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Purpose: To determine whether alterations in knee joint muscle activation patterns during gait were related to structural severity determined by Kellgren-Lawrence (KL) radiographic grades, for those with a moderate knee OA classification.

Scope: Eighty-two individuals with knee OA, classified as moderate using a functional and clinical criterion were stratified on KL-grade (KL II, KL III and KL IV). Thirty-five asymptomatic individuals were matched for age and walking velocity. Lower limb motion and surface electromyograms from rectus femoris plus lateral and medial sites for the gastrocnemii, vastii and hamstring muscles were recorded during self-selected walking. Gait velocity and characteristics from sagittal plane knee angular displacement waveforms were calculated. Principal component analysis extracted amplitude and temporal features from electromyographic waveform. Analysis of variance models tested for main effects (group, muscle) and interactions (α=0.05) for these features. No differences in anthropometrics, velocity, knee muscle strength and symptoms were found among the three OA groups ($p>0.05$). Specific features from medial gastrocnemius, lateral hamstring and quadriceps amplitude and temporal patterns were significantly different among OA groups ($p<0.05$).

Conclusions: Systematic alterations in specific knee joint muscle activation patterns were associated with increasing structural severity based on KL-grades whereas other alterations were associated with the presence of OA.

Introduction

Knee osteoarthritis (OA) is a leading contributor to chronic morbidity in older adults and is costly to North American health care systems [Badley and DesMeules 2003; Kotlarz et al, 2009]. There is no cure and with the demand for total knee arthroplasty projected to increase exponentially [Kurtz et al, 2007], researchers are motivated to understand the knee OA process and identify mechanisms to delay progression [Lane et al, 2011]. Passive joint structures are the primary tissues impaired with the knee OA process [Altman 1991; Kellgren and LAWRENCE 1957], including articular cartilage lesions, joint margin and tibial spine osteophytosis, subchondral bone sclerosis, and bone attrition. Changes to joint structures from radiographic evaluation are used to diagnose (presence of osteophytes) [Altman 1991; Kellgren and LAWRENCE 1957] and monitor OA progression (joint space narrowing) [Ornetti et al, 2009]. While these features have been central to defining OA, alterations to other joint structures (i.e. muscles, nerves) are apparent [Brandt et al, 2008] and can impact function and clinical status.

Studies have reported alterations in biomechanical variables during functional tasks such as walking with knee OA, such as less knee flexion excursion during early stance, reduced early stance knee flexion moments and altered knee adduction moments [Heiden et al, 2009; Landry et al, 2007; Lewek et al, 2004]. Biomechanical changes are also associated with increased disease severity [Astephen et al, 2008b]. Fewer studies have examined muscle activation patterns. The interrelationship between passive osteoligamentous, muscular and the neural systems is fundamental to joint function, as muscle forces create moments of force that produce motion and maintain joint stability [Panjabi 1992; Solomonow and Krogsgaard 2001]. Thus, impairments to any one system will affect the other systems to maintain joint function.

Recent surface electromyographic (EMG) studies have found subtle alterations in muscle activation during walking in individuals with mild to moderate medial compartment knee OA compared to asymptomatic controls [Hubley-Kozey et al, 2006; Lynn and Costigan 2008; Zeni et al, 2010], with larger differences for more severe OA [Hubley-Kozey et al, 2009; Rutherford et al, 2011b] compared to asymptomatic controls. Alterations in the EMG patterns such as medial and lateral muscle site imbalances and increased agonist/antagonist co-activation were thought to be responses aimed to reduce medial compartment loading or improve joint stability. The few studies that have examined muscle activation characteristics across knee OA groups compared samples that were heterogeneous on more than one factor such as structural severity, pain, walking velocity and clinical characteristics [Astephen et al, 2008b; Hubley-Kozey et al, 2009; Rutherford et al, 2011b; Zeni et al, 2010]. Thus understanding how individual factors contribute to changes in muscle activation characteristics is difficult.

Only one study examined structural severity in a moderate OA group defined by clinical status and function with a range of radiographic severity [Astephen Wilson et al, 2011]. A significant association between severity, based on a proprietary visual analogue score of structural severity from radiographs and the overall knee adduction moment magnitude (R^2=21%) was found but no significant relationships with knee joint muscle activation patterns. Muscle activation patterns were however related to pain scores. Although visual analogue scores were correlated to the standardized Kellgren-Lawrence (KL) grade, 60% of the variance was not explained, limiting the conclusions on whether progressive increases in specific structural impairments are related to muscle activation patterns could not be made. The present study aimed to further evaluate the relationship between muscle activation patterns and structural severity using the standard radiographic scale that systematically graded osteophytes and joint

space narrowing as both variables are thought to influence knee joint muscle activation [Lewek et al, 2004; Zeni et al, 2010]. Understanding this relationship has the potential to provide objective metrics that can complement knee OA diagnosis and monitor progression of structural impairments. Furthermore, examining these relationships during functional tasks such as walking may shed light on limitations in functional activities such as walking with increased OA severity.

