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ScienceDirect
Clinical Biomechanics 23 (2008) 71–80
CLINICAL BIOMECHANICS
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Muscle co-activation patterns during walking in those with severe knee osteoarthritis

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Received 23 May 2007; accepted 15 August 2007

Abstract

Background. Sensory and motor impairments have been found for those with knee osteoarthritis; however, how these impairments are manifested during functional movements such as walking is not well established. A few studies suggest an increase in co-activity among lower limb muscles. The objective of this study was to characterize the neuromuscular patterns of knee joint muscles during walking for those with severe knee osteoarthritis using pattern recognition techniques on the entire waveform.

Methods. Fifty-one subjects received a gait assessment within one-week prior to total knee replacement surgery. Subjects walked along a 6-m walkway at their preferred walking speed while surface electromyograms from seven muscles were recorded. The electromyographic data were entered into a pattern recognition procedure that captured both the amplitude and shape characteristics of electromyographic waveforms. ANOVA models tested whether differences existed both among and within muscle groups for these waveform characteristics.

Findings. Four principal patterns explained 97% of the variance in the waveform data, with principal pattern one explaining 86% of the total variance. There were statistically significant differences ($P < 0.05$) among muscle sites for all principal pattern *scores*. The analyses supported the hypothesis that similarities existed in patterns among muscles from different groups indicating (i) a general co-activity pattern and (ii) differential recruitment between muscles within a muscle group.

Interpretation. In addition to the roles during impact loading and propulsion, the muscle responses were consistent with attempts to (i) decrease medial knee joint loading, (ii) decrease peak knee joint loading during push off and (iii) increase stiffness during stance phase to improve joint stability. The technique employed provides a novel approach to quantify synergistic co-activity.

Keywords: Severe osteoarthritis; Gait; Electromyographic patterns; Co-activation; Pattern recognition

1. Introduction

There is evidence of sensory (proprioceptive) and motor impairments affecting force generation and motor unit recruitment of the knee extensors and flexors in the presence of knee joint osteoarthritis (OA) (Fisher and Pendergast, 1997; Hall et al., 1993; Hurley, 2003; Hurley and Newham, 1993; Hurley and Scott, 1998; Marks et al., 1994; Pap et al., 2004; Slemenda et al., 1997; Slemenda et al., 1998). How these impairments are altered during functional movements such as walking is not well understood. Electromyography provides information on both neural drive (amplitude) and temporal/phasic (shape) activation characteristics of the musculature (Yang and Winter, 1985). Several studies have presented ensemble-average electromyographic (EMG) profiles for asymptomatic controls showing that the muscle activation patterns of the major muscle groups such as the knee flexors, knee extensors and plantarflexors are distinct from one another and are related to specific roles during gait (Hof et al.,

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doi:10.1016/j.clinbiomech.2007.08.019

2002; Hubley-Kozey et al., 2006; Ivanenko et al., 2004; Prentice et al., 2001; Shiavi et al., 1987; Winter and Yack, 1987; Yang and Winter, 1985). In contrast there are only a few EMG gait studies for those with knee OA examining various degrees of moderate OA with no studies on those with severe OA (Childs et al., 2004; Hubley-Kozey et al., 2006; Lewek et al., 2004a).

Consistent among EMG gait studies of knee OA is the concept of increased muscle co-activation compared to asymptomatic subjects (Childs et al., 2004; Hubley-Kozey et al., 2006; Lewek et al., 2004a). Co-activation in those with knee OA is believed to increase joint stiffness in response to pain (Fisher and Pendergast, 1997), medial joint loading (Andriacchi, 1994) and instability (Lewek et al., 2004a) and presumably should be present in those with more severe knee OA. Different methods of quantifying co-activation were used in all three studies of OA gait. Childs et al. (2004) reported increased amplitude and onset times; however these variables do not capture the shape and amplitude characteristics of the entire waveform. Lewek et al. (2004a) calculated a co-activation index from waveform data over the initial 10–15% of the gait cycle. This approach provides a good estimate of co-activity if the time interval is short and minimal variation is expected during that time period, but co-activation indices do not have unique solutions and are unable to capture waveform characteristics (Falconer and Winter, 1985; Kellis et al., 2003; Lewek et al., 2004a; Unnithan et al., 1996).

Hubley-Kozey et al. (2006) used pattern recognition techniques to quantify the amplitude and shape characteristics of EMG waveforms among muscles within an agonist group to examine medial and lateral site differences. The subject sample was classified as mild to moderate OA. The differences found, while significant, were subtle. Differences were found between the medial and lateral hamstrings in the moderate OA group and the patterns were different for the medial and lateral gastrocnemius muscles between the OA and asymptomatic control groups (Hubley-Kozey et al., 2006). These patterns were consistent with a strategy that would reduce medial joint loading in those with mild to moderate knee OA. Pattern recognition approaches have an advantage over those techniques that calculate a single co-activation (co-contraction) index since the former captures both amplitude and timing (shape) characteristics. Correlational analysis has also been used to evaluate the timing (shape) and amplitude between two EMG waveforms however, this technique is limited to comparing two muscles at one time (Sirin and Patla, 1987). Co-activation refers to the simultaneous recruitment of synergistic muscles (Sirin and Patla, 1987), with synergistic muscles referring to all muscles that participate in producing moments of force around a joint during dynamic tasks (Nigg et al., 2003). Most studies of gait that have applied pattern recognition techniques include either individual muscles (Wootten et al., 1990) or muscles within a group into the analysis (Hubley-Kozey et al., 2006) and not all synergist (agonists and antagonists) waveforms. Therefore pattern recognition approaches that simultaneously analyze multiple EMG waveforms should be valuable in evaluating co-activation among several muscles.

