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Rutherford, D.J., Hubley-Kozey, C.L., Stanish, W.D. (2014). Hip Abductor function in individuals with medial knee osteoarthritis: implications for medial compartment loading during gait. Clinical Biomechanics, 29 545-50.

Background: Hip abductor muscles generate moments of force that control lower extremity frontal plane motion. Strengthening these muscles has been a recent trend in therapeutic intervention studies for knee osteoarthritis. The current study investigated the relationship between hip abductor muscle function (strength and activation) and the net external knee adduction moment during gait in those with medial compartment knee osteoarthritis.

Methods: 54 individuals with moderate knee osteoarthritis walked at their self-selected velocity while gluteus medius electromyograms, segment motions and ground reaction forces were recorded. Net external knee adduction moment (KAM) and linear enveloped electromyographic profiles were calculated. Peak KAM was determined and then principal component analyses (PCA) were applied to KAM and electromyographic profiles. Isometric hip abductor strength, anthropometrics and gait velocity were measured. Multiple regression models evaluated the relationship between walking velocity, hip abductor strength, electromyographic variables recorded during gait and KAM waveform characteristics.

Findings: Minimal peak KAM variance was explained by abductor strength (R^2=9%, *P*=0.027). PCA-based KAM waveform characteristics were not explained by abductor strength. Overall gluteus medius amplitude (*PP1-scores*) was related to a reduction in the bi-modal KAM (*PP3-scores*) pattern (R^2=16%, *P*=0.003).

Interpretation: There was no clear relationship between hip abductor muscle strength and specific amplitude and temporal KAM characteristics. Higher overall gluteus medius activation amplitude was related to a sustained KAM during mid-stance. 84 to 90% of the variance in

KAM waveform characteristics was not explained by hip abductor muscle function showing hip abductor muscle function has minimal association to KAM characteristics.

Key Words: Gait Analysis, Knee Osteoarthritis, Electromyography, Gluteus Medius, Knee Adduction Moment, Hip Abduction Strength,

1. Introduction

Gait mechanics are central to understanding joint loading in knee osteoarthritis (OA) (Andriacchi et al., 2004). Of particular interest is the net external knee adduction moment (KAM), a surrogate measure of medial compartment loading. This moment is highly correlated (R^2=0.77) to *in vivo* medial contact loads (Zhao et al., 2007) where greater magnitudes have been related to medial compartment cartilage and bone defects (Creaby et al., 2010), lower cartilage thickness (Andriacchi et al., 2004; Bennell et al., 2011) and poor clinical outcomes (Wang et al., 1990) in individuals with knee OA. Longitudinal studies have found increased odds of medial compartment structural OA progression associated with higher baseline peak KAM (Miyazaki et al., 2002) and KAM impulse (Bennell et al., 2011). While gait related factors, such as reduced walking velocity have been suggested as a way to reduce peak KAM (Mundermann et al., 2004), a recent focus has been on hip abductor muscle-strengthening protocols as a method to alter gait mechanics, specifically the peak KAM (Foroughi et al., 2011; Sled et al., 2010; Thorp et al., 2010; Bennell et al., 2010). Three studies, including randomized control (Bennell et al., 2010; Foroughi et al., 2011) and clinical trials (Sled et al., 2010), found that hip abductor muscle resistance training improved hip abductor strength and reduced symptoms, but no significant differences were found in the peak KAM during gait.

A paper by Chang et al., (2005) found that greater peak net internal hip abduction moments reduced the odds of medial compartment knee structural progression provided the rationale for the hip abductor strengthening focus. Chang and Mundermann et al., (2005) theorized that low peak hip abductor moments reflected decreased hip abductor muscle strength and hence an inability to control frontal plane hip motion which in turn could impact the KAM by changing the location of the ground reaction force vector. Neither hip abductor activation nor strength was investigated in either study (Mundermann et al., 2005; Chang et al., 2005). While the hip abductors can produce a moment in the frontal plane (Neumann, 2010) and these muscles are active during gait (Rutherford and Hubley-Kozey, 2009; Winter and Yack, 1987), there was no significant relationships found between hip adduction moment features normalized to body mass (Nm/kg) during walking and hip abductor strength or peak activation levels (Rutherford and Hubley-Kozey, 2009). Specifically, 52% of the variance in the initial peak hip adduction moment was explained by walking velocity and no variables in the model explained the mid-stance magnitude. What has not been established however is the link between hip abductor muscle function (strength/activation) and KAM features; two factors considered biomechanical targets for conservative management in individuals with knee OA.

The peak KAM typically occurs during early stance in healthy controls and those with mild to moderate OA, a period of the gait cycle where the gluteus medius (GM) is most active (Rutherford and Hubley-Kozey, 2009; Winter and Yack, 1987; Semciw et al., 2013). These muscles are also activated during mid-stance, a period of gait characterized by single-leg stance. Typically, mid-stance knee adduction moment amplitudes reduce or “unload” (Newell et al., 2008) a feature not evident for those with severe OA (Rutherford et al., 2008) and more recently found to be associated with progression to total knee arthroplasty (Hatfield et al., 2013). Whether hip abductor muscle strength or GM activation features are related to dynamic KAM features during specific phases of the gait cycle has not been established. Despite this equivocal evidence, exercise programs, which include hip abductor strengthening, are recommended in knee OA rehabilitation (Fernandes et al., 2013). Determining whether hip abductor muscle function (strength and/or activation) relate to the KAM dynamic waveform characteristics would shed light on its potential effectiveness as a biomechanical target for conservative management.

