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Abstract

To determine test-retest reliability of a surface electromyographic protocol designed to measure knee joint muscle activation during walking in individuals with knee osteoarthritis (OA). Twenty-one individuals with moderate medial compartment knee OA completed two gait data collections separated by approximately one month. Using a standardized protocol, surface electromyograms from rectus femoris plus lateral and medial sites for the gastrocnemii, vastii and hamstring muscles were recorded during walking. After full-wave rectification and low pass filtering, time and amplitude normalized (percent of maximum) waveforms were calculated. Principal component analysis (*PP-scores*) and co-contraction indices (CCI) were calculated from the waveforms. Intraclass correlation coefficients ($ICC_{2,k}$) were calculated for *PP-scores* and CCI's. No differences in walking speed, knee muscle strength and symptoms were found between visits ($p>0.05$). The majority of *PP-scores* (17 of 21) and two of four CCIs demonstrated $ICC_{2,k}$ values greater than 0.81. Remaining *PP-scores* and CCIs had $ICC_{2,k}$ values between 0.61 to 0.80. The results support that reliable EMG characteristics can be captured from a moderate knee OA patient population using a standardized protocol.

1. Introduction

Surface electromyography (EMG) has been used for decades to understand neuromuscular activation during walking with typical EMG patterns presented in the literature for healthy individuals [Winter and Yack, 1987]. Of interest to the present study is to understand how and why these typical responses are altered with pathology, in particular with knee osteoarthritis (OA).

OA is the most prevalent form of arthritis and the knee is the most common joint affected [Lawrence et al, 2008]. Joint structural impairments, including osteophytosis and articular cartilage degeneration, and changes to the surrounding tissue such as muscles, ligaments and nerves [Brandt et al, 2008] can help to explain the altered muscle activation characteristics previously reported for those with knee OA compared to asymptomatic controls during functional tasks [Heiden et al, 2009; Hubley-Kozey et al, 2006; Lewek et al, 2004a; Zeni et al, 2010]. Based on cross-sectional studies, specific muscle activation differences have been related to degree of OA severity [Hubley-Kozey et al, 2009; Zeni et al, 2010]; however, longitudinal studies are needed to establish relationships between OA progression and neuromuscular responses during walking. These findings provide the foundation for evaluating the effect of interventions on muscle activation characteristics during gait and alterations have been reported for both surgical and non-surgical treatments [Hubley-Kozey et al, 2010; Ramsey et al, 2007].

While reliability of surface EMG has been found for healthy individuals during gait [Bogey et al, 2003; Kadaba et al, 1989; Murley et al, 2010] few studies exist on patient populations [Bolgla et al, 2010]. Individuals with knee OA can have fluctuating symptoms and EMG recording variability greater than asymptomatic controls [Hubley-Kozey et al, 2009; Zeni et al, 2010]. Given recent increases in the number of studies examining surface EMG as an

evaluative tool in knee OA research, the present study sought to examine the reliability of EMG characteristics from an OA population using a standardized protocol.

Guidelines to improve reliability and validity exist including standard electrode placement, normalization procedures, validation checks and equipment characteristics [Burden, 2010; Hermens et al, 2000; Winter et al, 1994]. However, protocols for those with knee OA may require modifications given that patient anthropometrics, pain, ability to complete repeat trials, and difficulties in producing maximal effort activations at different knee joint positions can exist compared to healthy controls. A wide range of methods are found in reporting OA-gait related EMG characteristics, and to our knowledge no study has investigated reliability.

The purpose of this study was to determine test-retest reliability of a protocol designed to measure knee joint muscular activity characteristics during walking in individuals with moderate medial compartment knee OA. Characteristics were calculated from principal component analysis (PCA) of the waveform data and from knee joint muscle co-contraction indices. We hypothesized that reliable EMG measures will be found between days using a standardized protocol that considered factors specific to the OA population. If not, do fluctuations in clinical status such as symptoms explain these differences?

2. Methods

2.1 Participants

The main cohort included twenty-two participants (reliability group) with medial compartment knee OA recruited between August 2008 and September 2011 who were tested twice, separated by approximately one month. A second group included a larger cohort (n=149) of participants with moderate medial compartment knee OA recruited between May 2003 and October 2011 that was used to construct stable PCA models (PCA group). PCA group included

participants that were tested once (n=127) and participants from the reliability group for one of their visits (n=22). See Table 1 for participant details. Medial compartment knee OA diagnosis was made by a single orthopaedic surgeon (W.D.S.) using radiographic and clinical criteria of the American College of Rheumatology [Altman et al, 1986]. Moderate knee OA classification was based on clinical (managed conservatively) and functional status as previously described [Hubley-Kozey et al, 2006]. Standard anterior-posterior and lateral radiographs were scored by a single experienced (W.D.S.) reader using Kellgren-Lawrence radiographic grading [Kellgren and Lawrence, 1957]. Participants were excluded who had lower extremity surgery or major trauma within the last year, previous lower extremity joint replacement, other arthritic conditions (e.g. rheumatoid arthritis), neurological disorders (e.g. Parkinson's Disease) or severe cardiovascular disease (e.g. angina pectoris). All participants provided informed consent and the study was approved by the local research ethics board.