Approaches based on orthogonal expansion theory have been employed to quantify co-activation among synergistic trunk musculature in those with and without low back pain (Hubley-Kozey and Vezina, 2002). A similar approach was applied to waveforms from the lower limb muscles of asymptomatic subjects during gait in an attempt to determine the presence of a central pattern generator. Ivanenko et al. (2004) found that five different patterns clearly linked to the major muscle groups of the lower limb explained from 10 to 30% of the variance for each set of EMG waveform data from asymptomatic controls included in their analyses. The approach proposed in this study attempted to determine if a general pattern of co-activation among the major muscles surrounding the knee joint exists in those with severe OA or not. Establishing such a pattern in severe OA could serve to distinguish disease progression assisting clinicians in establishing disease severity. As well, a better understanding of the neuromuscular alterations associated with severe knee OA could provide a framework for prescribing appropriate interventions aimed to improve the mechanical environment of the joint and perhaps prolong the need for an invasive intervention.

The objective of this study was to determine if activation patterns of the major muscles crossing the knee joint were distinct from one another or similar to one another (co-activation) in magnitude and shape in those with severe knee OA during walking. We hypothesized that there would be similarities in the patterns of activity (magnitude and shape) among muscles belonging to different muscle groups (supporting a general co-activation), and that there would be differences between muscles within a group (supporting differential recruitment of medial versus lateral muscle sites) for those with severe knee OA.

2. Methods

Fifty-one subjects with severe knee osteoarthritis received a gait assessment within one-week prior to total knee replacement surgery. Subjects were included if they were able to walk the length of the 6-m walkway without an aid. They were excluded if they had any neurological, cardio respiratory or musculoskeletal condition other than the knee OA that would affect their gait or place them at risk by participating. Subjects signed an informed consent approved by the Capital Health Research Ethics Board.

Standard anterior–posterior and lateral radiographs of the knee were graded for osteoarthritis severity by one orthopaedic surgeon (MD) using the Kellgren and Lawrence global rating scale (Kellgren and Lawrence, 1957). Subjects were classified as severe based on (i) a Kellgren Lawrence global score of 3 or 4, (ii) a diagnosis of severe end-stage knee OA based on a clinical assessment by an orthopaedic surgeon and (iii) the treatment option prescribed included a total knee replacement.

Silver/silver chloride surface electrodes (0.79 mm^2 contact area, Bortec Inc., Calgary, Canada) were placed in a bipolar configuration (20 mm centre-to-centre) in line with the muscle fibers on the prepared skin over the rectus femoris, vastus lateralis, vastus medialis, lateral hamstring, medial hamstring, lateral and medial gastrocnemius using standardized placements (Hubley-Kozey and Smits, 1998; Leveau and Andersson, 1992). A reference electrode was placed over the mid-tibial shaft. Crosstalk was assessed (Shiavi et al., 1987; Winter et al., 1994) and electrode placements were validated while subjects performed isolated manual muscle tests (Kendall et al., 1993). The ratio of the skinelectrode impedance to the input impedance of the amplifier was less than the 1% recommended ratio (Winter, 1996). Raw EMG signals were preamplified (500×) then further amplified (bandpass 10–1000 Hz, CMRR = 115 dB (at 60 Hz), input impedance ~10 Gohm) using an eight channel surface EMG system (AMT-8 EMG, Bortec Inc.™, Calgary, Alberta, Canada). The raw EMG signals were digitized at 1000 Hz, using the analog data capture feature of the Optotrak™ (Northern Digital Incorporation, Waterloo, ON, CA) motion analysis system. All equipment, acquisition and processing of the EMG met published standards (SENIAM, 1999; Winter et al., 1992).

Surface EMG data were collected while subjects walked along a 6-m walkway at their self-selected walking speed. Five trials within 5% of their self-selected speed were completed. The EMG data analysis was the focus of this study, and motion and force data were simultaneously collected to define the events for one gait cycle for analysis.