The main purpose was to determine whether alterations in knee joint muscle activation patterns were associated with structural severity by examining an asymptomatic (non-OA) group and a knee OA group, that was homogeneous with respect to knee OA clinical treatment (non-surgical) and functional limitations, yet a wide spectrum of structural impairments based on KL-grades. We hypothesized that increased structural impairment would result in systematic changes in knee joint muscle activation patterns during walking.

Materials and Methods

Participants

Participants with knee OA were recruited from local orthopaedic clinics over the period of 2003-2010. Knee OA was determined using the American College of Rheumatology clinical and radiographic criteria [Altman 1991]. Participants were, required to meet a functional status, consistent with a previous moderate OA classification [Hubley-Kozey et al, 2006], and were clinically managed using non-surgical interventions.

Asymptomatic participants were recruited from the general community using email, website and poster board advertisements from 2003-2007. These individuals had no lower

extremity injuries within six months prior to data collection, no symptoms of lower extremity degenerative joint disease or fracture and no prior knee surgery. Seventy-seven asymptomatic individuals were identified, and a subset was matched to the knee OA group based on age and walking velocity.

All participants were required to be 35 years of age or older, have no cardiovascular/respiratory disease or neurological disorders, fracture or injury other than a sprain or strain (within one-year) or major injury or knee joint surgery. The protocol was approved by the local institutional ethics review committee and participants provided written informed consent.

Standard weight-bearing anterior-posterior and lateral radiographs were acquired for each participant with knee OA. Radiographs were graded using the KL ordinal radiographic scale [Kellgren and LAWRENCE 1957] by a single, experienced reader (WDS) as recommended by Vignon et al., [1999]. The reader was blinded to participant identification and gait analysis outcomes. Participants with lateral joint space narrowing greater than medial joint space narrowing were excluded. Fair to good reliability for this assessment has been previously reported (ICC=0.59, 95% CI (0.42-0.74)) [McKean et al, 2007].

Procedures

Western Ontario McMaster Osteoarthritis questionnaire (WOMAC-LK3.1) was completed by all participants with knee OA. The most symptomatic lower extremity was tested in participants with knee OA and the tested leg was randomly assigned for asymptomatic individuals. Consistent with guidelines [SENIAM 1999], standard skin preparation and

placement of surface electrodes (Ag/AgCl, 10 mm diameter, 20 mm interelectrode distance, (Meditrace, Tyco Health Care Group, Mansfield, MA, USA)) in a bipolar configuration over vastus medialis (VM), vastus lateralis (VL), rectus femoris (RF), semitendinosis/membranosis (MH), biceps femoris (LH), lateral gastrocnemius (LG) and medial gastrocnemius (MG) was completed [Hubley-Kozey et al, 2006]. Muscle palpation and standard contractions were used to validate electrode placement and for setting appropriate gain adjustments. EMG signals were amplified using an AMT-8 (Bortec, Inc., Calgary, Alberta, Canada), eight-channel EMG system (Input Impedance: ~10GΩ, CMRR:115dB at 60 Hz, Band-pass (10-1000 Hz)), analogue to digital converted at 1000Hz (16bit, +/-2V) and stored for processing.

Triangular sets of infrared emitting diode (IRED) skin markers were secured to the pelvis, femur, tibia and foot. Single IRED skin surface markers were placed on the lateral malleolus, femoral lateral epicondyle and greater trochanter and lateral aspect of the shoulder. Eight virtual landmarks were also digitized [Landry et al, 2007]. Marker motion was captured in three-dimensions at 100Hz using two, optoelectronic motion analysis sensors (Optotrak™, Northern Digital Inc., Waterloo, ON, Canada) and used to calculate knee joint angles and gait velocity. Marker motions in combination with three-dimensional ground reaction forces, captured at 1000Hz, from a single force plate (AMTI™, Advanced Mechanical Technology Incorporation, Newton, MA, USA) embedded in the walkway were used to identify heel strike and toe off events for waveform time normalization.