At each data collection, participants completed the Western Ontario McMaster Universities Osteoarthritis Index (WOMAC LK3.1) [Bellamy et al, 1988]. For the reliability group, active knee flexion and extension range of motion was recorded in supine using a standard goniometer, knee joint was assessed for effusion using the stroke test [Cibere et al, 2004] and a numerical pain rating scale assessed intensity of pain at the beginning of testing (0 no pain, 10 being the worst pain) [Spadoni et al, 2004].

2.2 Procedures

An EMG protocol [Hubley-Kozey et al, 2006] consistent with published guidelines [Hermens et al, 2000] included standard skin preparation, then surface electrode (Ag/AgCl, 10 mm diameter, 20 mm inter-electrode distance, Medi-Trace 133 electrodes, Covidien, Mansfield, MA, USA) placement in a bipolar configuration along the muscle fibre orientation of the lateral

gastrocnemius (LG), medial gastrocnemius (MG), vastus lateralis (VL), vastus medialis (VM), rectus femoris (RF), medial hamstring (MH-semimembranosus/semitendinosus), and lateral hamstring (LH-biceps femoris) based on standardized landmarks [Rutherford et al, 2011]. See Figure 1 for electrode placement. For the reliability group, one of three examiners (S.M.R., D.J.R., G.H.M.) applied the electrodes, but the same examiner did not necessarily complete data collection for the same participant on both testing visits. Examiner choice was based on availability. Following electrode placement, muscle palpation and a series of submaximal isometric contractions for specific muscle groups were used for EMG signal validation [Winter et al, 1994] and gain adjustment (500x – 5000x). No recordings were made within 10 minutes of applying the electrodes. Signals were pre-amplified (500X) then amplified using an eight channel EMG measurement system (Bortec Inc., Calgary, AB, Canada) (impedance=~10 GΩ, common mode rejection ratio=115dB at 60 Hz, band-pass 10-1000 Hz).

Infrared Emitting Diode (IRED) triangular sets of markers were affixed to the lower extremity segments, individual IRED markers were secured on the lateral malleolus, femoral epicondyle and greater trochanter and virtual points were digitized as previously reported [Landry et al, 2007].

Participants were given practice trials to establish their self-selected walking speed and for equipment familiarization. Participants then completed five to seven walking trials along a six-metre walkway that were within 10% of their self-selected speed (monitored in real-time using photoelectric gait timers). Footwear was self-selected, but participants were asked to wear comfortable walking shoes and the reliability group was asked to wear the same footwear for both visits.

Three-dimensional IRED motion was sampled at 100Hz with an Optotrak 3020 optoelectronic motion capture system (Northern Digital, Inc., Waterloo, ON, Canada). Three-dimensional ground reaction forces and moments were recorded from a single AMTI force platform (Advanced Mechanical Technology, Inc., Watertown, MA, USA), embedded in the walkway aligned with the global coordinates of the motion capture system. EMG and force plate signals were analog to digital converted at 2000 Hz using the analogue data capture feature of the Optotrak System (16 bit, +/-2 V) (Northern Digital Inc., Waterloo, ON, Canada), synchronized and stored for later processing.

Following the gait trials, resting muscle activity was recorded from a supine position. Participants then performed a series of eight maximal voluntary isometric contractions (MVIC) aimed at eliciting maximal activation from each muscle [Hubley-Kozey et al, 2006]. Exercises included: 1) knee extension with the knee at 45^{o} of flexion in sitting, 2) combined isometric hip flexion plus knee extension with the knee in 45^{o} of flexion in sitting, 3) knee flexion with the knee at 55^{o} of flexion in sitting, 4) knee extension with the knee at 15^{o} of flexion in supine, 5) knee flexion with the knee at 15^{o} of flexion in supine, 6) ankle plantarflexion with the ankle in neutral position in long sitting, 7) standing unilateral heel rise and 8) knee flexion with the knee in 55^{o} of flexion in prone. Standardized verbal encouragement was given to elicit maximal effort with a steady state effort and participants were given one practice trial prior to performing two trials of each exercise. Torque was measured using a Cybex™ isokinetic dynamometer (Lumex, NY, USA) during exercises 1, 3-6 and 8. The maximum torque over a 1 second steady state window from the two trials was determined. Trials were repeated if torque values for the two trials differed by greater than 10%. However, only one additional trial was performed for any

given exercise to minimize fatigue or discomfort. All exercises were held for three seconds with a minimum rest period of 60s between trials.