Following the walking trials subjects performed a set of eight voluntary maximal-effort isometric contractions (MVIC). These served two purposes: (i) to assess muscle strength for the knee extensor, knee flexor and ankle plantar flexor groups (Hubley-Kozey et al., 2006) and (ii) to provide a physiological reference for comparing the EMG amplitudes among muscle sites for normalization purposes (Burden et al., 2003; Kasman et al., 1998). The exercises included: (1) plantar flexion in long sitting with the knee in a slightly flexed position (less than 5°) with a pillow under the knee and the ankle in neutral position, (2) standing heel raise on one foot against a manual resistance applied vertically downward against the shoulders, (3) knee extension in sitting with knee at 45° of flexion, (4) same contraction as 3 above while adding a simultaneous hip flexion action with the hip joint at approximately 90° of flexion, (5) knee extension in supine lying at 15° of knee flexion, (6) knee flexion in sitting with knee flexed to 55°, (7) knee flexion in supine lying with knee flexed to 15°, and (8) knee flexion in prone lying with knee flexed to 55°. Exercises 1 and 2 targeted the gastrocnemius muscles, 3 and 5 the two vasti muscles, 4 the rectus femoris and 6, 7 and 8 the hamstrings. All exercises were held for 3 s and repeated once. Subjects were given practice, encouragement and feedback on their performance consistent with recommended protocols that showed both OA and asymptomatic controls could voluntarily elicited 93% or more of their maximal stimulated quadriceps activity (Lewek et al., 2004b). Torque and angle data from the Cybex™ dynamometer (Lumex, NY, USA) were recorded at 1000 Hz simultaneously with the EMG data using the Optotrak™ data capture feature for exercises 1, 3, 5, 6, 7 and 8.

3. Strength measures

Custom Matlab™ (version 7.0) software calculated the gravity corrected torque in Newton meters (Nm) for exercises 1, 2 and 6 above for plantar flexor, knee extensor and knee flexor strength measures respectively. A 1-s maximal steady state window of torque data within the 3-s contraction between the two trials for each exercise was recorded as the measure of muscle strength (Nm) (Hubley-Kozey et al., 2006).

4. EMG processing

Custom Matlab™ (version 7.0) software corrected the raw EMG signals for subject bias, converted amplitudes into μV, full-wave rectified and low pass filtered the signals at 6 Hz using a zero-lag Butterworth filter (Winter, 1990). The EMG waveforms for each muscle were amplitude normalized to the maximal 0.1-s amplitude that occurred during the MVIC exercises (Hubley-Kozey et al., 2006) and time-normalized to 100% of the gait cycle using a linear interpolation. Five trials were averaged to create an ensemble-average waveform for each muscle for each subject (Winter and Yack, 1987). All seven waveforms were input to the pattern recognition algorithms (Hubley-Kozey and Vezina, 2002). The intent of this procedure was to explain as much of the variance for the EMG dataset while minimizing redundancy in the data. The procedure has been described elsewhere (Hubley-Kozey et al., 2006; Hubley-Kozey and Vezina, 2002), however a graphical depiction of the procedure is found in Fig. 1. Briefly, X is a 101 (stride normalized points) by 357 (7 muscles by 51 subjects) matrix of EMG waveforms. A cross product matrix C was calculated, and then an eigenvector decomposition of matrix C resulted in the transform matrix, T. T contains the orthonormal eigenvectors that capture the different features from the measured waveform data. *Scores* (weighting coefficients-$\boldsymbol{y}_i$) for each principal pattern were calculated for all of the measured waveforms using the T matrix and the original matrix, X. These *scores* reflected how much a principal pattern contributed to the measured waveform. The number of principal patterns (k) included in the analysis were based on two criteria (i) a percent trace greater than 90% for the k principal patterns to capture the salient features from the waveforms, and (ii) principal patterns that explained less than 1% of the variance were excluded (Hubley-Kozey et al., 2006; Hubley-Kozey and Vezina, 2002). The *scores* for the k principal patterns were used in the statistical hypothesis testing.