Data Acquisition

After three familiarization trials, participants were instructed to complete at least five walking trials at a consistent self-selected velocity along a six-meter walkway. Trials were included if they were within 10% of their self-selected speed. After the walking trials, a baseline recording was made while participants lay supine. A series of eight standardized exercises to elicit maximal voluntary isometric contraction (MVIC) efforts were used for normalization purposes [Hubley-Kozey et al, 2006; Rutherford et al, 2011a]. Following at least one practice and warm-up contraction, two, three-second maximal isometric contractions were completed for each exercise. A minimum 60-second rest period separated each contraction, and standardized verbal encouragement was given.

Data Processing

Raw EMG signals were corrected for resting bias and gain, full-wave rectified and low-pass filtered (Butterworth, 4^{th} order, Fc-6Hz) using custom MatLab™ Ver 7.1 programs (The Mathworks Inc., Natick, Massachusetts, USA). Waveforms were time normalized to 100% of gait cycle and amplitude normalized to MVIC [Hubley-Kozey et al, 2006]. Isometric torque values were corrected for gravity. Maximum torque for a 500ms window was identified for seated knee extension, seated knee flexion, and plantarflexion exercises. See Rutherford et al., [2011a] for MVIC exercises. The average of two trials was recorded as muscle strength in Newton meters (Nm) and normalized to body mass (Nm/kg).

Local anatomical bone embedded coordinate systems for the thigh and tibia were derived from skin surface markers and digitized points [Cappozzo et al, 1997; Costigan et al, 1992].

Sagittal plane knee joint angles were calculated through Cardan/Euler rotations using a *z-y-x* rotation sequence where positive angles indicate knee flexion [Grood and Suntay 1983].

Analysis

Four groups were defined; i) asymptomatic individuals and individuals with knee OA with ii) minimal structural impairment (KL II), iii) moderate structural impairment (KL III) and iv) severe structural impairment (KL IV). For each participant, ensemble average waveforms from five trials were calculated for sagittal plane knee angles and for each muscle. Discrete sagittal plane knee angles were determined for i) heel strike, ii) early stance maximum and iii) mid to late stance minimum. Principal component analysis (PCA) was applied to each muscle group separately (gastrocnemii, quadriceps and hamstrings) to capture amplitude and temporal electromyographic waveform features using custom MatLab™ Ver.7.1 programs (The Mathworks Inc., Natick, Massachusetts, USA). This analysis has been previously described in detail [Hubley-Kozey et al, 2006]. Briefly, for each muscle group, principal patterns were derived through an eigenvector decomposition of a cross product matrix that included time-normalized electromyograms from all participants. The principal patterns (eigenvectors) explaining the greatest percent of variation in the waveforms were retained and referred to as PP1, PP2 etc. 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 for each principal pattern related to each measured EMG waveform. The measured EMG waveform can be accurately reconstructed by the linear combination of the principal patterns multiplied by the corresponding *PP-scores*.

Statistical Analysis

One way analysis of variance (ANOVA) models tested for significant group differences for WOMAC sub-scores, age, mass, body mass index (BMI), gait velocity, strength measures and knee flexion angles at heel strike, early stance maximum and mid to late stance minimum. Normality and equal variance of the *PP-scores* were determined from Kolmogorov-Smirnov and Levene's tests respectively. Two-factor (group, muscle) mixed model ANOVAs tested main effects and interactions for the *PP-scores* for each muscle group (alpha=0.05). All significant findings were post hoc tested using a Bonferroni adjusted alpha level to determine pair-wise significant differences. Statistical procedures were completed on Minitab™ Ver.15 (Minitab Inc. State College, PA, USA).

Results

Group demographics, muscle strength, WOMAC scores and knee flexion angle measures are shown in Table 1. The proportion of women to men was greater in asymptomatic (54%) and KL IV (45%) groups compared to KL II and III groups. Asymptomatic individuals had greater quadriceps strength than the KL II group ($p<0.05$) and lower mass and BMI ($p<0.05$) than all OA groups (Table 1). No other descriptive measures were different among groups.

Group ensemble-averaged waveforms for gastrocnemii, quadriceps and hamstrings qualitatively illustrate that specific changes were systematic with increased structural severity (Figure 1) for some muscles and at certain phases in the gait cycle whereas others were not. These changes were quantitatively compared through statistical analysis of three principal

patterns that explained over 94% of the waveform data variance for each muscle grouping. All data with unequal variances or non-normal distributions were transformed using either a natural logarithm or inverse hyperbolic sine function. Salient feature descriptions, captured by the principal patterns and mean *PP-scores* for each group and muscle are found in Tables 2 and 3. Post hoc results are found in Table 4.