2.3 Data Processing

Data processing used custom programs written in Matlab version 7.4 (Mathworks, Natick, MA, USA). EMG waveforms were band-pass filtered (20-500Hz), corrected for resting bias, rectified, and low-pass filtered (4^{th} order Butterworth filter) at 6 Hz. Maximum EMG amplitudes for each muscle during MVIC exercises were calculated using a 100 ms moving-average window [Hubley-Kozey et al, 2006]. Maximum EMG amplitudes, regardless of the MVIC exercise in which it occurred, were used for amplitude normalization (%MVIC).

Net external frontal plane knee moments were calculated using inverse dynamics from marker data, force plate data, and previously published segment inertial properties [Vaughan et al, 1999]. Moments were described about the axes of the joint coordinate system and frontal plane knee moments were used to calculate the co-contraction indices as described below.

2.4 Principal Component Analysis

EMG waveforms were amplitude normalized to %MVIC and time normalized to 100% of the gait cycle. For each participant, ensemble averages from five to seven gait trials were created for each muscle for each testing visit. Absolute difference between the two waveforms was calculated for each muscle for the reliability group participants. PCA was applied to the ensemble average waveforms from the PCA group (n=149) as previously described [Hubley-Kozey et al, 2006]. Briefly, separate PCA models were performed for each muscle group (quadriceps, hamstrings and gastrocnemii) and data were arranged into a matrix $\boldsymbol{X}$ (n=149*number of muscles in the group, p=101). An eigenvector decomposition of a cross product matrix ($\boldsymbol{X}'*\boldsymbol{X}$) was completed yielding the corresponding eigenvectors ($\boldsymbol{U}$), named

principal patterns (PP), and associated eigenvalues. A percent trace was calculated from the eigenvalues for each muscle group, and PPs were examined that accounted for >90% of the EMG waveform variance [Hubley-Kozey et al, 2006]. Principal pattern scores (*PP-scores*) were computed (*PP-scores=**X*U**)* for each PP to provide a weighting coefficient for how each individual waveform related to the PP. To determine how well the PPs from the PCA group captured the salient features in the reliability group, waveforms were reconstructed from the PPs for the reliability group on both visits. Absolute differences were calculated between reconstructed and measured waveforms. For each participant in the reliability group, 42 *PP-scores* were calculated (7 muscles, 3 *PP-scores* for each muscle, 2 visits). Only *PP-scores* from the reliability group were extracted for statistical hypothesis testing.

2.5 Co-Contraction Index

Co-contraction indices (CCI) were calculated from the EMG waveforms using the equation below [Lewek et al, 2004a].

$$CCI = \frac{1}{100}\sum_{i=1}^{100}\left[\frac{lower\ EMG_i}{higher\ EMG_i} \times (lower\ EMG_i + higher\ EMG_i)\right]$$

Within each participant, ensemble average EMG waveforms from the five to seven gait trials, time normalized from 100ms prior to heel-strike to the peak knee adduction moment (0-100% interval), were calculated for each muscle. The CCI was calculated for the vastus medialis – medial gastrocnemius (VM-MG), vastus medialis – medial hamstring (VM-MH), vastus lateralis – lateral gastrocnemius (VL-LG) and vastus lateralis – lateral hamstring (VL-LH) muscle pairs.

2.6 Statistical Analysis

Descriptive statistics were calculated for all demographic and dependent variables. Paired t-tests determined significant differences between visits for gait speed, active knee range of

motion, WOMAC subscales, numerical pain rating scale and torque measures. Changes in effusion (stroke test) were noted between visits.

For each muscle, sample ensemble averaged EMG waveforms for each reliability group visit were graphed. *PP-scores* and CCI test-retest reliability was examined using intraclass correlation coefficients ($ICC_{2,k}$) with 95% confidence intervals [Shrout and Fleiss, 1979]. $ICC_{2,k}$ values greater than 0.81 were considered excellent, 0.61 to 0.80 good , and 0.40 to 0.60 fair. Additionally, the standard error of the measurement (SEM) with 95% confidence intervals was calculated for the CCIs [Stratford and Goldsmith, 1997].

3. Results

Group descriptive statistics for the reliability group (n=21, data from one visit for a participant in the reliability group was excluded due to data collection errors) and PCA group (n=149) are provided in Table 1. As seen, reliability and PCA groups had similar descriptive statistics including walking speeds. Mean time between testing visits was 5.3 (2.7) weeks. No significant between visit differences were found for variables shown in Table 1 ($p>0.05$). Differences in the effusion test between visits occurred for 5 out of 17 participants indicating a change in their knee effusion status (i.e. effusion vs. no effusion). Additionally, no significant between visit differences in the torque measures were found (Table 2). The reliability group (n=21) included 11 participants with mild (KL=1 or 2), 4 participants with moderate (KL=3) and 5 participants with severe (KL=4) radiographic knee OA. Radiographs were not available for one participant.