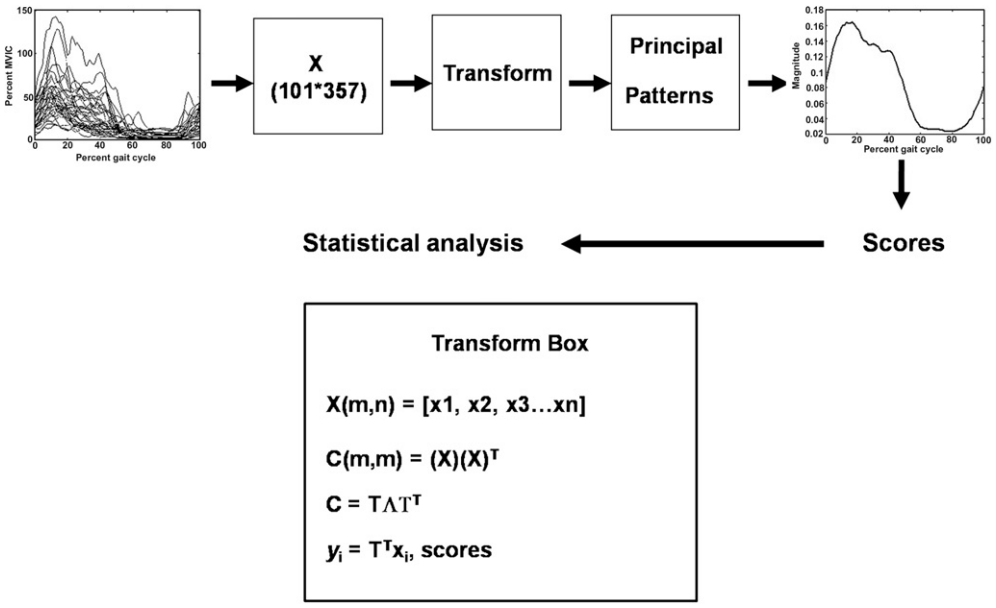

Fig. 1. The application of the pattern recognition procedure (i) the time and amplitude normalized measured EMG waveforms for all seven muscle sites, for each subject (eg. in the top left) form the Matrix **X(101 × 357)**, (ii) application of the transform with the equations in the lower transform box in which a cross product matrix **C of X** ($X = 101 \times 357$) is formed and the transform matrix T (101,101) calculated from an eigenvector decomposition of matrix **C**. T is a matrix of patterns (orthonormal eigenvectors) and Λ is a diagonal matrix of the associated variances (eigenvalues). (iii) a principal pattern is depicted in the top right, (iv) the *scores* are derived as indicated in the transform box and (v) these *scores* are used in the statistical analysis.

In addition to the quantitative analysis, the ensemble-average profiles (Winter and Yack, 1987) for each muscle were examined qualitatively to describe the amplitude and shape of the EMG waveforms for this sample and for interpreting the principal patterns.

5. Statistical analysis

Means and standard deviations were calculated for age, height, mass, BMI, walking speed, stride characteristics, and maximal isometric strength measures. One-factor (muscle) repeated measures ANOVA models determined if differences existed among the seven muscle sites for the principal pattern *scores* for the k principal patterns separately. Bonferonni post hoc procedures tested for pair-wise differences among muscles correcting α based on 21 comparisons ($\alpha = 0.0024$) (Zar, 1996). Statistical analyses were performed by Minitab™ (version 14) statistical software.

6. Results

Demographic data for 26 men and 25 women with severe OA are found in Table 1. The radiographic assessment showed that 13 subjects had a Kellgren Lawrence grade of IV with the rest grade III. All 51 subjects had medial joint space narrowing and in addition 44 and 46 had lateral and patellar femoral joint space narrowing, respectively. The mean (SD) for the medial, lateral and patellofemoral joint space narrowing scores were 2.0(.8), 1.2(.8) and 1.5(.8), respectively. Walking velocity, stride characteristics and muscle strength measures are in Table 1.

The sample ensemble-average profiles for all 7-muscle sites are in Fig. 2. Visual inspection of the EMG profiles show that the lateral gastrocnemius and medial gastrocnemius profiles (Fig. 2a) were similar to each other in both shape and amplitude. The two vasti profiles (Fig. 2b) were similar in shape and amplitude, whereas the rectus femoris waveform had a similar shape, but lower amplitude during early to mid stance. The quadriceps muscles were activated during most of the stance phase (up to about 50% of the gait cycle) with the peak amplitude around 15% of the gait cycle. The lateral hamstring and medial hamstring waveforms (Fig. 2c) were different from each other in both shape and amplitude.

The waveform characteristics were captured by four principal patterns (depicted in Fig. 3) explaining 97% of the variance in the EMG waveform data from all seven muscles. Principal pattern 1 (PP1) (Fig. 3a) captured 86%

Table 1
Subject demographics, walking speed and muscle strength measures

	Age (yrs)	Height (m)	Mass (Kg)	BMI	Speed (m/s)	Quads (Nm)	Hams (Nm)	PF (Nm)
Mean	64.7	1.7	90.6	31.3	0.93	77.9	33.8	56.4
SD	8.4	0.1	15.1	4.7	0.03	4.2	2.5	3.8

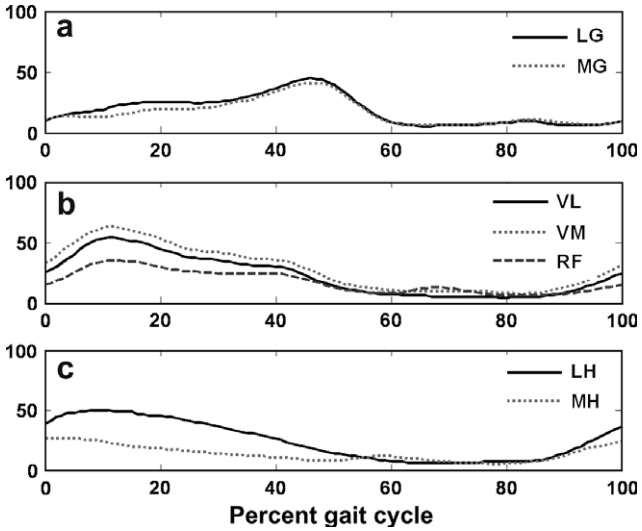

Fig. 2. The sample ensemble-average waveforms for the seven muscle sites for the severe OA subjects. The *y*-axis is normalized EMG amplitude in %MVIC and the *x*-axis is percent gait cycle. The upper panel (a) includes the lateral gastrocnemius (LG) (solid) and medial gastrocnemius (MG) (dotted); the middle panel (b) includes the vastus lateralis (VL) (solid), vastus medialis (VM) (dotted) and rectus femoris (RF) (dashed); and the lower panel (c) includes the lateral hamstring (LH) (solid) and medial hamstring (MH) (dotted).