Significant group by muscle interactions were found for gastrocnemii *PP1-scores* and *PP2-scores* ($p<0.05$). Significant group and muscle main effects were found for *PP3-scores* ($p<0.05$). In general, MG had a greater number of significant differences among groups than LG with increasing structural severity (Table 4). MG and LG waveform differences were not found between the asymptomatic and KL II groups or between KL III and KL IV groups. KL III and KL IV groups had lower overall MG amplitude (PP1) and a delayed increase in MG activation (PP2) than asymptomatic and KL II groups.

Significant muscle and group main effects were found for all *PP-scores* associated with quadriceps activation ($p<0.05$) (Table 4). In general, all knee OA groups had greater overall amplitudes (PP1) and greater mid-stance activity compared to early stance (PP2) than the asymptomatic group where the KL IV group had the highest activity levels throughout the gait cycle (PP1, PP2). Differences in mid-stance activity compared to late stance (PP3) were found among all three OA groups.

A significant group by muscle interaction was found for hamstrings *PP1-scores* ($p<0.05$). Muscle and group main effects were found for *PP2-scores* and *PP3-scores* ($p<0.05$) (Table 4). All knee OA groups had higher LH amplitudes (PP1), more prolonged hamstrings activity during stance (PP2) and a burst of hamstrings activity during early stance (PP3) indicative of a delayed response compared to the asymptomatic group. For the knee OA group, LH had a higher overall

magnitude feature (PP1) for the KL III and KL IV groups compared to the KL II group. Subsequently, a significantly higher LH than MH activation magnitude was found for KL III and IV groups. Only the prolonged activity feature (PP2) was different between KL III and IV groups with the KL III group having lower mid-stance activity.

Discussion

A range of structural severities existed in this knee OA sample. Clinical management and self-reported ability to perform three functional tasks [Hubley-Kozey et al, 2006] were used to define the moderate knee OA grouping. These individuals were similar across KL-grades with respect to their function (WOMAC physical function), symptoms (WOMAC pain and stiffness) and walking speed with minimal differences in muscle strength. In previous work, knee flexion excursion during loading response reduced progressively with increased severity [Astephen et al, 2008a], however walking velocities, symptoms and levels of structural severity differed. Knee flexion range of motion remained similar among the KL groups in the current study. Despite similar motion, strength, walking velocity and symptoms, 18/21 principal patterns capturing EMG waveform features differed with the presence of OA or showed a trend for progressive changes with increased KL-grade.

Gastrocnemii

All six gastrocnemii waveform features changed in a progressive manner with increasing structural severity (Table 2). Gastrocnemii activation patterns were not altered with minimal

structural impairments (KL II) compared to asymptomatic controls.. However, lower overall MG amplitudes (PP1) and phase-shifted MG activity (PP2) compared to asymptomatic individuals were found with greater structural severity (KL III and KL IV groups). In addition, high early stance compared to late stance gastrocnemii activity (negative *PP3-scores*) was specific to higher KL-grades. These altered features are consistent with responses aimed to increase early stance active stiffness, reduce joint contact force, in particular medial force during late stance, and to temporally synchronize medial and lateral sites with increased structural severity.

Temporal asynchrony between MG and LG for KL II and asymptomatic groups was consistent with previous findings for asymptomatic controls [Hubley-Kozey et al, 2006]. In contrast, the reduction in MG and temporal synchrony between MG and LG for the KL III and KL IV groups was consistent with a severe OA group made up predominantly of those with KL III and IV grades [Rutherford et al, 2011b]. That group was scheduled for total knee arthroplasty and self-reported poor function and severe symptoms [Rutherford et al, 2011b]. Thus, the present findings suggest the relationship between gastrocnemii activation and structural severity may be stronger than with self-report measures. Increased early stance gastrocnemii compared to late stance activity partially corroborate previous work. Higher vastus medialis-medial gastrocnemius co-contraction index (CCI) was found during early stance [Lewek et al, 2004] as well as increased LG activity during early stance in individuals with knee OA [Rudolph et al, 2007]. The former was thought to be a response to medial compartment laxity whereas the latter, a mechanism to reduce knee motion. Reduced and phase-shifted gastrocnemii activity towards late stance has been reported in asymptomatic individuals for slower walking velocities [Hof et al, 2002; Shiavi et al, 1987], but similar walking velocities among groups in the present study do not explain these findings. Systematic increases in structural severity were associated with

specific amplitude and temporal gastrocnemii activation alterations that differ between lateral and medial sites during gait in individuals with moderate knee OA.