The present study investigated the relationship between hip abductor muscle function (strength and activation) and KAM characteristics during gait in individuals with knee OA. The objectives were two fold. To determine the contribution of hip abductor strength, GM activation patterns captured during self-selected gait, and gait velocity to the variance in i) the peak KAM and ii) the KAM waveform features derived from principal component analysis. Based on the current literature, we hypothesize that hip abductor strength will not explain a significant portion of the variance in the peak KAM or magnitude characteristics from PCA. We also hypothesize that GM activation amplitudes and temporal patterns will be associated with KAM amplitudes and temporal patterns.

2. Methods

2.1 Subject Selection

Participants with unilateral symptomatic knee OA (n=54) were recruited from the caseload of one orthopedic surgeon (WDS). Knee OA was diagnosed using the American College of Rheumatology guidelines (Altman, 1991). Standard anterior/posterior radiographs confirmed predominant medial compartment radiographic disease presence and were scored using the Kellgren-Lawrence global scoring scale (Kellgren and Lawrence, 1957). All participants met a functional status based on self-report ability to i) reciprocally ascend and descend 10 stairs, ii) safely walk one city block, and iii) jog five meters and were not candidates for total knee arthroplasty (Hubley-Kozey et al., 2006). Participants were over 40 years of age, had no previous injury other than a sprain or strain and were excluded if cardiovascular/respiratory disease or neurological disorders were present that affected their ability to complete the data collection protocol safely. Written informed consent was provided in accordance with the Research Ethics Board.

2.2 Gait Analysis

Height and mass were recorded. Circular electrodes (Ag/AgCl, 10 mm diameter, 0.79cm^2 surface area, 20 mm inter-electrode distance) were placed in a bipolar configuration on the skin in the direction of GM muscle fibers based on SENIAM guidelines (Surface Electromyography for the Non-Invasive Assessment of Muscles), after lightly shaving and cleaning with isopropyl alcohol wipes. A reference electrode was placed on the anterior tibia shaft. Ipsilateral and contralateral isometric hip abduction in single leg stance was performed for validation of electrode placement to evaluate crosstalk (Winter et al., 1994) and to set appropriate gains to maximize signal amplitude. At least 20 minutes elapsed before recordings were made. Electrodes, pre-amplifiers and lead wires were further secured with adhesive tape and Lycra/spandex shorts.

Infrared emitting diode (IRED) skin surface markers were affixed to the lateral aspect of the lower extremity. This marker cluster and the motion capture procedures have been previously described (Landry et al., 2007). Triangular sets of IRED markers were secured to the foot, tibia, femur and pelvis. Single IRED skin surface markers were placed on the lateral malleolus, lateral epicondyle of the femur, greater trochanter and the lateral aspect of the shoulder. After a standing calibration trial, the digitization of eight virtual points on predefined anatomical landmarks was completed, including right and left anterior superior iliac spines, medial epicondyle of the femur, fibular head, tibial tuberosity, medial malleolus, base of the second metatarsal and center of the posterior calcaneus.

Lower extremity motion during gait was captured in three-dimensions at 100Hz using two optoelectronic motion analysis sensors (Optotrak™, Northern Digital Inc., Waterloo, ON, Canada). Three-dimensional ground reaction forces were recorded from a single force plate (AMTI™, Advanced Mechanical Technology Incorporation, Newton, MA, USA) at 1000Hz that was aligned to the global coordinates of the motion capture system. The electromyogram of GM was recorded using an AMT-8 (Bortec, Inc., Calgary, AB, Canada) eight channel EMG measurement system (Input Impedance: ~10GΩ, CMRR: 115dB at 60 Hz, Band-pass (10-1000 Hz)). All EMG signals were analog to digitally converted at 1000Hz (16bit, +/- 2V) using the analogue data capture feature of the Optotrak™ system and stored for processing.

Participants were instructed to walk at their self-selected velocity along a six-meter walkway. After three familiarization trials, at least five walking trials were collected. Velocity was monitored during the data collections with a photo-electric timing component, positioned at known distances on the walkway. Walking trials that differed by greater than 10% of average self-selected speed were re-collected. Velocity was calculated for the analysis using marker positional data at the time of force plate contact and gait cycle completion.

