Sex-specific hip osteoarthritis-associated gait abnormalities: alterations in dynamic hip abductor function differ in men and women

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Abstract

***Background*:** Hip osteoarthritis results in abnormal gait mechanics, but it is not known whether abnormalities are the same in men and women. The hypothesis tested was that gait abnormalities are different in men and women with hip osteoarthritis vs. sex-specific asymptomatic groups.

***Methods*:** 150 subjects with mild through severe radiographic hip osteoarthritis and 159 asymptomatic subjects were identified from an Institutional Review Board-approved motion analysis data repository. Sagittal plane hip range of motion and peak external moments about the hip, in all three planes, averaged from normal speed walking trials, were compared for men and women, with and without hip osteoarthritis using analysis of variance.

***Findings*:** There were significant sex by group interactions for the external peak hip adduction and external rotation moments (P=0.009-0.045). Although asymptomatic women had peak adduction and external rotation moments that were respectively 12% higher and 23% lower than asymptomatic men (P=0.026-0.037), these variables did not differ between men and women with hip osteoarthritis ($P \geq 0.684$). The osteoarthritis vs. asymptomatic group difference in the peak hip adduction moment was 45% larger in women than in men. The osteoarthritis vs. asymptomatic group difference in the peak hip external rotation moment was 55% larger for men than for women ($P < 0.001$). Sex did not influence the association between radiographic severity and gait variables.

***Interpretation*:** Normal sex differences in gait were not seen in hip osteoarthritis. Sex-specific adaptations may reflect different aspects of hip abductor function. Men and women with hip osteoarthritis may require different interventions to improve function.

Keywords: hip osteoarthritis, gait, sex differences, biomechanics

Introduction

Hip osteoarthritis (OA) is associated with abnormal gait mechanics (Ardestani and Wimmer, 2016, Chabra, Shakoor, & Foucher, 2012, Chabra and Foucher, 2013, Constantinou et al., 2014, Eitzen et al., 2012, Eitzen et al., 2015, Foucher et al., 2012, Hurwitz et al., 1997, Kumar et al., 2015b, Leigh, Osis, & Ferber, 2016, Rutherford, Moreside, & Wong, 2015, Watelain et al., 2001). There is overlap between the gait variables that have been found to differ between people with and without hip OA and those that differ between healthy men and women. For example, reduced dynamic sagittal plane hip range of motion,(Eitzen et al., 2012, Foucher et al., 2012, Hurwitz et al., 1997, Hurwitz et al., 1998, Watelain et al., 2001) and reductions in the peak external hip adduction moment (Ardestani and Wimmer, 2016, Foucher, Hurwitz, & Wimmer, 2007, Foucher et al., 2011, Hurwitz et al., 1997, Hurwitz et al., 1998) are commonly seen in hip OA. These same variables reportedly differ between healthy men and women.(Boyer, Beaupre, & Andriacchi, 2008, Kerrigan, Todd, & Della Croce, 1998, Ko et al., 2011b, Moisio et al., 2003) Moreover, it has been shown that knee OA affects gait in sex-specific ways (Ko et al., 2011a, Kumar et al., 2015a, McKean et al., 2007, Phinyomark et al., 2016). There may be sex-specificity in hip OA gait abnormalities as well. If so, there may be a need for sex-specific biomechanically-based interventions to improve function in men and women with hip OA.

Because of a dearth of sex-specific analyses in the hip OA biomechanics literature, the aim of this study was to identify sex-specific hip OA-related gait abnormalities in a previously described cohort of subjects with and without hip OA (Foucher et al., 2012). The hypothesis tested was that men with hip OA, when compared to asymptomatic men, would have different gait abnormalities than women with hip OA compared to asymptomatic women. Although there was no a priori expectations regarding the specific variables, or the direction or magnitude of the differences, the sagittal plane hip range of motion and peak external hip adduction moment were of particular interest. These variables are known to be different in healthy men and women, and are both linked to hip OA. Other gait variables discussed in the parent publication (Foucher et al., 2012), were included as well. Within the OA group, interactions between sex and radiographic OA severity were also investigated.