of the variance and the overall amplitude and general shape of muscle activity during the stance phase of gait. Principal pattern 2 (PP2) (Fig. 3b) explained 6.5 % of the variance and captured the peak in activity at 50% of the gait cycle consistent with the shape of the ensemble-average profile for the gastrocnemius muscles. Principal pattern 3 (PP3) (Fig. 3c) explained 3.1% of the variance and captured two shape characteristics (i) the decrease in activity following heel strike and (ii) a small rise in activity around toe off, consistent with the shape of the medial hamstring ensemble-average profile. Principal pattern 4 (PP4) (Fig. 3d) explained 1.4% of the variance and captured a burst of activity at 10–15% of the gait cycle typical of the quadriceps profile.

The ANOVAs of the principal pattern *scores* revealed statistically significant ($P < 0.05$) muscle main effects for all 4 *scores* confirming the similarities and differences noted in the amplitude and shape characteristics from the qualitative analysis of the profiles. The effect size was calculated for each principal pattern *score* using a pooled variance and was greater than 1.0 for all 4 *scores*. The post hoc results are depicted in Fig. 4. PP1 *scores* illustrate differences in amplitude and general shape with the vastus lateralis, vastus medialis and lateral hamstring significantly higher ($P < 0.0024$) than the other muscles. As expected PP2 *scores* were significantly higher ($P < 0.0024$) for the two gastrocnemius muscles compared to all other muscle sites. Medial hamstring PP3 *score* was statistically higher ($P < 0.0024$) than all other muscles except medial gastrocnemius. PP4 *scores* were significantly higher ($P < 0.0024$) for the quadriceps than the hamstrings and gastrocnemius muscles. Although the lateral hamstring was not different from the two vasti muscles for three of the four principal patterns *scores*, the difference in the waveforms during initial stance was captured by the significant difference for PP4 *score*.

Fig. 5 illustrates how these statistical differences among principal pattern *scores* can be interpreted in a composite

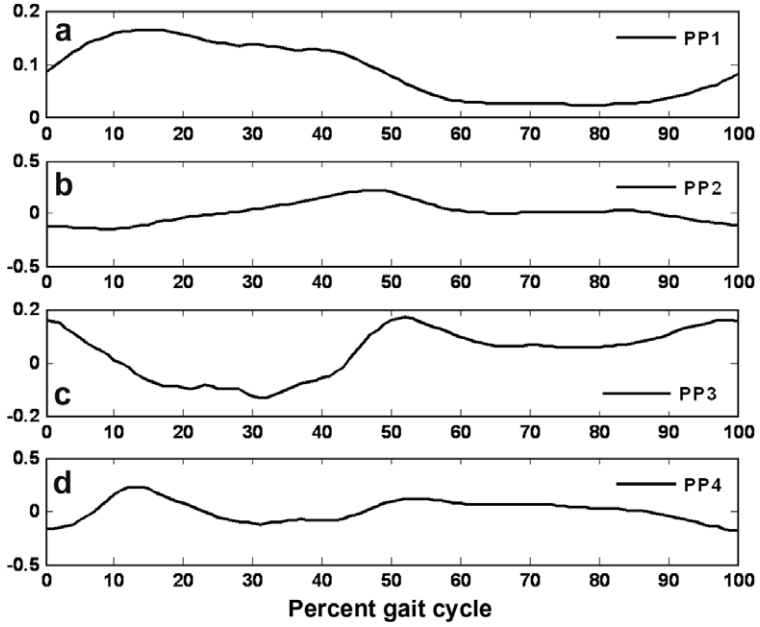

Fig. 3. The four principal patterns explaining 97% of variance in the waveform data. The *y*-axis is magnitude and the *x*-axis is percent gait cycle. The upper panel (a) principal pattern 1 explains 86.0%, the second panel (b) principal pattern 2 explains 6.5% of the variance, the third panel (c) principal pattern 3 explains 3.1% of the variance and the lower panel (d) principal pattern 4 explains 1.4% of the variance.