Figure 2 and 3 illustrate reliability group ensemble averaged EMG waveforms for both testing visits. Three principal patterns captured both amplitude and temporal EMG characteristics explaining over 94% of the variance in the EMG waveforms for each muscle group for the PCA

group (feature description in Table 3). Supplemental 1 to 3 provides a graphic display of the PPs and the high and low *PP-scores* for each PP are depicted to assist with interpretation. Mean absolute difference between visits for all waveforms was less than 4.5 %MVIC (Table 4). Mean absolute errors between reconstructed and measured waveforms were less than 3.5 %MVIC for all muscles in the reliability group illustrating that the salient features were captured from the PCA group (Supplemental 4).

For the test-retest reliability of the *PP-scores*, 17 of 21 *PP-scores* had $ICC_{2,k}$ values greater than 0.81 (Table 4). Four remaining *PP-scores* had $ICC_{2,k}$ values between .61 to 0.80. These four included *PP1-score* for MG (overall magnitude) and *PP3-scores* for VL, VM and RF (amplitude difference between late stance/early swing compared to mid-stance). Mean *PP-scores* for the visits are in Supplemental 4.

Mean CCI values are shown in Table 5 (n=19 as frontal plane moments of force were not available for two participants). Two of four CCIs (VM-MH and VL-LG) had $ICC_{2,k}$ values greater than 0.81 with two values between .61 to 0.80 (Table 5). The lowest SEM was for the VM-MG CCI (SEM=4.24) and the highest for the VL-LH CCI (SEM=11.89) (Table 5).

4. Discussion

The findings illustrate that good to excellent ICC values between visits for all EMG characteristics in individuals with moderate knee OA based on a standardized protocol that considered factors related to the knee OA patient population studied. While the average time between tests was approximately one month, participants had minimal fluctuation in their symptoms between visits, or in quantitative measures of muscle strength, range of motion and walking speed. The high reliability estimates between visits reflect the waveform similarities illustrated in Figures 2 and 3 for all muscles. These results, and the fact that examiners used a

standardized protocol but they did not necessarily do the paired tests for any given participant, illustrates the robustness of the protocol, supporting the feasibility of using EMG features to evaluate change over time in either longitudinal progression or interventional studies of knee OA.

4.1 Protocol

The foundation for the protocol was based on standard guidelines including instrumentation and data acquisition characteristics, electrode placement, validation of signals, amplitude normalization, and processing [Hermens et al, 2000]. Specific considerations for this knee OA patient population protocol were three fold. First, electrode placement occurred in either prone or supine. However, in a few cases quadriceps electrodes needed repositioning once a participant was standing due to soft tissue motion. Validations utilized standardized submaximal isometric contractions, to minimize fatigue and symptom provocation prior to gait evaluations.

Secondly, although a minimum of six to ten strides to form a representative profile of lower extremity muscle activation have been recommended [Shiavi et al, 1998], the protocol included five to seven walking trials. The rationale was to minimize fatigue and symptom provocation with repeated trials. In some instances, appropriate force plate contacts were difficult making additional walking trials necessary, so requiring more than seven trials would increase the overall number of actual trials collected to attain appropriate trials.

Thirdly, differences in body mass and hence soft tissue volume conducting properties highlights the need for amplitude normalization procedures to allow for comparisons across muscles and groups [Burden, 2010]. At this time, normalization to maximal voluntary isometric activations has been considered the best approach [Burden, 2010]. Concern has been expressed

with performing maximal activations in patient populations, but no literature demonstrates that this is not feasible in the moderate knee OA population. In fact previous work based on supramaximal electrical stimulation testing revealed no differences between asymptomatic controls and those with moderate knee OA in their ability to recruit their quadriceps muscles (96 and 93% of maximum) during voluntary activations with feedback [Lewek et al, 2004b]. The present study included feedback to participants and produced reliable amplitude measures based on both *PP1-score* and CCI results. This finding is consistent with reliability estimates during stair ascent for VL and VM amplitude measures normalized to maximum for those with patella femoral pain [Bolgla et al, 2010].

We previously reported that one single exercise was ineffective for eliciting maximal levels of activity for all muscles within a group for participants with and without knee OA [Rutherford et al, 2011], supporting the use of this exercise series. Different exercises were included in part based on the findings that muscles within the same group, such as biceps femoris and semimembranosus/semitendinosus, can produce maximal activity at different knee positions during MVICs [Onishi et al, 2002]. Furthermore, given that different joint compartments can be affected in knee OA (i.e. tibiofemoral and patella femoral), knee position during testing was an important consideration given that it can alter contact forces.