Quadriceps

Quadriceps activation patterns were different in the OA compared to the asymptomatic group, clearly showing a distinct pattern for the KL IV group compared to all other groups (Figure 1). Differences were not restricted to greater overall amplitudes (PP1) in the OA group as other waveform feature (PP2 and PP3) differences were not systematic throughout the gait cycle (Figure 1) nor were they stepwise with increased KL-grades. Marked joint space narrowing, large osteophytes, severe sclerosis and bone attrition characteristic of the KL IV group were associated with greatest overall amplitudes (PC1) and more prolonged activation (PC2). This combination has implications for increased metabolic cost and increased knee joint loading in both tibio-femoral and patella femoral compartments. The mid-stance finding was driven by RF activity ((RF *PP2-scores* ;Table 3; Figure 1) suggesting that the relative demand for increased activity during single support was highest with more severe structural impairment.

No other study has compared across structural severity groups that were similar on a number of potentially confounding variables. For example, Zeni et al., [2010] found peak and average VL activity during self-selected gait to be similar between individuals with KL IV grades and individuals with KLII/III, however gait velocities were slower for their more severe group. Elevated mid-stance VL amplitudes were found in individuals categorized as severe OA based on functional limitations and clinical (total knee arthroplasty candidate) criteria compared to a moderate OA group (minimal functional limitations and conservative management)

[Rutherford et al, 2011b] despite similar walking speeds. A range of structural severity was represented in both OA groups along with differences in symptoms and function, possibly explaining the differences between these two studies. The closest comparative study to the present one used a visual analogue score for severity making it difficult to compare directly to the changes in the present study that were attributed to a set of specific progressive changes in joint structure [Astephen Wilson et al, 2011]. In the present study, increases in structural impairments specific to the KL-grading were associated with altered quadriceps activation characteristics, but the increases were not all systematic as the most prominent alterations were found for individuals with KL IV grade.

Hamstrings

All six hamstrings *PP-scores* changed in a progressive manner with increasing structural severity. Greater overall LH amplitudes (PP1) and more prolonged hamstrings activity during stance (PP2) were found with increased structural impairment. Increased hamstring co-activation has been estimated to improve knee joint stability [Schipplein and Andriacchi 1991], with the present findings suggesting greater active stiffness was required in the lateral compartment as KL-grade increased. Concomitantly, increased tensile strain on lateral tibio-femoral joint structures is likely given the adduction moment typically reported [Heiden et al, 2009]. LH has been shown to respond to this strain in an experimental study [Buchanan et al, 1996] providing another potential mechanism for the specific increase in overall LH activity with increasing KL-grade. Less prominent MH changes were found, with increased activity primarily during mid-stance for all OA groups. This perhaps reflects less fluctuation in medial

compartment stability resulting from the interaction between increased joint space narrowing combined with increased osteophytosis. The overall effect would contribute to a decrease in medial compartment loads as previously suggested [Hubley-Kozey et al, 2006; Lynn and Costigan 2008].

In both hamstrings, prolonged activation during mid-stance (PP2) and the distinct burst of activity during early stance (PP3) were found in individuals with knee OA compared to the asymptomatic group corroborating previous finding for individuals with moderate knee OA compared to asymptomatic individuals [Hubley-Kozey et al, 2006], and for individuals with severe knee OA [Rutherford et al, 2011b]. Shiavi et al., [1987] found peak MH activity occurred during early stance loading phase when asymptomatic individuals walked slower, but comparable walking velocities among groups in the present study does not support this explanation. These altered hamstring activation dynamics between late swing and heel strike suggests a delay in muscle response during heel strike and weight acceptance and may reflect proprioceptive deficits reported in individuals with knee OA [Koralewicz and Engh 2000]. Collectively, hamstrings amplitude and temporal activation patterns were altered with medial compartment knee OA but not all alterations were systematic across structural severity groups, phases of gait or between the two muscle sites.

Limitations exist in detecting early changes in OA and there is a ceiling effect when using structural severity determined from the KL radiographic scale [Kellgren and LAWRENCE 1957]. While other procedures are being developed, radiographic assessment, the KL-grades remains widely used for classifying radiographic knee OA structural severity [Emrani et al, 2008]. The ceiling effect was minimized given the moderate OA classification of our group. We did not have radiographs for asymptomatic participants; but the effect on our results were

deemed as minimal based on reported KL II prevalence for asymptomatic individuals of similar ages (3-9%) [Laxafoss et al, 2010]. If asymptomatic individuals with KL II grades were included, increased variability would reduce our ability to detect significant differences; hence, the differences found were conservative estimates. Potential for error in classification exists given that radiographic procedures and joint positioning can alter perception of joint space narrowing [Ravaud et al, 1996]. Despite this potential for error, differences in activation patterns (Figure 1) illustrate a progressive change throughout the gait cycle associated with increased KL-grade as confirmed from the statistically significant findings. These findings differ from the results reported using the VAS assessment of the radiographs, which showed no relationship with EMG features [Astephen Wilson et al, 2011]. Thus specific features such as joint space narrowing which should affect joint stability are associated with specific muscle activation pattern alterations whereas the general grading of severity was not.