2. Methods

2.1. Subjects

An Institutional Review Board-approved data repository was used to identify 150 subjects with symptomatic, radiographically-verified hip OA. 159 asymptomatic subjects were identified from the same repository by selecting subjects whose ages were within two standard deviations of the mean age of the hip OA group. All subjects provided written informed consent for the original studies in which they were enrolled, and for the inclusion of their data in the repository, for secondary analyses. Asymptomatic subjects were slightly younger and had lower Body Mass Indices (BMIs) ($P \leq 0.006$) than the subjects with hip OA, but these differences did not influence the results of the previous study (Foucher et al., 2012). This difference persisted when the groups were separated by sex (Table 1), so these factors were considered in the statistical analysis. For the hip OA subjects, radiographic severity information was included in the database. A modified Kellgren-Lawerence (KL) grading system (0 – no OA to 4 – most severe) had been used to rate the severity of the osteoarthritic changes from Anterior-Posterior pelvic radiographs that were originally obtained for clinical purposes. The rater was a rheumatologist who was aware of a subject's status as an OA patient, but not necessarily aware of their participation in a research study.

Table 1. Subject Characteristics

	Hip Osteoarthritis			**Asymptomatic**				
	Women (N = 86)	**Men (N = 64)**	***P* value**	**Women (N = 104)**	**Men (N = 55)**	***P* value**	**OA vs. Asympto-matic Women**	**OA vs. Asympto-matic Men**
Age (yrs)	63.5 (SD 9.1) (44 – 85)	60.6 (SD 10.8) (29 – 79)	0.082	55.6 (SD 8.6) (41 – 78)	55.8 (SD 8.0) (42 – 80)	0.869	<0.001	0.008
BMI (kg/m^2)	27.8 (SD 5.5) (16.1 – 46.3)	28.9 (SD 4.6) (21.8 – 41.9)	0.190	26.6 (SD 5.9) (16.5 – 46.9)	26.8 (SD 3.7) (21.4 – 36.3)	0.818	0.141	0.006
Walking Speed (m/s)	1.0 (SD 0.2) (0.3 – 1.5)	1.1 (SD 0.2) (0.4 – 1.4)	0.009	1.3 (SD 0.2) (0.8 – 1.9)	1.4 (SD 0.2) (0.8 – 1.9)	0.195	<0.001	<0.001
KL Grade (N)	KL 1: 6 KL 2: 9 KL 3: 24 KL 4: 47	KL 1: 0 KL 2: 3 KL 3: 7 KL 4: 54	0.001					

2.2 Gait Analysis

Previously published (Foucher et al., 2012) gait analysis data were used. Methods have been described in detail elsewhere (Andriacchi, Natarajan, & Hurwitz, 2005, Andriacchi, 1990, Hurwitz et al., 1998). Briefly, an optoelectronic camera system (Qualisys North America, Deerfield IL) tracked the motion of reflective markers placed at bony landmarks, while a multicomponent forceplate (Bertec, Columbus OH) measured ground reaction forces as subjects walked across a 10 m walkway at self-selected speeds of slow, ‘normal’, and fast. Between 2 and 8 trials for each limb were collected at the self-selected normal walking speed, depending on the protocol of the original study. These trials were selected for the present analysis. To identify the ankle and knee joint centers, calipers were used to measure the width of the respective joint (distance from medial to lateral malleoli and the width of the knee at the joint line). The anterior-posterior position of the hip center was assumed to be at the location of the superiormost aspect of the greater trochanter, which was located by palpation and indicated with a marker. The superior-inferior position was determined by location a point 2.5 cm inferior to the midpoint of the distance between the anterior superior iliac spine and the pubic tubercle, which were identified by palpation. Custom software (CFTC — Computerized Functional Testing Corporation, Chicago, IL) was used to determine spatiotemporal gait variables and sagittal plane joint kinematics, from marker positions, and to calculate external moments in the sagittal, frontal, and transverse planes, using inverse dynamics. For the OA subjects, we selected data from the affected hip side. For the asymptomatic subjects, a random study limb was selected. There were no differences between the distribution of right and left limbs between the hip OA group and the asymptomatic group (Chi-square $P = 0.452$).

The variables of interest here were the dynamic sagittal plane range of motion (RoM) and the peak external moments about the hip joint in the sagittal, frontal, and transverse planes, as in the parent study (Foucher et al., 2012). These variables were averaged from normal speed walking trials. External moments were normalized to subjects' body weight and height (%BWH) (Moisio et al., 2003).