2.3 Hip abductor strength and electromyogram amplitude normalization

Hip abductor strength and maximal GM activity were measured using two maximal voluntary isometric contractions (MVIC). A Cybex™ Isokinetic dynamometer (Lumex, NY, USA) recorded the isometric torque produced by the hip abductor musculature. Participants were positioned in side-lying on a secure, height adjustable exercise table (Rutherford and Hubley-Kozey, 2009). On a small subset (n=19) of the larger sample, which completed testing on two occasions within approximately one month, we found excellent between-day (average five weeks) reliability for this exercise ($ICC_{2,1}$= 0.91 (95% CI = 0.79, 0.97)). The lever arm pad was positioned and secured on the distal femur. After one practice trial and gravity correction trial, two maximum isometric hip abduction trials were collected, separated by a 60-second rest period. Participants were instructed to abduct their lower limb into the lever arm pad and hold for three-seconds while minimizing movement in the sagittal and transverse plane. Standardized instructions and verbal encouragement were given to maximize effort.

2.4 Data Processing

Data processing was completed using custom programs written in MatLab™ version 7.1 (The Mathworks Inc., Natick, MA, USA). Technical and local anatomical bone embedded coordinate systems for the thigh, tibia and foot were derived from the skin surface markers and digitized points (Cappozzo et al., 1997). Joint angles were specified through Euler/Cardan rotation methods (Grood and Suntay, 1983). The knee joint center was estimated as midway between the medial and lateral femoral epicondyles (Landry et al., 2007). Net external KAM was calculated using an inverse dynamics model, which combines ground reaction force and moment data, kinematic positional data, limb anthropometrics and inertial properties (Vaughan et al., 1999). Net external moments were projected into a non-orthogonal joint coordinate system (i.e. adduction axis was considered a floating axis between the embedded lateral-medial axis in the distal femur and embedded distal-proximal shank axis) (Grood and Suntay, 1983). The KAM was amplitude normalized to body mass (Nm/kg) (Landry et al., 2007).

GM activity was pre-amplified 500x and then further amplified to best utilize the dynamic range of the data collection hardware. Raw signals were visually inspected to ensure quality recordings, corrected for gain, subject bias to represent muscle activity at the level of the skin. All corrected signals were full-wave rectified and low-pass filtered (Butterworth 6-Hz, 4^{th} order low pass filter) (Hubley-Kozey et al., 2006). A 100-ms moving window algorithm (99ms overlap) identified the maximal EMG amplitude for each MVIC trial to amplitude normalize walking trial EMG data. All waveforms were time normalized to represent 100 percent of the gait cycle using a cubic spline interpolation.

Maximum hip abduction strength was determined using a static model that included torque generated by leg weight from the gravity correction trial and the torque recorded by the dynamometer during the MVIC. A 500-ms moving window algorithm (no overlap) was employed to capture the maximum torque generated over the three-second steady state contraction. The average torque between the two trials was recorded as hip abductor strength.

2.5 Analysis

Peak KAM and peak GM amplitude were identified from all waveforms. Principal component analysis (PCA) was applied to capture amplitude and temporal KAM features and

GM electromyograms using custom MatLab™ Ver.7.1 programs (The Mathworks Inc., Natick, Massachusetts, USA). Two separate PCA were performed, consistent with previous knee OA electromyogram (Rutherford et al., 2010; Hubley-Kozey et al., 2006) and biomechanics analyses (Rutherford et al., 2008). An eigenvector decomposition of a cross product matrix ($[S] = [X^T]*[X]$) (GM) and a covariance matrix (KAM) was performed, using standard notation U'SU=L, yielding the predominant orthonormal components called eigenvectors ([NO STYLE for: Jackson 1991]). Reliability for these analyses has been determined (KAM PP's ($ICC_{2,k}$ = 0.93-0.94) (Robbins et al., 2013), GM PP's ($ICC_{2,k}$ = 0.73-0.85). For this report, these eigenvectors will be referred to as principal patterns. Principal patterns that together explain the greatest percent of variation in the waveforms (>90%) based on the percent trace were retained and referred to as PP1, PP2 and PP3 (Hubley-Kozey et al., 2006; Rutherford et al., 2008). Principal pattern scores (*PP-Scores*) were computed for individual gait waveforms in each separate analysis (*PP-Score* = [X]*[U]). The *PP-score* is a weighting coefficient of how each principal pattern related to each measured waveform.

2.6 Statistical Analysis

Four forward stepwise regression models (p_{in} = 0.1, p_{out} 0.1) were employed. Response variables included the peak KAM (Nm/kg) and the three KAM (Nm/kg) principal patterns. Six explanatory variables were included in each model. These variables were walking velocity (m/s), peak GM activity (% MVIC), hip abductor strength (Nm/kg) and three GM principal patterns. Variance inflation factors were used to assess multi-collinearity and the suitability of the regression model was evaluated by examining the plots of the residuals against the predicted values. Significance was determined by alpha = 0.05. All statistical analyses were computed on Minitab™ V.16 (Minitab Inc. State College, PA, USA).

3. Results

Demographics, hip abductor strength and gait characteristics for the 54 participants are shown (Table 1). The average peak net external knee adduction moment was 0.58 Nm/kg (Fig. 1). GM activity peaked at 70 percent MVIC (Table 1). During mid to late stance (30 – 60 percent of the gait cycle), activity was sustained at approximately 30% MVIC (Fig. 1).