Although causality between structural severity and altered muscle activation patterns cannot be definitively determined from cross-sectional designs, the current study provides a comprehensive assessment of muscle activation patterns throughout the gait cycle across OA structural severity. Sample size and the comprehensive nature of the EMG data collection and analysis provide strengths to the findings. Evidence was found to support a relationship between changes to passive osteoligamentous structures in knee OA and neuromuscular system alterations to maintain joint function during gait; consistent with previous frameworks [Panjabi 1992; Solomonow and Krogsgaard 2001]. Additional explanations are plausible to explain muscle activation alterations such as changes in mechanics at other joints; however, groups had no known ankle/foot or hip pathologies and were similar for characteristics known to alter knee joint mechanics and muscle activation. No obvious systematic relationship with structural

severity was evident (Table 1). Given that some knee joint muscles cross the hip or the ankle, investigating the relations among the three joints along with other hip and ankle joint muscles would shed light on potential interactions.

In summary, the combination of differences found was unique to each grade and muscle site examined. In individuals with lower levels of structural severity, differences occurred in the quadriceps and hamstring muscles only whereas moving along the severity spectrum resulted in alterations predominantly in medial gastrocnemius and lateral hamstring characteristics. Differences unique to severe structural impairment were increased quadriceps activation overall but also in combination with increased hamstrings activity during mid-stance, increased gastrocnemius during early stance with further delays in medial gastrocnemius only.

Conclusion

In conclusion, these results support the hypothesis that specific amplitude and temporal knee joint muscle activation patterns are altered during gait in a systematic manner with increasing level of structural knee OA severity based on the KL scoring features. These muscle activation pattern differences are consistent with systematic delays in temporal responses, increased demand for active stiffness overall and in particular during mid-stance, and decreased medial compartment joint loading throughout the stance phase with increased structural severity.

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Contributions

All authors made substantial contributions to conception and study design, analysis and interpretation of data, drafting the manuscript, editing for important intellectual content and preparing for submission to Journal of Electromyography and Kinesiology.

Conflict of Interest

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

Table 1: Mean and standard deviation (SD) subject demographics, gait characteristics, knee joint strength and WOMAC scores.

	KL-grade			
	ASYM	II	III	IV
N	35	38	33	11
# females	19	11	5	5
Age (years)	56 (6)	56 (8)	59 (8)	59 (8)
Mass (kg)	71.9 (14.0)*	93.0 (18.2)	96.0 (17.7)&	80.6 (16.8)
BMI (kg/m^2)	24.6 (3.5)*	30.5 (5.1)	31.2 (5.6)	28.4 (4.3)
Walking Velocity (m/s)	1.29 (0.12)	1.28 (0.20)	1.25 (0.16)	1.21 (0.22)
Muscle Strength (Nm/kg)				
KE45	1.48 (0.44)#	1.17 (0.41)	1.29 (0.45)	1.24 (0.51)
KF55	0.64 (0.26)	0.53 (0.20)	0.62 (0.23)	0.59 (0.27)
PF	1.08 (0.35)	0.89 (0.43)	0.94 (0.35)	0.97 (0.34)
WOMAC				
Pain	-----	6.8 (3.8)	6.7 (3.5)	6.2 (3.4)
Stiffness	-----	3.5 (1.7)	3.7 (1.6)	3.5 (1.1)
Physical Function	-----	23.0 (12.1)	20.5 (13.0)	15.7 (12.4)
Knee Flexion Angle (deg)				
Heel Strike	0.7 (5.9)	-1.0 (5.6)	0.5 (7.7)	0.2 (6.7)
Maximum§	20.6 (5.7)	19.5 (6.2)	18.8 (7.2)	15.9 (8.0)
Minimum^	6.9 (5.5)	6.2 (6.7)	8.2 (7.6)	9.4 (8.8)

Note: symbols indicate significant differences (Bonferroni corrected alpha)
* indicates ASYM < KLII and KL III, ASYM = KL IV
& indicates KLIII > KLIV
# indicates ASYM > KL II
§ maximum early stance (0-30% gait cycle)
^ minimum mid to late stance (30-60% gait cycle)

Table 2: Gastrocnemii and hamstrings principal pattern description and *PP-scores*