2.3 Statistical Analysis

Statistical analysis was performed using IBM SPSS Statistics V.24 (IBM Corporation, Armonk, NY). Two way ANOVAs were used to compare gait variables for men and women, with and without hip OA. Sex, group (OA vs. Control), and a sex by group interaction term were included in the models. Age, BMI, and walking speed were included as covariates. For each gait variable, a statistically significant ($P < 0.05$) sex by group interaction term indicated that the difference between OA and control subjects varied between men and women. Effect sizes (Cohen's d) were calculated and post-hoc *t*-tests were used to assess the magnitude of the difference. This analysis was repeated within the OA group, using KL grade as the grouping variable and a KL by sex interaction term.

3. Results

In the sagittal plane (dynamic hip range of motion and peak external hip flexion and extension moments), there were no statistically significant sex by group interaction terms (respectively, P = 0.895, 0.052, 0.409; Table 2). All three variables were significant lower in the OA group than in the asymptomatic group (main effect of group P < 0.001). There was a significant main effect of sex for the dynamic sagittal plane hip RoM (P < 0.001) and peak external hip extension moment (*P* = 0.030). In both the OA and the asymptomatic groups, values of these variables were higher for women than men (Fig. 1). There were no sex differences for the peak external hip flexion moment (*P* = 0.389).

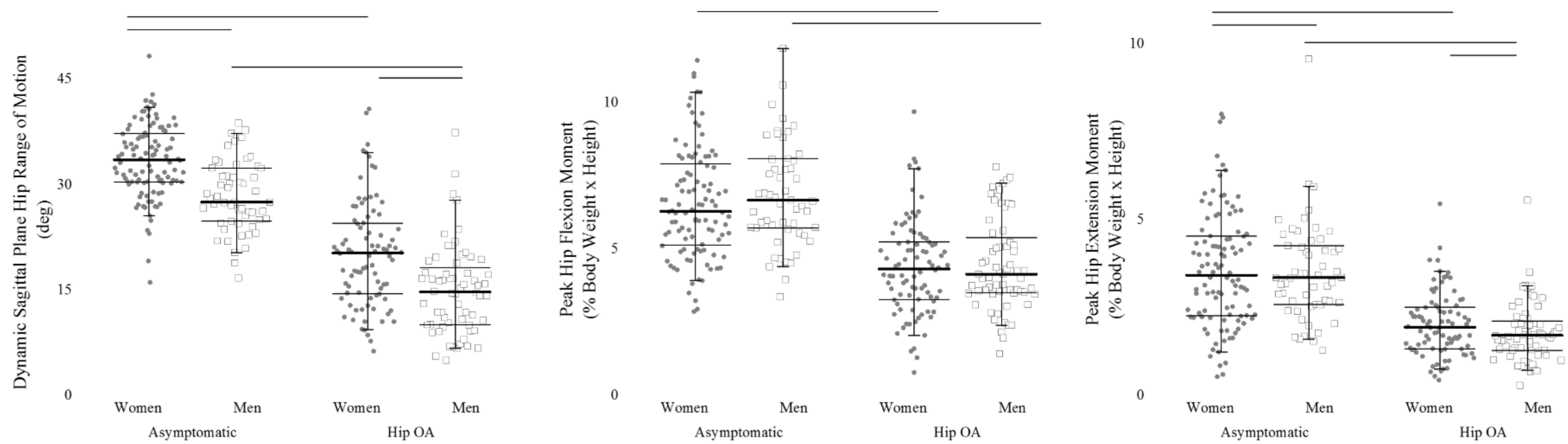

Fig. 1. Sagittal plane dynamic hip range of motion and peak sagittal plane hip external moments for asymptomatic women and men and for women and men with hip OA. Lines represent the median, 25th and 75th percentile; whiskers represent the 5th and 95th percentile. Horizontal lines above data represent pairwise comparisons with $P \leq 0.05$. There were no sex-specific group differences in the sagittal plane.

Table 2. Mean, standard deviations, P values and effect sizes(Cohen's d) for gait variables in women and men with and without hip OA. All moments refer to peak external moments about the hip. P values shown in table refer to main effect comparisons. Footnotes indicate significant sex by group interactions (i.e. presence of sex-specific deficits in the hip OA groups compared to the sex-matched asymptomatic groups).