Three principal patterns explained >90% of the KAM waveform variability. PP1 captured overall shape and magnitude, explaining 55.1% variability. The second pattern captured a difference operator between early to mid-stance (0-50% stance) and mid to late stance (50-100% stance), explaining 22.1% variability. A high *PP2-score* indicates a greater difference. PP3 captured the mid-stance amplitude with respect to early and late stance, explaining 7.8% variability respectively. High *PP3-score* indicated lower mid-stance amplitude with respect to early and late stance (Rutherford et al., 2008)(Fig.2). For GM activation, three principal patterns together explained 97.5% variability (Fig.3). PP1 captured the overall magnitude and shape, explaining 93.6% variability. PP2 captured a difference operator between early and mid to late stance, explaining an additional 2.6% variability. The third principal pattern, a difference operator between heel strike, early and mid to late stance, explained 1.3% variability.

Nine percent of the variability in the peak KAM (Nm/kg) was explained by hip abductor strength (Nm/kg) (P=0.027). This relationship was positive (Fig. 4). No variables explained significant variability in the KAM PP1 model. Walking velocity explained 52% of the variability in the KAM *PP2-scores* ($P<0.001$). The relationship was positive, indicating a greater difference between early and mid to late stance KAM was associated with faster walking speeds. No amplitude or temporal GM features explained significant variance in this KAM PP2 model. GM *PP2-scores* were however related to walking velocity ($r=-0.557$) and thus they were not included in the overall KAM PP2 model. Greater GM activity early in stance and lower activity later in stance (lower GM *PP2-scores*) was related to faster walking velocities.

The magnitude of GM (*PP1-scores*) explained significant variability in the KAM *PP3-scores* ($R^2=16\%$, $P=0.003$). This relationship was negative, indicating that greater GM amplitudes were related to greater mid-stance KAM amplitudes with respect to early and late stance (lower *PP3-scores* - indicative of a reduction in the bimodal KAM pattern) (Fig. 2 & 4).

4. Discussion

Minimal relationships between hip abductor muscle function and KAM characteristics during gait found in this study for individuals with knee OA provides a plausible biomechanical explanation for the lack of effect on knee joint mechanics found in large-scale interventional studies targeting hip abductor strengthening (Foroughi et al., 2011; Sled et al., 2010; Bennell et al., 2010). Consistent with our hypothesis, minimal KAM waveform variance (peak, overall magnitude and temporal characteristics) was explained by hip abductor strength. Regarding our second hypothesis, overall GM shape and activation amplitudes (PP1) did explain 16% percent of the KAM waveform feature that identified mid-stance unloading with respect to early and late stance (*PP3-scores)*. While representing a small percentage of the total variability, this suggests that working at a higher percentage of maximum is related to a reduced ability to lower the KAM during mid-stance.

Moderate knee OA group demographics and gait characteristics were similar to previously reported values. Gait velocity was consistent with previous reports (Mundermann et al., 2005; Hubley-Kozey et al., 2006). Compared to our previous work in asymptomatic individuals, isometric hip abductor strength (Nm/kg) was approximately 16% lower in this moderate OA group. Others have reported a 25% difference between individuals with knee OA and an asymptomatic cohort (Hinman et al., 2010). This suggests that as a percentage of body mass, individuals with moderate knee OA have hip abductor strength deficits. The KAM was consistent with previously presented data for individuals with moderate knee OA in shape (Mundermann et al., 2005; Baliunas et al., 2002; Rutherford et al., 2008) and in amplitude (Rutherford et al., 2008). GM waveforms had similar amplitudes as asymptomatic individuals (Rutherford and Hubley-Kozey, 2009; Semciw et al., 2013) however; a distinct burst of activity during mid-stance was not as evident in the knee OA sample.

The positive association of hip abductor strength with peak KAM magnitudes in individuals with moderate knee OA does not support previous theories that individuals with greater hip abductor strength have lower peak medial compartment loading during gait. Interesting, walking velocity was not a significant explanatory variable for peak KAM, which contrasts previous findings (Mundermann et al., 2004) however, KAM PP2 captured a difference between early and mid to late stance magnitudes and was explained by walking velocity only, which is consistent with previous studies (Landry et al., 2007; Rutherford et al., 2008). Together, percent variability explained in the peak KAM was similar for hip abductor strength (9%) and walking velocity (R^2=7%, not significant), and the positive association suggests that increasing strength and walking faster would increase the peak KAM. Regarding the KAM *PP2-scores*, these findings support a greater difference between early and mid to late stance magnitudes occurs with faster walking speed. This low percent variance explained in peak KAM (9%) by hip abductor strength, helps to explain findings from three recent hip strengthening interventional studies (Foroughi et al., 2011; Sled et al., 2010; Bennell et al., 2010) where increasing hip abductor strength had no effect on peak KAM magnitudes. Bennell et al., (2010) found that the strengthening group showed a tendency (p=0.19) towards increased peak KAM (~4.6%), which is consistent with the positive relationship that was found in the current study.