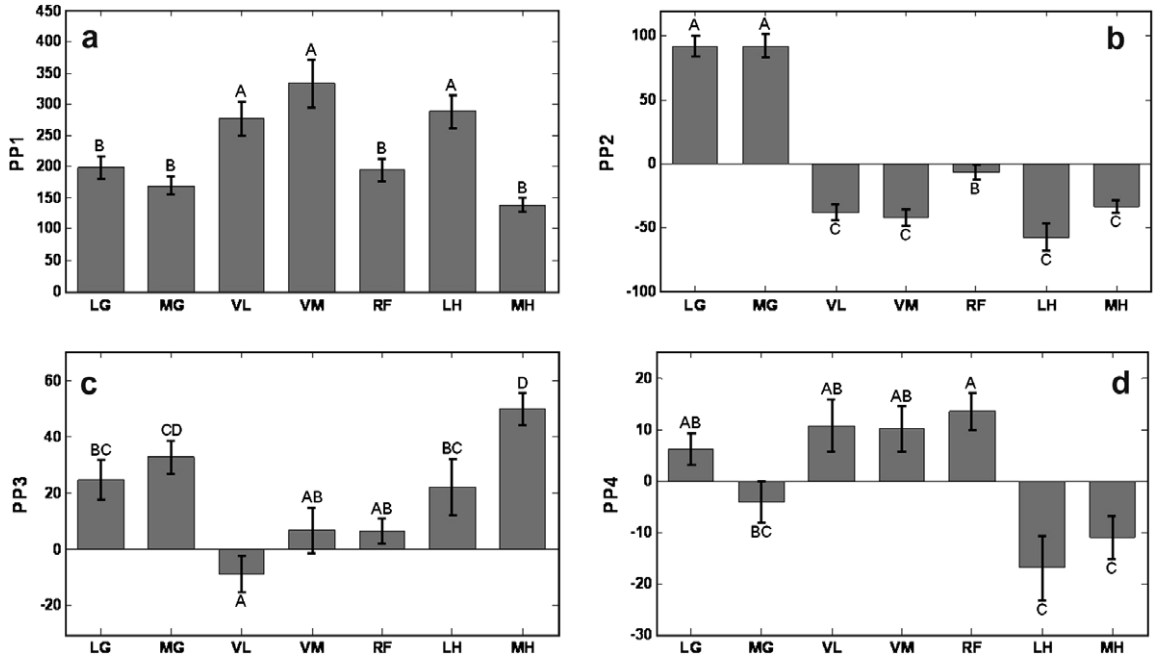

Fig. 4. The mean and standard error of the mean for the *scores* from the four *principal patterns that explained the highest variance* are indicated in (a–d). All four *scores* had a significant muscle main effect ($P < 0.05$). The post hoc results demonstrated differences among the muscle pairs for (a) PP1 *scores* (b) PP2 *scores* (c) PP3 and (d) PP4 *scores.* The results of the Bonferoni post hoc analysis are indicated on each graph. Means with similar lettering indicate *scores* that were not statistically different ($\alpha_{adj} = 0.0024$).

graph of hamstrings and a quadriceps profiles. The only difference between the vastus medialis and the lateral hamstring waveforms was the shape difference around 15% of the gait cycle (captured by the statistically significant PP4 *score* difference) whereas the medial hamstring differed from both the vastus medialis (PP1, PP3, and PP4 *scores*) and lateral hamstring (PP1 and PP3 *scores*) in shape and amplitude. In summary, the statistical analyses of the *scores* provided a quantitative comparison of the amplitude and shape characteristics among the EMG waveforms with a degree of statistical certainty.

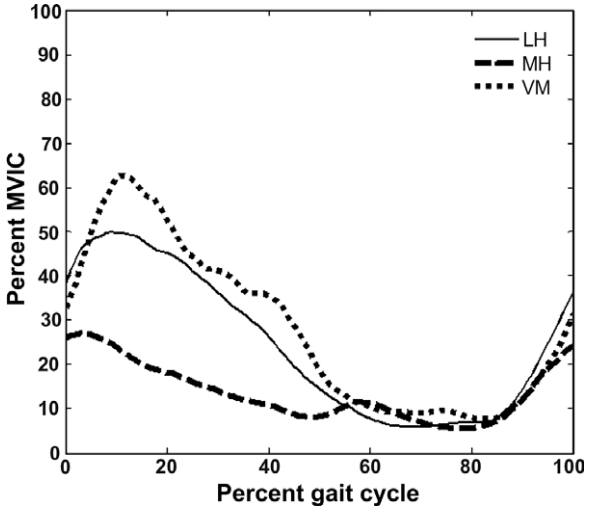

Fig. 5. Comparison of the ensemble-average waveforms for the lateral hamstring, medial hamstring and vastus medialis.

7. Discussion

The sample was a well-defined severe knee OA group that was at the end of conservative management options i.e. within one-week prior to total knee replacement surgery. They had significant joint involvement based on their the Kellgren Lawrence grades of III and IV, and their joint space narrowing measures were higher than measures previously reported for a severe group (Mundermann et al., 2005). Their function was impaired as illustrated by walking velocities that were slower or similar to previous reports for severe OA (Benedetti et al., 2003; Mundermann et al., 2005). Finally their knee extensor, knee flexor and plantar flexor torques (strength measures in Table 1) were between 62 and 67% of values recently reported for asymptomatic controls and for those with moderate knee OA using a similar methodology (Hubley-Kozey et al., 2006). This implies a strength impairment.

The EMG profiles in Fig. 2 for the severe OA group differ from published profiles for those with asymptomatic knees (Hubley-Kozey et al., 2006; Ivanenko et al., 2004; Shiavi et al., 1987; Winter and Yack, 1987; Yang and Winter, 1985) and those with moderate knee OA (Hubley-Kozey et al., 2006). The severe OA group activated all seven muscles over the majority of the stance phase rather than having distinct on/off periods throughout the gait cycle. The slower self-selected walking speed for the severe group

compared to reports for asymptomatic subjects (Hubley-Kozey et al., 2006) does not explain all of the alterations in the neuromuscular patterns found in this study. Previously it was reported that asymptomatic subjects demonstrated decreased EMG amplitude (neural drive) with minimal changes in shape for the averaged EMG profiles with decreased walking speed (Shiavi et al., 1987; Yang and Winter, 1985). In contrast our results showed high activation amplitudes throughout stance phase for most muscle sites. The low peak amplitude late in stance phase for the gastrocnemius muscles was the only finding consistent with these previous reports for asymptomatic subjects (Shiavi et al., 1987; Yang and Winter, 1985).

