5	344.2	897.1	243.3	-9.6	15.3	2.16	8.00	0.062
Resultant	3183.9	534.3	3097.6	603.7	-2.3	12.3	0.65	8.00	0.536

df = degrees of freedom.