While GM activation patterns did not explain significant variability in peak KAM, the overall magnitude and shape (PC1) did explain significant variability in the dynamic KAM unloading characteristic (PC3), which captures mid-stance amplitude relative to early and late-stance (Astephen et al., 2008; Newell et al., 2008; Rutherford et al., 2008). In this study, lower scores indicate a reduced difference (i.e. higher mid-stance amplitudes with respect to early and late stance (Fig.2)). Overall mid-stance unloading with respect to early and late stance was associated with less GM overall activity. This relationship could be interpreted as a strength difference as hip abductor strength explained 10% of the *PP1-scores* (negative), however this low variance explained (16%), suggests that the relationship cannot be entirely explained by muscle strength. Possibly those with higher GM activation, who do not unload during mid-stance (low *PP3-scores* – Fig. 2) require more hip abductor activity during stance to stabilize the lower extremity. As mentioned above, the OA group GM activation waveform shape did not have a bimodal pattern as was previously found for asymptomatic individuals using surface (Rutherford and Hubley-Kozey, 2009) and fine wire techniques (Semciw et al., 2013) but had more sustained activity during mid-stance (Fig. 3). This suggests that the role of GM during gait, particularly during mid stance may be different between asymptomatic individuals and those with moderate knee OA.

The interpretation of the results needs to be done within the limitations of the study. There is often concern for validity and reliability of both strength and maximal activations in those with joint pathology. A Cybex™ dynamometer quantified hip abductor muscular strength and maximal activation in an attempt to reduce investigator influence on strength measures that result from hand-held devices and to improve patient control and stability and we found excellent between-day reliability for this exercise. This corroborates the work of Widler et al., (2009) where the side-lying position was most valid and reliable for assessment of unilateral hip abductor strength. EMG recordings from this position are also reliable (Bolgla and Uhl, 2007) and of higher amplitudes (Cynn et al., 2006) when compared to other positions. While the current hip abductor strength findings (Nm/kg) were greater than previously found for individuals with knee OA (Hinman et al., 2010) differences between asymptomatic individuals (Rutherford and Hubley-Kozey, 2009) and those with moderate knee OA of the current study using the same protocol were comparable to this previous work. Finally, the KAM inverse dynamic models used established equations (Vaughan et al., 1999). Anthropometric measures were standardized (i.e. foot width, calf and thigh circumferences and limb segment lengths based on IRED and digitized data), as were the placements of skin surface markers for knee joint center calculations. Reliability for these analyses has been determined previously (KAM PP's ($ICC_{2,k}$ = 0.93-0.94) (Robbins et al., 2013) thus, we are confident in our KAM calculations for this analysis.

In summary, hip abductor strength was positively associated with peak KAM whereas higher overall GM activation amplitudes were related to higher relative KAM magnitudes during mid-stance. The first hypothesis of the study was not supported as contrary to previous hypotheses, greater peak KAM was significantly related to greater hip abductor strength. The second hypothesis was partially supported. As shown in Figure 4, individuals with greater GM activation had greater mid-stance KAM amplitudes with respect to early and late stance (i.e. the knee adduction moment was not the typical bi-modal pattern)

The variance explained was low overall; hence the relationship between hip abductor function and frontal plane mechanics was not strong. Although current guidelines suggest hip abductor strengthening exercises for those with medial knee OA, the present findings are consistent with interventional studies that did not find decreased KAM peaks. They do not rule out potential benefits on joint unloading, symptom or structural progression. Furthermore, subpopulations may exist where hip abductor strengthening should be indicated, suggesting a patient specific approach. To develop and evaluate clinical interventions that target individuals with knee OA requires an understanding of the biomechanical and neuromuscular features that contribute to the local knee joint mechanical environment. While our knowledge of knee OA joint mechanics and muscle activation is increasing, no papers that have examined hip abductor function (strength and activation) and its relationship to the KAM in individuals with knee OA despite previous work suggesting a link.

5. Conclusion

This study showed that hip abductor muscle strength and GM activation features did explain small, but significant variability in KAM peak and unloading features respectively during self-selected gait in individuals with moderate knee OA. However, for the peak KAM over 90% of the variance was not accounted for by hip muscle strength. GM activation explained slightly higher (16%) variance in the dynamic feature of the KAM that captured the ability of participants to unload during mid-stance. Higher GM activation was associated with decreased mid-stance unloading but 84% of this KAM feature variability was not explained by hip abductor activation. Therefore, these results provide a plausible explanation as to why hip abductor strengthening exercises have not consistently altered the peak knee adduction moment, but perhaps further exploring the effect of hip abductor strength/function on the ability to alter loading patterns might shed light on why symptoms improve with hip strengthening exercise.

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Conflict of Interest

The authors acknowledge that there are no conflicts of interest pertaining to this manuscript.

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Table 1: Demographic and gait characteristics of the sample [mean (SD)]

Demographics	
N	54
Female (%)	30
Age (yrs)	58 (10)
Mass (kg)	90.2 (18)
Height (m)	1.73 (0.08)
Body Mass Index (BMI)	30.2 (4.8)
Hip Abductor Strength (Nm/kg)	1.12 (0.27)
Kellgren Lawrence Grade (n)*	
I	9
II	15
III	13
IV	9
Gait characteristics	
Gait velocity (m/s)	1.24 (0.17)
Peak knee adduction moment (Nm/kg)	0.58 (0.14)
Peak GM (% MVIC)	70 (25)

* 8 participants did not have radiographs available for grading.