Variable	Asymptomatic Group Women	Hip OA Group Women	Asymptomatic vs. Hip OA Women	Asymptomatic Group Men	Hip OA Group Men	Asymptomatic vs. Hip OA Men	Asymptomatic Groups Women vs. Men	Hip OA Groups Women vs. Men
Dynamic Sagittal Plane Hip Range of motion (Deg)	33.39 (SD 5.25)	20.18 (SD 7.52)	$P < 0.001$ d = 2.07	28.32 (SD 4.98)	15.02 (SD 6.39)	$P < 0.001$ d = 2.34	$P < 0.001$ d = 0.99	$P < 0.001$ d = 0.74
Flexion Moment (%BWH)	6.59 (SD 1.96)	4.39 (SD 1.63)	$P < 0.001$ d = 1.23	7.05 (SD 2.05)	4.48 (SD 1.55)	$P < 0.001$ d = 1.43	$P = 0.175$ d = 0.23	$P = 0.734$ d = 0.06
Extension Moment (%BWH)	3.58 (SD 1.63)	2.03 (SD 0.92)	$P < 0.001$ d = 1.21	3.50 (SD 1.40)	1.80 (SD 0.85)	$P < 0.001$ d = 1.52	$P = 0.783$ d = 0.05	$P = 0.110$ d = 0.27
Abduction Moment (%BWH)	5.13 (SD 1.16)	3.35 (SD 1.01)	$P = 0.052$ d = 1.64	4.53 (SD 1.04)	3.29 (SD 1.06)	$P = 0.021$ d = 1.19	$P = 0.006$ d = 0.54	$P = 0.051$ d = 0.07
Adduction Moment (%BWH)†	1.74 (SD 0.87)	1.50 (SD 0.81)	$P < 0.001$ d = 0.29	2.16 (SD 0.94)	1.77 (SD 0.87)	$P < 0.001$ d = 0.43	$P = 0.002$ d = 0.46	$P = 0.684$ d = 0.32
External Rotation Moment (%BWH)‡	0.62 (SD 0.32)	0.35 (SD 0.23)	$P < 0.001$ d = 1.00	0.76 (SD 0.32)	0.34 (SD 0.21)	$P < 0.001$ d = 1.57	$P = 0.009$ d = 0.44	$P = 0.908$ d = 0.02
Internal Rotation Moment (%BWH)	0.85 (SD 0.28)	0.40 (SD 0.24)	$P < 0.001$ d = 1.74	0.87 (SD 0.27)	0.37 (SD 0.19)	$P < 0.001$ d = 2.13	$P = 0.694$ d = 0.07	$P = 0.439$ d = 0.13

†Sex by group interaction $P = 0.045$
‡Sex by group interaction $P = 0.009$

In the frontal plane (peak external hip adduction and abduction moments), there was a significant sex by group interaction term for the peak external hip adduction moment only (*P* = 0.045). Asymptomatic women had a peak external hip adduction moment that was 13% higher than asymptomatic men (d = 0.54, *P* = 0.002). By contrast (Fig. 2), women with OA had a peak external hip adduction moment that was not different than that of the men with OA (*P* = 0.684). Accordingly, the difference between the peak external hip adduction moment for asymptomatic men compared to men with hip OA was 1.25 %BWH, while the difference between the peak external hip adduction moment for asymptomatic women compared to women with hip OA was 1.77%BWH. In other words, the magnitude of the OA vs. asymptomatic group difference in the peak external hip adduction moment was 43% larger for women than men, as reflected by the statistically significant interaction term. By contrast, the peak external hip abduction moment did not differ between the asymptomatic and OA groups (*P* = 0.073), however the value of this variable was higher for men compared to women in both the hip OA and the asymptomatic groups (*P* = 0.012).