In contrast to asymptomatic individuals, day-to-day fluctuations in clinical signs and symptoms could confound reliability estimates in patients with knee OA. For example, knee pain [Henriksen et al, 2007], walking speed [Zeni et al, 2010] and effusion [Rutherford et al, 2012] can affect muscle activation amplitudes. In the current study, clinical characteristics were relatively stable between visits. Participants did not report increased pain with testing, and all completed the series of normalization exercises. Walking speeds and muscle torque were also

similar (Table 1). Thus, small fluctuations in symptoms did not impact the reliability estimates. The next question is to determine when symptom fluctuations occur, are EMG measures sensitive or are they only impacted when structural changes associated with disease progression occur or with mechanical treatment options?

4.2 Principal Component Analysis

Understanding the muscle activation dynamics across the gait cycle has been enhanced by PCA [Hubley-Kozey et al, 2006; Ivanenko et al, 2005]. The general shape and overall amplitude characteristics (PP1) had excellent ICC values except MG EMG waveforms which was in the upper end of the good range ($ICC_{2,k=}$0.73). Very good to excellent between-session reliability for medial gastrocnemius has been reported [Kadaba et al, 1989] and low coefficients of variation have been found [Winter and Yack, 1987]. Lower $ICC_{2,k}$ for MG PP1 may reflect the sensitivity of this measure to knee OA disease, as has been previously reported [Hubley-Kozey et al, 2006]. ICC values for *PP-scores* that examined temporal characteristics were all close to 0.9 except for *PP3-scores* for quadriceps muscles (0.77-0.79). This was interesting as the lowest ICC values reported by Bolgla et al. (2010) were for the pre-swing measure (0.4 and 0.5), which was the feature captured in our *PP3*. The difference in ICCs between studies perhaps illustrates difficulty with apriori end point determination for discrete amplitude measures versus features captured from the data itself through PCA.

4.3 Co-contraction Index

CCI has been employed to understand co-contraction of knee joint muscle pairs [Lewek et al, 2004a; Ramsey et al, 2007; Zeni et al, 2010], yet reliability estimates in patient populations are lacking. CCI means were similar between visits, varying by less than two index units with ICCs good to excellent (Table 5). Given the reliance on EMG amplitude for CCI calculations,

comparable reliability estimates between *PP1-scores* and CCI results were expected. Differences greater than two index units have been shown previously as a result of intervention [Ramsey et al, 2007] and may reflect true change in knee joint muscle co-activation and not change due to measurement error.

4.4 Considerations

Many factors including testers, instruments, protocols and participants can affect reliability. Three examiners were trained in knee OA clinical assessment and in employing a standardized EMG protocol using calibrated equipment and standard processing procedures to maximize reliability. However, other potential confounders such as altered symptoms between testing could potentially affect reliability. Despite these potential confounders, all EMG measures in this investigation, whether amplitude or temporally based, showed at minimum moderate reliability. Absolute differences between testing visits were low, with differences smaller than those previously reported for severity and treatment effects [Hubley-Kozey et al, 2009; Hubley-Kozey et al, 2010; Ramsey et al, 2007]. Since *PP-scores* were generated from PPs from a large data set of individuals with moderate knee OA (i.e. PCA group), muscle activation characteristics that were unique to the reliability group may not have been readily identified. Demographic and gait speed were however similar between groups and reconstruction differences were small (Supplemental 4) supporting that the salient features for the reliability group were captured in the PCA group. Lastly, this protocol was well tolerated by the moderate knee OA group, which included individuals with mild to severe joint degeneration based on radiographic scoring. However, future studies should examine whether pre surgical groups with poor symptoms and severe joint degeneration have similar reliability.

4.5 Limitations

ICCs are a standard index of correlation between repeated measures using the same methods, but interpretation of ICCs can be misleading particularly in cases where between-subject variability is high. However, in the present study this was not the case as there was no clear pattern of higher ICCs being associated with more between-subject variability, and the average waveforms support between day reliability. Furthermore while terms such as poor, fair, good, moderate, substantial or excellent reliability based on ICCs values have been proposed [Shrout, 1998] and generally used, caution needs to be exercised when using these descriptors. Specifically differences found between days need to be related to the magnitude of clinically significant differences. Continued research on the effects of interventions and progression as mentioned above [Hubley-Kozey et al, 2009; Hubley-Kozey et al, 2010; Ramsey et al, 2007] will help to establish clinically relevant differences upon which to judge reliability estimates.

4.6 Conclusion

A controlled standardized protocol was used to record and measure surface EMG signals during gait in participants with moderate knee OA who had minimal changes in clinical status between testing sessions. Good to excellent test-retest reliability estimates were achieved for all amplitude and temporal knee muscle EMG waveform characteristics based on PCA and CCI calculations with over half (11/21) of the *PP-score* $ICC_{2,k}$ values above 0.9. These results support the feasibility of muscle activation features to evaluate change over time in either longitudinal progression or interventional studies of knee OA.

Conflict of Interest

The authors report no conflict of interests.