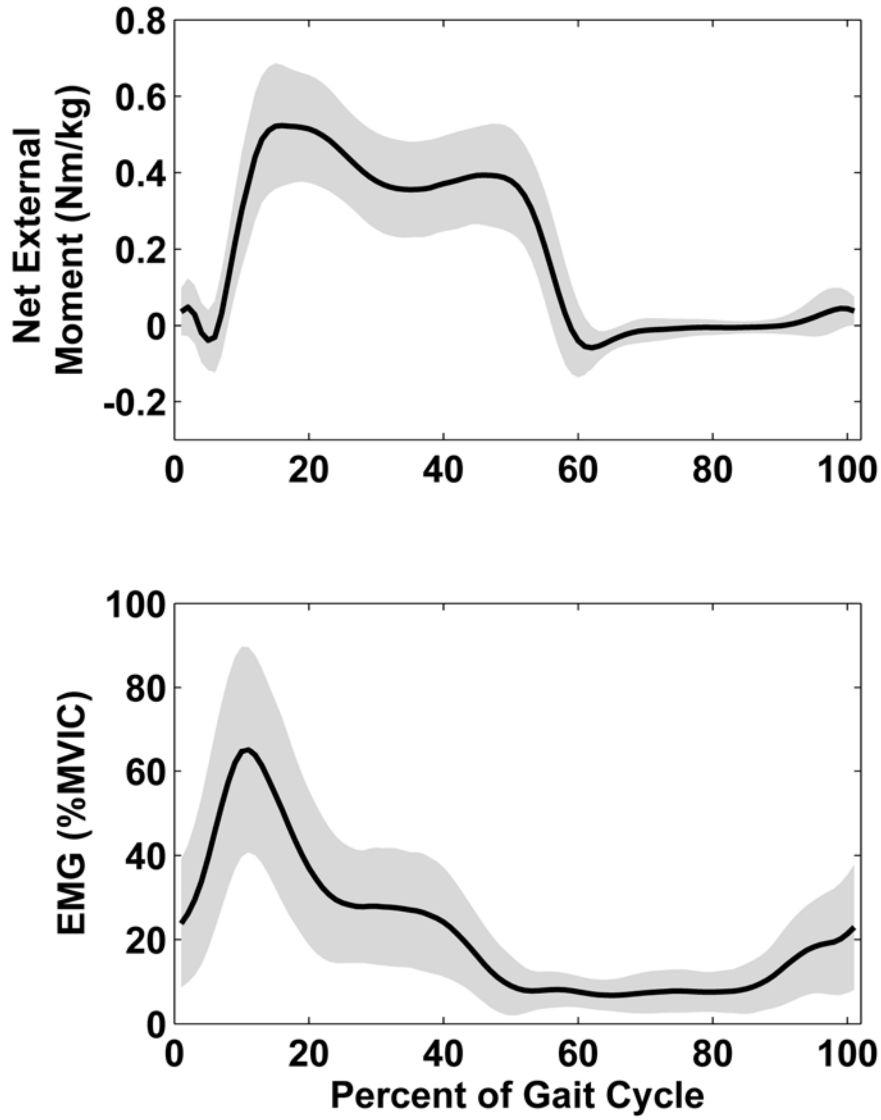

Figure 1: Top Panel) Net external knee adduction moment waveform, amplitude normalized to body mass (Nm/kg). Bottom Panel) Gluteus medius electromyogram, amplitude normalized to a percentage of MVIC. Ensemble average waveforms are time normalized to one gait cycle. Shaded area represents one standard deviation above and below the mean.