	Gastrocnemii*			Hamstrings[&]		
	PP1	PP2	PP3	PP1	PP2	PP3
Principal Pattern Description	Greater scores = Greater amplitude	Greater scores = Earlier activity	Greater scores = larger difference between early and late stance activity levels	Greater scores = Greater amplitude	Greater scores = higher activity during mid-stance and late swing burst of activity attenuation	Greater scores = burst of activity during early stance compared to activity during mid gait cycle
Lateral						
ASYM	210.2 (84.4)	-23.9 (34.7)	6.1 (27.8)	97.4 (42.8)	-26.6 (24.6)	-11.2 (26.7)
KL II	194.4 (91.5)	-21.7 (54.6)	-6.7 (42.7)	139.6 (68.1)	-9.1 (46.0)	6.8 (26.2)
KL III	184.0 (78.3)	-11.9 (28.0)	-9.9 (33.0)	188.2 (93.0)	1.3 (53.0)	12.0 (40.7)
KL IV	176.6 (62.4)	-6.7 (31.4)	-25.7 (49.2)	223.0 (115.6)	59.3 (84.9)	13.7 (54.7)
Medial						
ASYM	248.7 (99.9)	25.3 (42.1)	12.1 (40.8)	102.5 (37.9)	-35.3 (24.2)	-13.7 (20.8)
KL II	229.6 (75.7)	10.4 (51.6)	8.1 (34.7)	108.7 (45.9)	-22.5 (32.4)	-8.7 (23.5)
KL III	170.2 (81.4)	-0.7 (39.3)	-2.8 (34.9)	110.5 (60.8)	-8.2 (48.1)	-2.2 (16.9)
KL IV	155.5 (51.7)	-16.1 (44.9)	-17.5 (46.3)	119.3 (57.0)	-6.6 (37.0)	2.3 (35.3)

*Three principal patterns captured 95% of the gastrocnemii waveform variance.
[&]Three principal patterns captured 94% of the hamstring waveform variance

Table 3: Quadriceps principal pattern description and *PP-scores*

	Quadriceps*		
	PP1	PP2	PP3
Principal Pattern Description	Greater scores = Greater amplitude	Greater scores = larger difference between early and mid-late stance activity levels	Greater scores = higher activity during late stance compared to mid-stance and swing phase
VL			
ASYM	124.1 (60.4)	17.5 (17.4)	0.3 (19.3)
KL II	169.8 (102.7)	4.2 (40.8)	-3.5 (30.9)
KL III	162.5 (96.5)	5.1 (37.2)	-15.0 (17.3)
KL IV	222.7 (169.9)	-9.6 (48.1)	-30.7 (45.7)
VM			
ASYM	137.9 (89.6)	15.1 (21.1)	12.3 (26.2)
KL II	171.7 (111.4)	10.6 (44.3)	9.8 (38.4)
KL III	156.3 (91.8)	-2.0 (36.6)	-5.7 (22.9)
KL IV	182.0 (118.8)	-24.3 (45.2)	-14.4 (27.3)
RF			
ASYM	75.5 (36.7)	-3.6 (14.4)	8.7 (9.5)
KL II	94.5 (46.7)	-13.8 (27.9)	4.5 (12.5)
KL III	98.7 (45.4)	-16.1 (30.0)	3.6 (12.1)
KL IV	137.7 (51.6)	-54.6 (66.4)	-6.9 (14.0)

*Three principal patterns captured 94% of quadriceps waveform variance

Table 4: Post Hoc results for significant group and muscle main effects and interactions.

	Quadriceps	Hamstrings	Gastrocnemii
PP1-scores	ASYM<KLII=KLIII<KLIV VL=VM>RF	LH-ASYM<KLII<KLIII=KLIV MH-no group differences ASYM LH=MH KLII LH=MH KLIII LH>MH KLIV LH>MH	MG-ASYM=KLII>KLIII=KLIV LG-no group differences ASYM LG=MG KLII LG=MG KLIII LG=MG KLIV LG=MG
PP2-scores	ASYM>KLII=KLIII>KLIV VL=VM>RF	ASYM<KLII=KLIII<KLIV LH>MH	MG-ASYM=KLII, >KLIII, >KLIV MG-KLII=KLIII=KLIV LG-no group differences ASYM LG<MG KLII LG<MG KLIIILG=MG KLIV LG=MG
PP3-scores	ASYM=KLII>KLIII>KLIV VM=RF>VL	ASYM<KLII=KLIII=KLIV LH>MH	ASYM=KLII, >KLIII, >KLIV KLII=KLIII, >KLIV KLIII=KLIV MG>LG

Note; (>) indicates *PP-scores* were significantly less than the preceding *PP-scores*. (<) indicates *PP-scores* were significantly greater than the preceding *PP-scores*. (=) indicates *PP-scores* were equal between the two *PP-score* groups. (, >) only applied to gastrocnemii PP2 and PP3 and indicates *PP-scores* were less than the *PP-scores* of the first group identified (i.e. most left-positioned group).