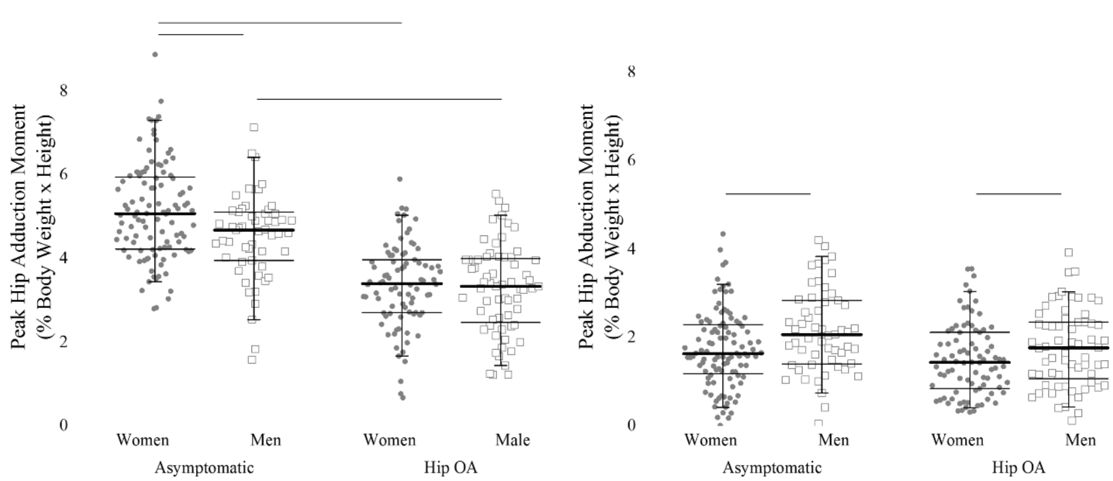

Fig. 2. Peak frontal plane hip external moments for asymptomatic women and men and for women and men with hip OA. Lines represent the median, 25th and 75th percentile; whiskers represent the 5th and 95th percentile. Horizontal lines above data represent pairwise comparisons with $P \leq 0.05$. As a group, asymptomatic women had higher peak adduction moments than asymptomatic men, but this difference was not seen in the hip OA group. There were no other sex-specific group differences.

In the transverse plane (peak external hip external rotation and internal rotation moments) there was a statistically significant sex by group interaction for the peak external hip external rotation moment ($P = 0.009$). The peak external hip external rotation moment (Fig. 3) was lower in asymptomatic women than asymptomatic men (d = 0.43, $P = 0.009$). As with the peak external hip adduction moment, there was no sex difference in the hip OA group ($P = 0.908$). Accordingly, the difference between the peak external hip external rotation moment for asymptomatic men compared to men with hip OA was 0.27%BWH, while the difference between the peak external hip external rotation moment for asymptomatic women compared to women with hip OA was 0.41 %BWH. In other words, the magnitude of the OA vs. asymptomatic group difference in the peak external hip external rotation moment was 34% smaller for women than men, as reflected by the statistically significant interaction term. The peak external hip internal rotation moment was smaller in the OA group vs. the asymptomatic group ($P < 0.001$) and there was no significant sex difference ($P = 0.130$).

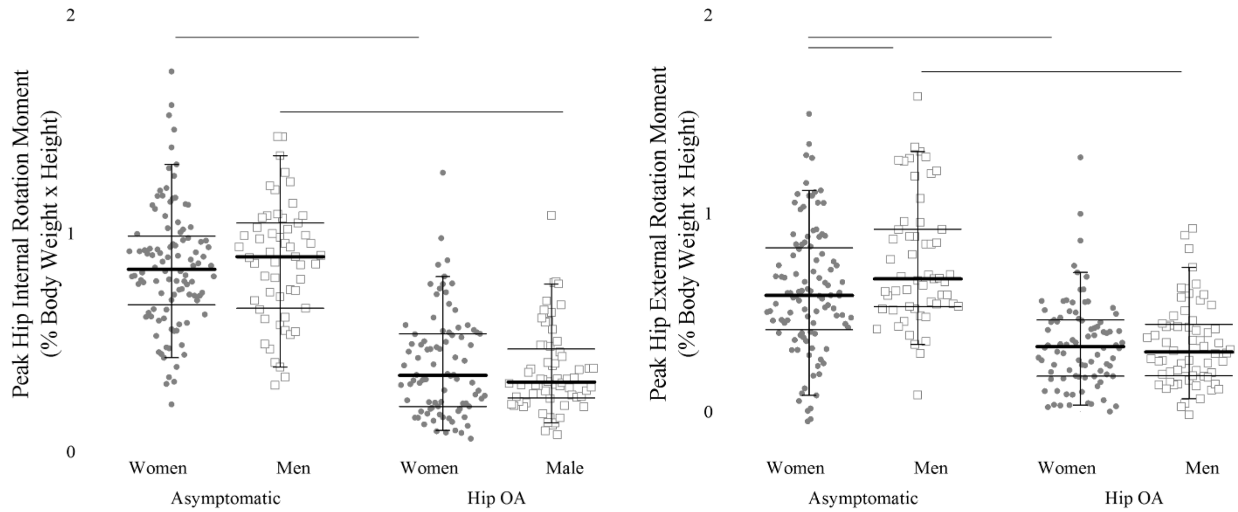

Fig. 3. Peak transverse plane hip external moments for asymptomatic women and men and for women and men with hip OA. Lines represent the median, 25th and 75th percentile; whiskers represent the 5th and 95th percentile. Horizontal lines above data represent pairwise comparisons with P ≤ 0.05. As a group, asymptomatic men had higher peak external rotation moments than asymptomatic men, but this difference was not seen in the hip OA group. There were no other sex-specific group differences.