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Table 1: Means (standard deviation) or frequency count for demographic, stride, and clinical characteristics for reliability (both visits) and Principal Component Analysis (PCA) groups.

Variable	Reliability Group (n=21) Visit 1	Reliability Group (n=21) Visit 2	PCA group (n=149)
Age (y)	57 (9)	57 (9)	58 (9)
Height (m)	1.73 (0.08)	1.73 (0.08)	1.72 (0.09)
Mass (kg)	92.3 (20.2)	92.2 (20.7)	91.0 (17.6)
BMI (kg/m^2)	30.6 (4.8)	30.7 (5.0)	30.6 (5.1)
Sex (frequency)	8 women 13 men	8 women 13 men	53 women 96 men
Gait speed (m/s)	1.23 (0.18)	1.25 (0.17)	1.24 (0.19)
WOMAC-pain	7 (3)	6 (3)	7 (4)
WOMAC-stiffness	4 (1)	4 (2)	4 (2)
WOMAC-function	22 (10)	20 (10)	22 (12)
WOMAC-total	33 (14)	30 (13)	32 (16)
NPRS	1 (2)	2 (2)	-
Stroke (effusion) test[*]	12 negative 6 positive	11 negative 6 positive	-
Flexion AROM (^{o})[*]	126	124	-
Extension AROM (^{o})[*†]	-3	-4	-

Abbreviations: BMI, body mass index; WOMAC, Western Ontario and McMaster Universities Osteoarthritis Index; NPRS, numerical pain rating scale; AROM, active range of motion. [*]Stroke test was not performed for three participants on visit 1 and four on visit 2. AROM was not measured for three participants. [†]Negative extension AROM values represent an inability to get to full extension.

Table 2: Means (standard deviation) for torque measures from the maximum voluntary isometric contractions (MVIC).

MVIC (Nm)	Reliability Group Visit 1	Reliability Group Visit 2	p value
Knee extension, 45 degrees	122.5 (46.9)	125.1 (43.7)	0.56
Knee extension, 15 degrees	79.2 (34.9)	84.2 (32.4)	0.28
Knee flexion, 55 degrees in sitting	65.8 (31.3)	67.3 (30.3)	0.67
Knee flexion, 15 degrees in supine	57.8 (22.2)	52.4 (20.6)	0.11
Knee flexion, 55 degrees in prone*	60.7 (24.2)	60.2 (20.7)	0.82
Ankle plantarflexion*	96.2 (26.9)	104.0 (26.1)	0.17

*Only 20 participants completed these MVIC for both testing visits.

Table 3: Explained variance and description of the principal patterns for each muscle group from the PCA group. See supplemental 1, 2 and 3 for additional interpretation.

Muscle Group	Principal Pattern	Description	Explained Variance (%)
Gastrocnemius	1	General shape and overall amplitude- Greater score = higher overall amplitude	89.2
	2	Phase shift in timing- Greater score = increase activity earlier in stance	4.3
	3	Difference operator- Greater score = smaller difference between early and late stance amplitudes	2.7
Quadriceps	1	General shape and overall amplitude- Greater score = higher overall amplitude	87.5
	2	Prolonged activity mid-stance- Greater score = smaller difference between mid and early stance activity	4.1
	3	Late stance burst- Greater score = burst of activity late stance/early swing	2.5
Hamstring	1	General shape and overall amplitude- Greater score = higher overall amplitude	81.4
	2	Prolonged activity mid-stance- Greater score = smaller difference between mid and early stance activity	9.7
	3	Phase shift- Greater score = burst of activity after heel strike compared to late swing	3.1

Table 4: Mean (standard deviation) of the absolute difference between waveforms on visit 1 and visit 2 and intraclass correlation coefficients ($ICC_{2,k}$) with confidence intervals (CI) of the principal pattern scores.

Muscle	Mean Absolute Difference (%MVIC)	Principal Pattern	$ICC_{2,k}$	Lower 95% CI	Upper 95% CI
LG	3.9 (2.5)	1	0.83	0.59	0.93
		2	0.87	0.69	0.95
		3	0.95	0.84	0.98
MG	4.2 (2.6)	1	0.73	0.32	0.89
		2	0.92	0.80	0.97
		3	0.92	0.80	0.97
VL	4.2 (4.3)	1	0.82	0.55	0.93
		2	0.94	0.86	0.98
		3	0.77	0.43	0.91
VM	3.9 (4.4)	1	0.83	0.59	0.93
		2	0.94	0.86	0.98
		3	0.78	0.46	0.91
RF	2.4 (1.8)	1	0.97	0.92	0.99
		2	0.98	0.95	0.99
		3	0.79	0.47	0.92
LH	3.7 (2.6)	1	0.94	0.85	0.98
		2	0.97	0.93	0.99
		3	0.89	0.72	0.95
MH	2.9 (2.3)	1	0.84	0.61	0.94
		2	0.91	0.77	0.96
		3	0.90	0.74	0.96

Abbreviations: LG, lateral gastrocnemius; MG, medial gastrocnemius; VL, vastus lateralis; VM, vastus medialis; RF, rectus femoris; LH, lateral hamstring; MH, medial hamstring; %MVIC, percent maximum voluntary isometric contraction.