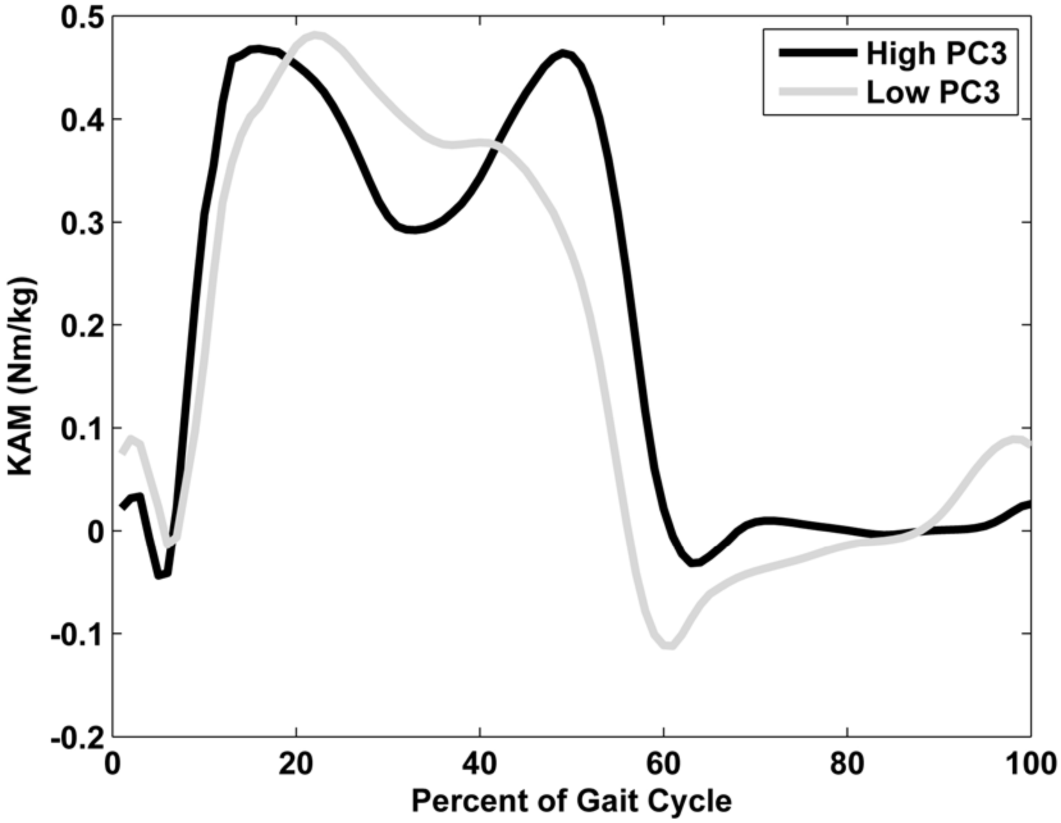

Figure 2: The average of five KAM waveforms representing individuals with high and low KAM *PP3-scores*.

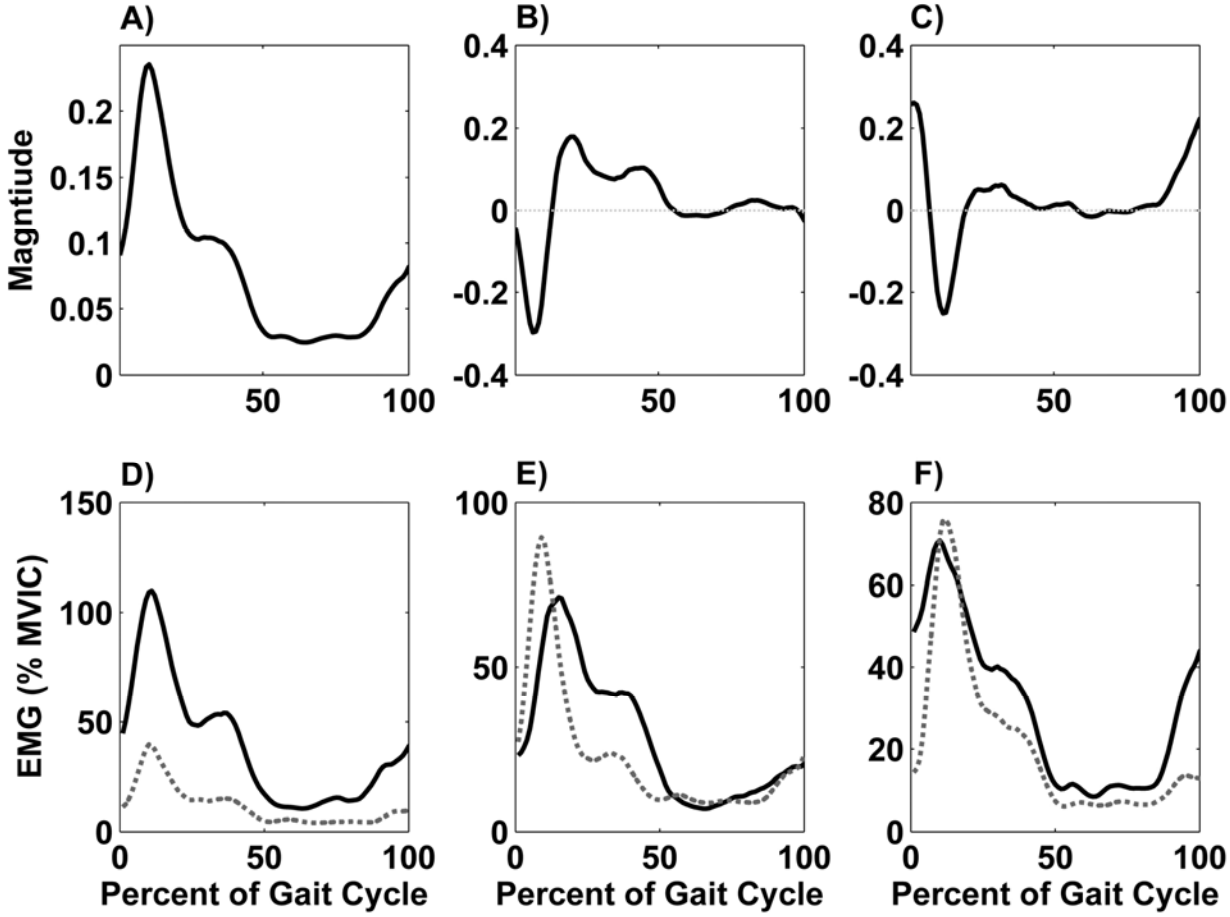

Figure 3: Gluteus medius principal patterns: A) PP1 captured overall amplitude and shape, explaining 93.6% of the variability, B) PP2 a difference operator between early and mid to late stance, explained 2.6% of the variability C) PP3 a difference operator between heel strike, early and mid to late stance, explaining 1.3% of the variability. The average of five GM waveforms (% MVIC) representing individuals with high and low *PP-scores* for PP1 (D), PP2 (E) and PP3 (F).