Within the OA group, radiographic disease severity affected gait variables in men and women in the same way, as indicated by a lack of statistically significant sex by KL grade interactions (P = -0.232 to 0.984). There was a significant main effect of KL grade for all three sagittal plane variables (P < 0.001 to P = 0.022). In all cases, the value of the gait variable decreased with increased radiographic disease severity ($R|_{\text{age, BMI, Speed}}$ = -0.223 to -0.573, P < 0.007). In the frontal plane, there were no statistically significant associations between KL grade and gait variables (P = 0.632 and P = 0.809). In the transverse plane, the peak external hip internal rotation moment decreased with increased KL grade ($R|_{\text{age, BMI, Speed}} = -0.392$, $P < 0.001$) but there was no association with the peak external rotation moment ($P = 0.190$). Sex differences in these models were the same as those described above.

4. Discussion

The purpose of this study was to investigate potential sex differences in gait associated with hip OA. The key finding was that gait differences between asymptomatic men and women were not present in the hip OA group. Specifically, sex-specific gait adaptations were seen in the peak external hip adduction and external rotation moments. Across both the hip OA and control groups, women had higher sagittal plane dynamic hip range of motion and peak external hip extension moments. Men and women did not have different associations between radiographic disease severity and any of the gait variables examined. As in previous reports (Foucher et al., 2012), this analysis confirmed a general apparent unloading (as reflected by reduced peak hip external moments) due to hip OA severity.

In the sagittal plane, sex differences in the OA group mirrored those seen in the asymptomatic group. In both, women had a larger sagittal plane dynamic hip range of motion than men. This finding was in contrast to a publication by Ko and colleagues, who found that men had a larger sagittal plane dynamic hip range of motion than women (Ko et al., 2011b). Ko, however, also found a significant association between age and hip range of motion. This is important because our group was younger than that in the Ko study. Some age-related gait changes are different in men and women (Kobayashi et al., 2016), so this age difference could explain the discrepancy in our findings.

Several studies have identified differences in peak external hip adduction moment between healthy men and women (Boyer, Beaupre, & Andriacchi, 2008, Ko et al., 2011b, Moisio et al., 2003). Here, this expected difference was not present in people with hip OA. Moreover, the OA vs. asymptomatic group difference in the hip adduction moment in women was larger than the group difference in men. To maintain mechanical equilibrium, internal structures must produce an equal and opposite moment to the external moments measured during gait analysis (Andriacchi, Natarajan, & Hurwitz, 2005). Thus, because the hip abductors are able to produce large internal abduction moments about the hip joint, when we measure an external hip adduction moment, we know that there must be an equal and opposite internal abduction moment, and we typically infer that this moment is produced largely by the hip abductors. Therefore the peak external hip adduction moment can be interpreted as a reflection of net dynamic hip abductor demand (Andriacchi, Natarajan, & Hurwitz, 2005). There are several factors that could contribute to modifying the peak external hip adduction moment, and these could potentially differ between men and women. Any factor that alters the magnitude of the ground reaction force or its position relative to the hip center may influence the external moment that is measured. These could include the body weight moment arm, which is typically larger in women due to differences in pelvic geometry or alterations in the base of support during walking (Wesseling et al., 2015). In addition, the external hip adduction moment has been linked to hip contact force in modeling studies of young healthy adults (Giarmatzis et al., 2015), older heathy adults (Wesseling et al., 2015) and people with total hip replacements (Foucher, Hurwitz, & Wimmer, 2009). Thus it may further be speculated that the reductions in the external hip adduction moment may reflect an improved ability of women with hip OA to reduce joint loading compared to men. By this interpretation, the larger difference in women would reflect a beneficial compensation. More work is needed to determine whether or not men and women utilize different mechanisms to alter these frontal plane moments, and to explore the consequences for joint loading.