Table 5: Means (standard deviation) for the co-contraction indices on both testing visits and reliability statistics.*

Co-contraction Indices	Visit 1	Visit2	$ICC_{2,k}$ (95% CI)	SEM (95% CI)
VM-MH	18.6 (11.2)	19.0 (14.5)	0.89 (0.70, 0.96)	5.99 (4.52, 8.85)
VM-MG	12.0 (8.2)	11.1 (6.4)	0.80 (0.49, 0.92)	4.24 (3.20, 6.26)
VL-LH	24.0 (15.2)	25.7 (22.1)	0.76 (0.38, 0.91)	11.89 (8.98, 17.58)
VL-LG	14.5 (9.3)	13.0 (10.9)	0.89 (0.72, 0.96)	4.50 (3.40, 6.65)

Abbreviations: $ICC_{2,k}$, intraclass correlation coefficient (2,k); CI, confidence interval; SEM, standard error of the measurement; VM, vastus medialis; MH, medial hamstring; MG, medial gastrocnemius; VL, vastus lateralis; LH; lateral hamstring; LG, lateral gastrocnemius.
*The co-contraction indices were only available for 19 participants in the reliability group.

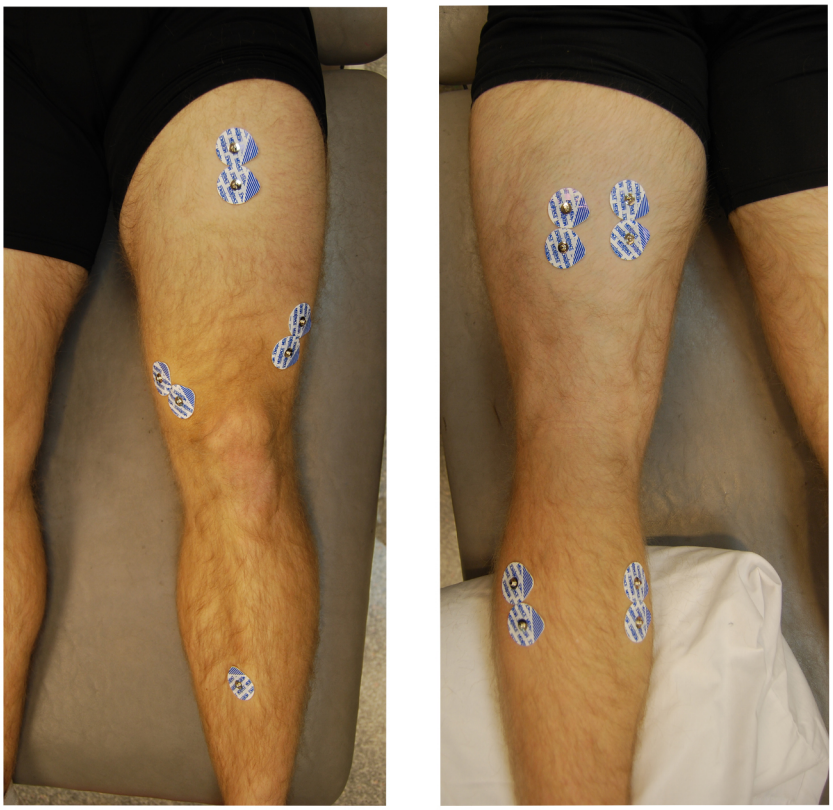

Figure 1: Electrodes were placed along the lead line in a bipolar configuration i) in left panel for vastus medialis (left), vastus lateralis (right) and rectus femoris (central) and ii) in right panel for lateral hamstring (top left), medial (top right) hamstring, lateral gastrocnemius (bottom left) and medial gastrocnemius (bottom right) [Rutherford et al, 2011]. Reference electrode placed on anterior tibial shaft (left panel). Left leg shown.