Only four principal patterns were required to explain 97% of the variance in the EMG waveform data from seven muscles. PP1 explained 86% of the variance indicating that this pattern was dominant in all seven EMG waveforms. This finding contrasts results presented for asymptomatic subjects in which each of the first four principal patterns explained approximately 30% of the variance in the waveform data (Ivanenko et al., 2004). Each of the patterns for the asymptomatic group (Ivanenko et al., 2004) represented an individual muscle group pattern, whereas PP1 for this severe OA group was a general activation pattern throughout stance. Only 10% of the variance was due to the subtle shape differences among the muscle groups captured by PP2, PP3 and PP4 scores.

The first hypothesis that co-activation (similarities in patterns) exist among muscles belonging to different groups was supported. The general pattern and overall amplitudes (PP1) were higher for the vastus lateralis, vastus medialis and lateral hamstring compared to the other four muscle sites indicative that these three muscles were recruited to a higher percentage of MVIC as seen in the ensemble-average profiles in Fig. 2. However, the lateral gastrocnemius, medial gastrocnemius, medial hamstring and rectus femoris were all similar in overall amplitude and had relatively high PP1 *scores* indicating that this pattern was a dominant pattern in all of the measured waveforms. This co-activation pattern is most likely to stabilize the joint given that there is a high degree of joint space narrowing based on the Kellgren Lawrence grades. The burst of activation just prior to toe off for the gastrocnemius (PP2), the continual gradual decrease in medial hamstring from heel strike to toe off (PP3) and the burst of quadriceps activity during initial loading (PP4) indicate that the characteristic roles during different phases of the gait cycle are present but represent minimal variance.

The principal patterns and the principal pattern *scores* in this study cannot be compared directly to those derived in other studies; however the features that the principal patterns capture can be compared to discrete measures from waveforms or to ensemble-average profiles from other studies. Therefore this co-activation strategy throughout the majority of the gait cycle contrasts the typical hamstring and quadriceps profiles reported for asymptomatic controls in several studies (Hubley-Kozey et al., 2006; Ivanenko et al., 2004; Shiavi et al., 1987; Winter and Yack, 1987; Yang and Winter, 1985). The pattern also differs from those with moderate OA who had high vastus lateralis and lateral hamstring co-activation in early stance only (Hubley-Kozey et al., 2006). Presumably the co-activation strategy throughout the gait cycle adopted for those with severe OA was necessary to function when pain, joint loading, muscle strength and instability are significant problems.

The statistical analysis of the principal pattern *scores* also supported the hypothesis that differential recruitment existed between muscles within an agonist grouping for the quadriceps and hamstrings only. The rectus femoris activation amplitude was lower in early to mid stance than the two vasti muscles (lower PP1 *score*) but all three quadriceps muscles responded to the initial impact loading (no difference in PP4 *score*). This burst is consistent with EMG profiles presented for asymptomatic controls (Hubley-Kozey et al., 2006; Shiavi et al., 1987; Winter and Yack, 1987) and is responsible for impact attenuation during initial loading.

The differences between the two hamstring muscle profiles demonstrated (Fig. 2 and 5) a differential role for the medial hamstring versus the lateral hamstring as captured by the significant amplitude (PP1 *scores*) and shape (PP3 *scores*) differences between the two sites. The higher lateral hamstring activity compared to medial hamstring following heel strike supports the theory that the lateral muscles attempted to increase lateral forces to decrease medial joint loading (Andriacchi, 1994). This is consistent with a recent report of higher lateral hamstring early in stance phase for those with moderate knee OA (Hubley-Kozey et al., 2006). The gradual decrease and constant low-level activity for the medial hamstring suggests a stabilizing role in particular during single stance for the severe OA group. This differential recruitment of the hamstrings contrasts the profiles for asymptomatic controls in which the two hamstrings are tightly coupled for both amplitude and shape and dramatically drop in activity within the first 15% of the gait cycle (Hubley-Kozey et al., 2006).