We further speculate that transverse plane abductor function may be more highly affected by hip OA in men. Based on their anatomical orientation, the hip abductors may also participate in balancing the peak moments in the transverse plane (Flack, Nicholson, & Woodley, 2012, Flack, Nicholson, & Woodley, 2014). Specifically, we know that the peak external hip external rotation moment must be primarily balanced by muscles that are able to internally rotate the hip joint. Based on anatomy and muscle activation patterns, this moment balance is most likely accomplished by the internal rotation function of the anterior portion of the gluteus medius, although other muscles and structures may participate as well. The sex difference seen in the asymptomatic group was not seen in the hip OA group. Moreover the difference in the peak external hip external rotation moment between men with and without hip OA was larger than in women. Again, previous modeling studies have found that the peak external rotation moment is associated with hip contact forces (Foucher, Hurwitz, & Wimmer, 2009). Thus, these findings may also indicate a different strategy in men that seeks to reduce hip loading. Together these findings suggest that the effect of hip OA on hip abductor mechanics during gait may be different in men and women, with more frontal plane influence in women and more transverse plane influence in men. However, it should be noted that the effect on the abductor musculature cannot be distinguished from the other potential biomechanical differences that could affect these gait variables, and that it is not possible to distinguish a harmful effect of OA from a beneficial compensation. It is interesting to note that pre-to-post surgical changes in both of these gait variables are associated with improvements in self-reported function after total hip arthroplasty

(Behery and Foucher, 2014). Future work should assess whether associations with clinical outcomes are also sex-specific.

Because the study relied on an existing dataset, there were several unavoidable limitations. First, some gait abnormalities in the OA group are potentially attributable to pain. Unfortunately pain scores were not available for all subjects in the database. There is some evidence in subjects undergoing total hip arthroplasty, that women typically report more severe pain relative to the radiographic disease stage, than men do.(Holtzman, Saleh, & Kane, 2002, Katz et al., 1994, Lavernia et al., 2011, Novicoff and Saleh, 2011) but this may or may not be the case for subjects with less severe disease and we do not know whether the influence on gait would be the same or different in men and women. Second, subjects with severe radiographic disease were overrepresented in the OA group, particularly in men. The subanalysis suggests that the findings are robust across KL Grades, however, future studies are needed to confirm that sex-differences are not present in earlier disease stages. Finally, because the prevalence of radiographic hip OA exceeds the prevalence of symptomatic hip OA,(Kim et al., 2014, Kim et al., 2015, Lawrence et al., 2008) it is possible that some subjects in the asymptomatic group had radiographic hip OA. Despite these limitations this study is an important first step toward a better understanding of the sex-differences in gait biomechanics seen in men and women with clinical hip OA. Future prospective studies are needed to address the issues raised above.

This work has several implications for future research. It has already been shown that sex-specific gait abnormalities are present in knee OA (Ko et al., 2011a, Phinyomark et al., 2016). These differences has been linked to structural differences (Kumar et al., 2015a). The present study shows that hip OA may also have different biomechanical effects on men and women. Future work should investigate structural links, as at the knee, and links to pain and symptoms. These results suggest that non-surgical, non-pharmacological interventions may require different strategies for men and women. Finally, this study highlights the critical importance of accounting for sex when designing and conducting biomechanical studies involving hip OA.

5. Conclusions

The aim of this secondary analysis was to determine whether or not there are sex-specific gait alterations in people with hip OA. The rationale was that differences in gait between healthy men and women have previously been observed, but we do not know whether these differences are also seen in hip OA. The data showed that normal sex differences in hip mechanics during walking were not present in hip OA. There were no sex-specific differences in sagittal plane range of motion, sagittal plane moments, the peak abduction moment, or the peak internal rotation moments. However, gait kinetics differed in frontal plane gait kinetics in men and women with hip OA. Specifically, when comparing women with hip OA to asymptomatic women, there was a larger difference seen in the peak hip adduction moment, than there was when comparing that variable for men with and without hip OA. The opposite trend was seen with the peak external rotation moment. The OA vs. asymptomatic group difference in this gait variable was larger in men than it was in women. These findings demonstrate that gait kinetics in the transverse and frontal plane associated with hip OA are different in men and women, compared to sex-specific control groups.

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Figure Captions