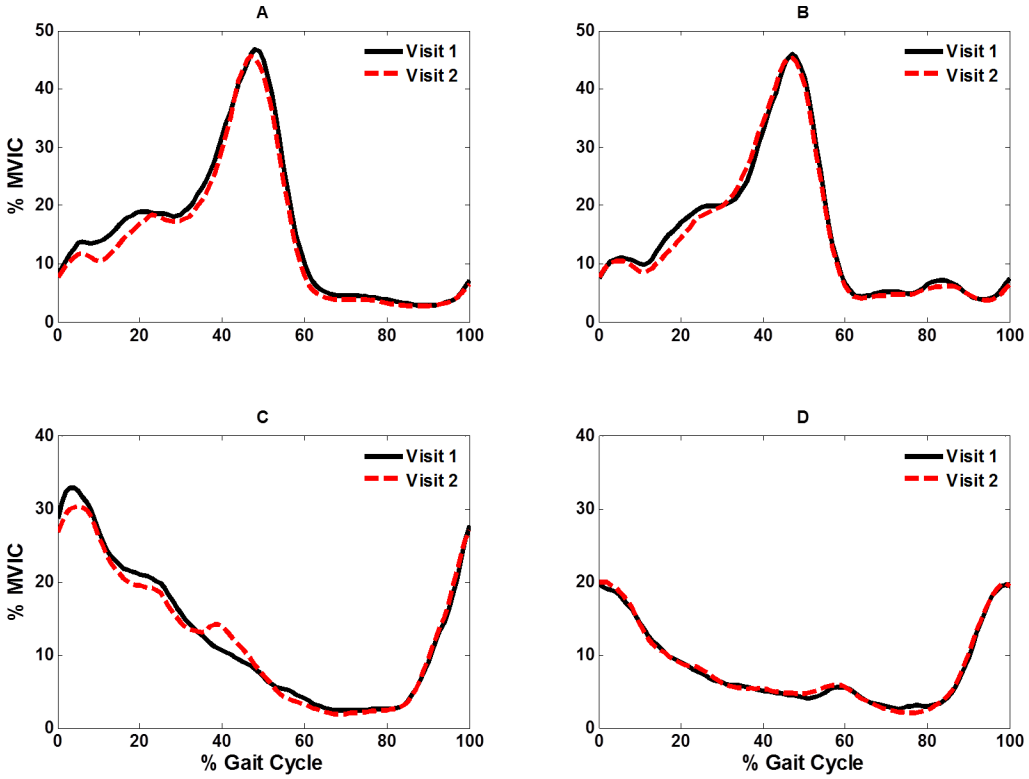

Figure 2. Group ensemble averaged electromyograms of A) lateral gastrocnemius, B) medial gastrocnemius, C) lateral hamstring, and D) medial hamstring for individuals on first (solid) and second (dashed) visits. Percent maximum voluntary isometric contraction (%MVIC) is on the y-axis and percent of gait cycle on the x-axis.

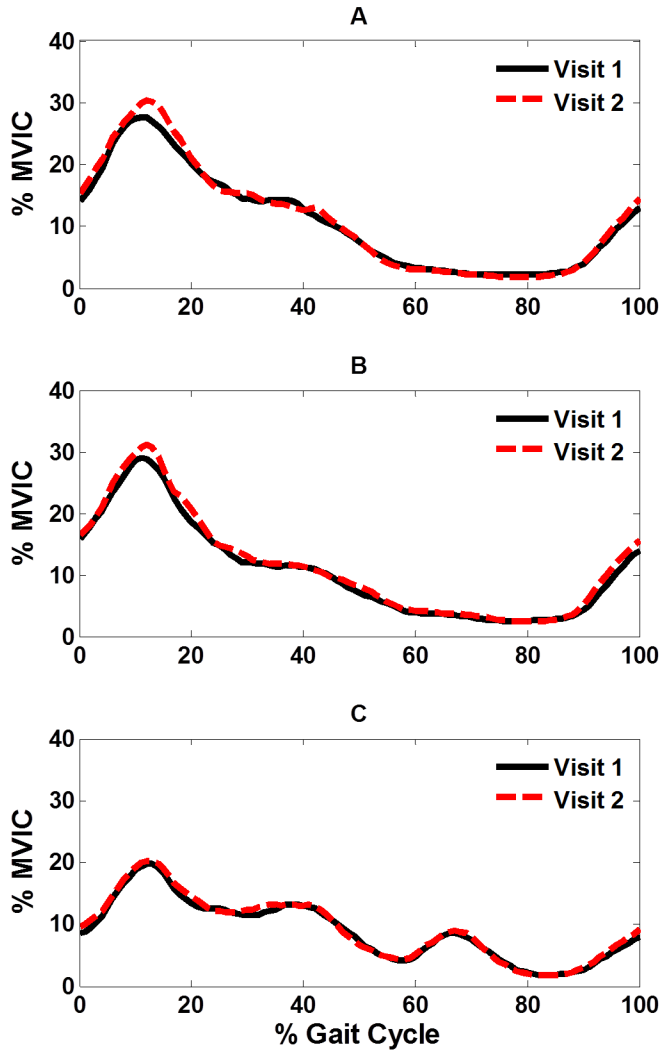

Figure 3. Group ensemble averaged electromyograms of A) vastus lateralis, B) vastus medialis, and C) rectus femoris for individuals on first (solid) and second (dashed) visits. Percent maximum voluntary isometric contraction (%MVIC) is on the y-axis and percent of gait cycle on the x-axis.

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