Finally, the two gastrocnemius muscles were co-activated with similar amplitudes and shapes throughout the entire gait cycle as seen in Fig. 2. This was confirmed by no significant differences between the two muscles for all four PP *scores*.This differs from profiles for asymptomatic controls in which higher medial gastrocnemius amplitudes and a phase shift to the left compared to the lateral gastrocnemius waveform were found (Hubley-Kozey et al., 2006). A medial gastrocnemius phase shift was also reported for those with moderate OA (Hubley-Kozey et al., 2006). The amplitudes with respect to MVIC were lower during the propulsive phase in the severe group compared to both asymptomatic and moderate OA groups (Hubley-Kozey et al., 2006). The present EMG results and the low plantar flexor strength measures provide an explanation for the lower peak plantar flexion moments previously reported for those with OA compared to control subjects during walking (Fisher et al., 1997). The slower walking speeds

(Winter and Yack, 1987) can partially explain this decrease in peak amplitude for the severe OA group, but it does not explain the higher activity in both gastrocnemius sites (20% MVIC) during early stance i.e. two times higher than amplitudes reported for both asymptomatic controls and those with moderate OA during early stance (<10% MVIC) (Hubley-Kozey et al., 2006). This medial gastrocnemius and lateral gastrocnemius activation in early stance is consistent with a general stabilizing role for the gastrocnemius and consistent with the higher medial gastrocnemius co-activation index reported for early stance phase for those with moderate OA who had high medial joint space narrowing (Lewek et al., 2004a).

In the present study there was a high degree of agonist/antagonist co-activity around the knee joint. While co-activity may improve joint stability it may also have an undesirable increase in joint loading. This co-activity supports the notion that the knee flexion moment does not accurately reflect the actual joint loading without considering muscle forces (Baliunas et al., 2002). In addition, the co-activity to relatively high percentages of maximum over the majority of the gait cycle increases the risk of muscular fatigue and thus impairing muscle force generation and its function to produce motion, alter joint loading and improve stability.

The present results provide a framework for assessing disease severity and for developing and evaluating pre and post surgical management strategies. High scores for the co-activation pattern (PP1) could be used as an objective measure to establish disease severity and triage the large number of patients considering joint replacement surgery. The differences between medial and lateral sites, for example the two hamstrings, may also indicate joint site involvement. Presumably the co-activation pattern revealed in this study would be accompanied by a high metabolic demand and thus the potential for those with severe OA to fatigue more quickly. This has implications for a reduction in physical activity as well as increased fatigue could also reduce the efficiency of the muscles to stabilize the joint. These findings provide objective data on which to design and evaluate therapeutic interventions. A key clinical question is whether these neuromuscular patterns can be altered and whether they have an impact on the effectiveness of both surgical and conservative management approaches that aim to alter asymmetric loading or provide stability to the joint (Chang et al., 2004; Draper et al., 2000; Kerrigan et al., 2002; Sharma et al., 2003). Conservative interventions would include exercises for improved strengthening and endurance as well as devices such as heel wedges or valgus braces that aim to redistribute joint loads as well as bracing to improve joint stability. Further research should also determine whether pre-surgical neuromuscular control patterns can predict surgical outcomes such as improved function and longevity of the implant. If pre-surgical neuromuscular patterns persists post-total knee replacement surgery, then the asymmetric loading throughout the gait cycle along with the increased risk of muscle fatigue could produce a harmful loading environment for the prosthesis.

There are several methods of quantifying co-activation, however the approach used in this study captured the correlational structure among all of the muscles tested. Quantifying co-activation and synergistic behaviours in pathological (Falconer and Winter, 1985; Lewek et al., 2004a; Unnithan et al., 1996) and normal movement (Kellis et al., 2003) is important to understanding neuromuscular control. The approach in this study quantifies co-activation of the major synergists crossing the knee joint during the entire dynamic movement and could prove useful in the study of other clinical populations in which co-activity presents a problem such as cerebral palsy, post stroke and Parkinsons.

A limitation of the study relates to interpreting EMG data from symptomatic subjects normalized to maximal voluntary efforts. Practice, feedback and motivation were employed during testing as recommended for eliciting maximal-efforts for those with knee OA (Lewek et al., 2004b). While different levels of inhibition may exist for asymptomatic controls and OA subjects, knowing at what percentage of a maximal-effort a subject is working is considered an important standard for evaluating EMG of symptomatic subjects (Kasman et al., 1998). Another important issue is the potential for cross talk, and validation techniques suggested in the literature were employed in this study (Shiavi et al., 1987; Winter et al., 1994) and excellent correlations between indwelling and surface recordings have been previously reported (Ivanenko et al., 2004) for the muscles examined in this study.

In conclusion, this is the first comprehensive study to quantify amplitude and shape characteristics of the main knee joint musculature for those with severe knee OA throughout the gait cycle. The results support the hypothesis that a general co-activation pattern among different muscle groups was the dominant characteristic pattern. Characteristics unique to the different muscle groups such as the bursts of activity for the gastrocnemius muscles during propulsion and the initial loading phase for the quadriceps muscles were responsible for small percentages of the variation. The second hypothesis that differences existed between muscles in the same agonist grouping was partially supported. Both shape and amplitude differences between the lateral hamstring and medial hamstring (indicative of selective recruitment of lateral and medial sites) and lower amplitude for rectus femoris (indicative of a lower neural drive) compared to the two vasti muscles were found.

8. Conflict of interest

There are no conflicts of interests.

Acknowledgement

The authors wish to acknowledge the assistance of Mina Agarabi, Allan Hennigar, Scott Landry, Jennifer McNutt

and Laura Diamond for their assistance with data collection and subject recruitment. The authors acknowledge the funding support from the Canadian Institutes for Health Research.

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