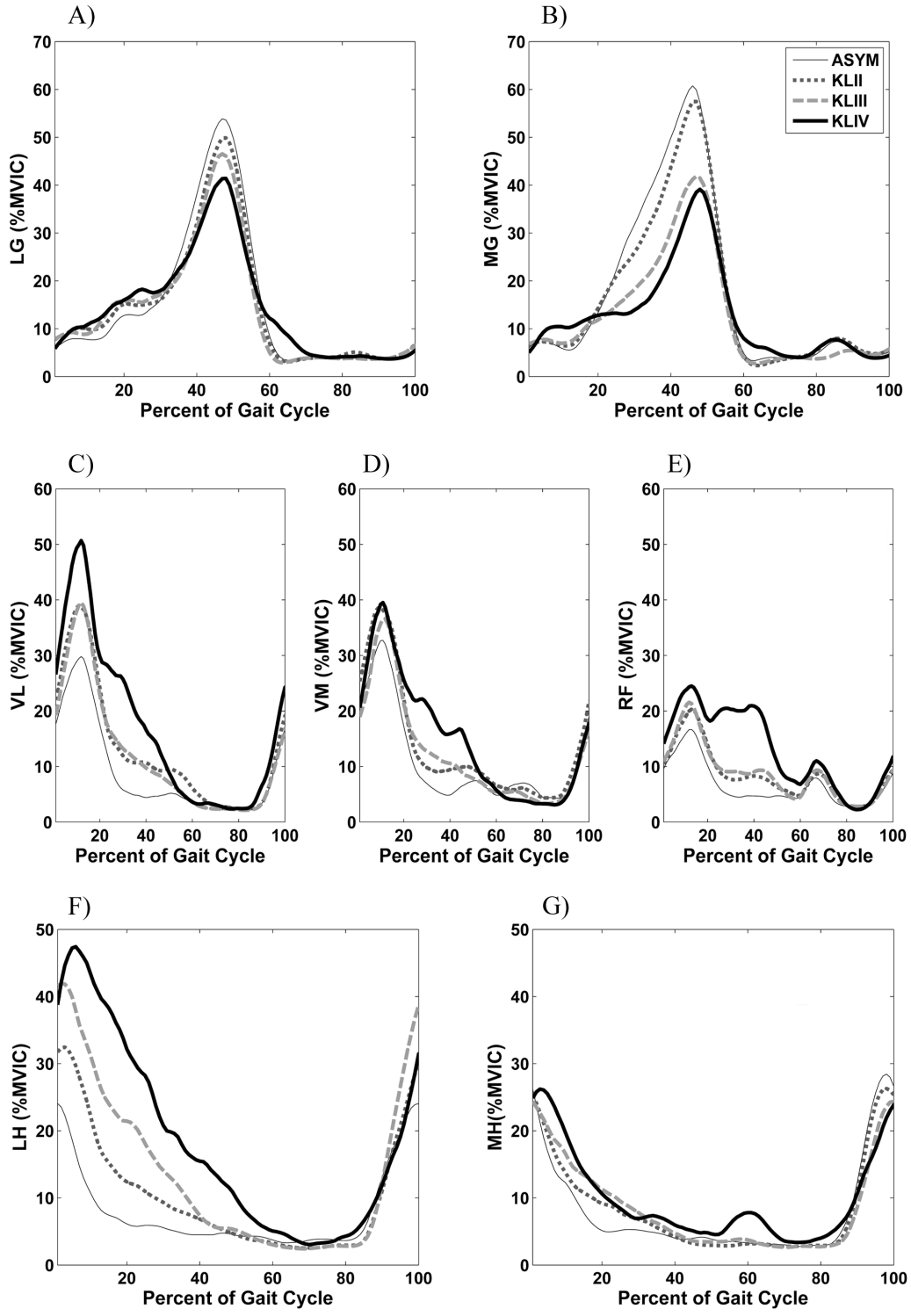

Figure 1: Ensemble-averaged electromyograms of A) lateral gastrocnemius B) medial gastrocnemius C) vastus lateralis D) vastus medialis E) rectus femoris F) lateral hamstrings G) medial hamstrings for each group.

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