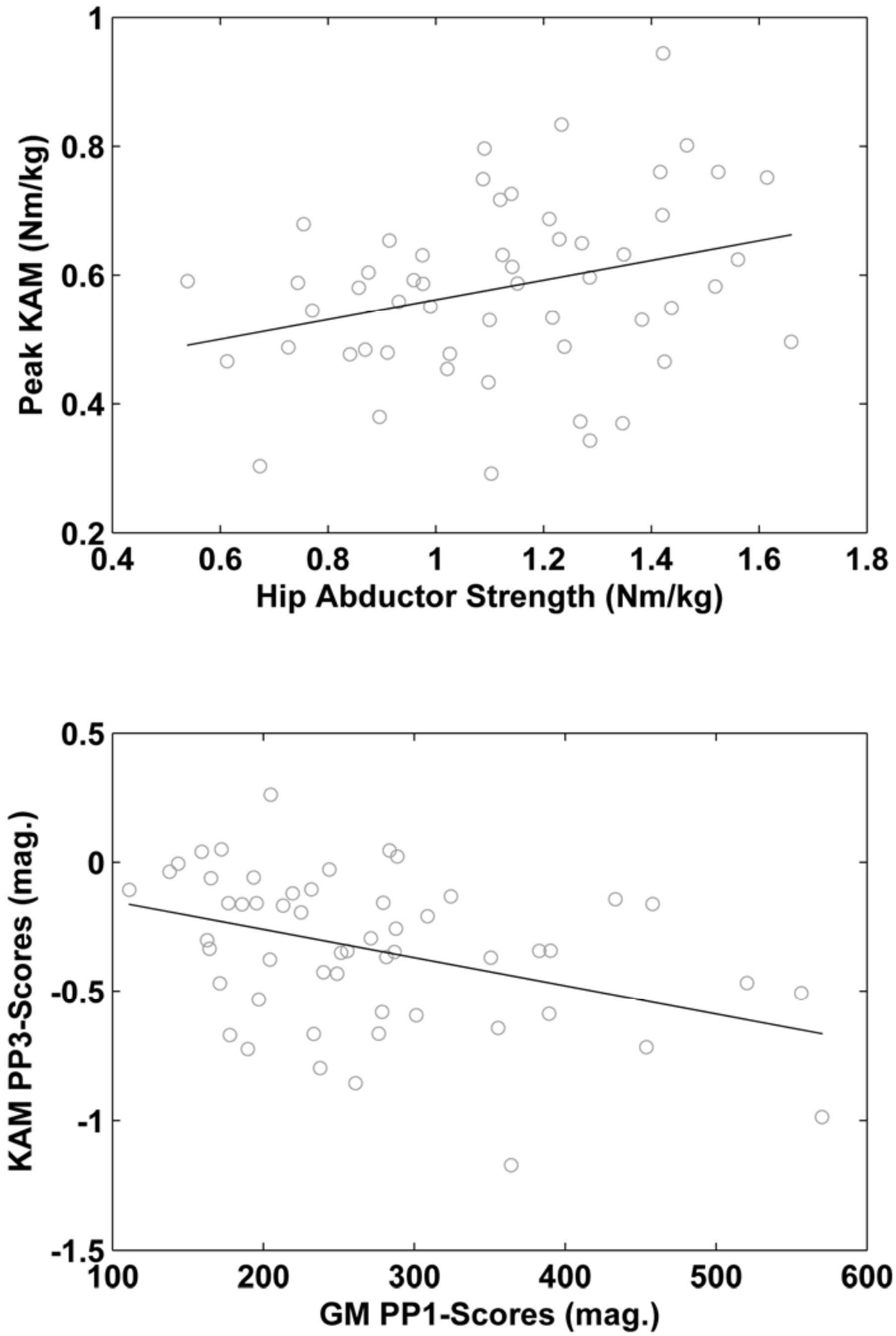

Figure 4: Top Panel) the association between hip abductor strength and the peak net external knee adduction moment normalized to body mass r=0.3, *P*=0.027. Bottom Panel) the association between gluteus medius *PP1-scores* (overall magnitude and shape) and net external knee adduction moment *PP3-scores* (difference operator of mid-stance amplitude with respect to early and late stance) r=0.4, *P*=0.003. Greater gluteus medius *PP1-scores* indicate greater overall amplitude. Greater knee moment *PP3-scores* indicate greater difference between mid-stance amplitude with respect to early and late stance.