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Muscle activity amplitudes and co-contraction during stair ambulation following anterior cruciate ligament reconstruction

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Abstract

The purpose of this study was to compare muscle activity amplitudes and co-contraction in those with anterior cruciate ligament (ACL) reconstruction to healthy controls during stair negotiation. Eighteen participants with unilateral ACL reconstruction and 17 healthy controls performed stair ascent and descent while surface electromyography was recorded from knee and hip musculature. During stair ascent, the ACL group displayed higher gluteus maximus activity (1–50% stance, $p = 0.02$), higher vastus lateralis:biceps femoris co-contraction (51–100% stance, $p = 0.01$), and higher vastus lateralis:vastus medialis co-contraction (51–100% stance, $p = 0.05$). During stair descent, the ACL group demonstrated higher gluteus maximus activity (1–50% stance, $p = 0.01$; 51–100% stance, $p < 0.01$), lower rectus femoris activity (1–50% stance, $p = 0.04$), higher semimembranosus activity (1–50% stance, $p = 0.01$), higher gluteus medius activity (51–100% stance, $p = 0.01$), and higher vastus medialis:semimembranosus co-contraction (1–50% stance, $p = 0.02$). While the altered muscle activity strategies observed in the ACL group may act to increase joint stability, these strategies may alter joint loading and contribute to post-traumatic knee osteoarthritis often observed in this population. Our results warrant further investigation to determine the longterm effects of altered muscle activity on the knee joint following ACL reconstruction.

Keywords

Anterior cruciate ligament, Stair ambulation, Electromyography

Disciplines

Biomechanics | Exercise Science | Kinesiology | Motor Control | Psychology of Movement

Comments

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1. INTRODUCTION

Post-traumatic osteoarthritis develops in 50-70% of people with anterior cruciate ligament (ACL) or meniscus injury, 10-15 years following the trauma (Lohmander et al., 2007; Lohmander et al., 2004; Neuman et al., 2008). Despite ACL reconstruction being routinely performed to restore mechanical function of the knee joint, this surgical intervention does not appear to reduce the risk of developing post-traumatic osteoarthritis (Delince and Ghafil, 2012; Frobell et al., 2010; Frobell et al., 2013). Thus, people following ACL injury constitute a good model to study early knee osteoarthritis onset during everyday tasks, such as stair negotiation.

In addition to immediate effects of the initial trauma, biomechanical alterations are thought to play a role in the pathogenesis of post-traumatic knee osteoarthritis (Little and Hunter, 2013). Biomechanical alterations during dynamic functional tasks, including a single-leg lateral step-up, vertical jump, jogging, walking, stair negotiation, and a single-leg countermovement jump have been reported in people following ACL reconstruction. Specific adaptations include reduced internal knee extensor moments (Bush-Joseph et al., 2001; Hall et al., 2012; Lewek et al., 2002) and increased internal hip extensor moments (Ernst et al., 2000; Hall et al., 2012; Hooper et al., 2002; Nyland et al., 2010). Increased external knee adduction moments have also been reported (Butler et al., 2009), albeit inconsistently (Hall et al., 2012; Webster and Feller, 2012). These altered biomechanics may reflect movement strategies to protect the previous injured knee, and may be accompanied by altered neuromuscular activity patterns. Furthermore, net joint moments do not provide insight into individual muscle function. Altered neuromuscular control might include increased muscle co-activation and altered medial and lateral thigh muscle activity, which have been previously reported in people with established knee osteoarthritis (Heiden et al., 2009; Hortobagyi et al., 2005; Zeni et al., 2010; Hubley-Kozey et al., 2009).

Neuromuscular activity alterations are important to investigate following ACL reconstruction as changes in muscle force distribution are likely to affect the mechanical environment of the knee joint (Hubley-Kozey et al., 2009) during functional tasks. Furthermore, long-term changes in neuromuscular control might precede the development of osteoarthritis and can be potentially addressed through conservative rehabilitation. Indeed, studies have demonstrated changes in lower limb muscle control and muscle activation while wearing a knee brace (Rebel et al., 2001; Smith et al., 2003) and following exercise training programs (Aagaard et al., 2002). Therefore, it is important to gain a better understanding of neuromuscular activity in people following ACL reconstruction so that therapeutic interventions can be more appropriately designed to prevent or potentially delay early knee osteoarthritis onset.

Stair negotiation is a complex daily task which is useful to investigate potential differences in neuromuscular activation strategies. Stair ascent requires a substantial amount of knee flexion and the generation of high joint moments compared to level walking (Hooper et al., 2002), while stair descents require high levels of control to slow the body down (McFadyen and Winter, 1988). To our knowledge, no studies have investigated muscle activation amplitudes during stair negotiation in people following ACL reconstruction. Therefore, the purpose of this descriptive cross-sectional exploratory study was to test whether or not altered muscle activity amplitudes and increased co-contraction intensities are present in people following ACL reconstruction compared to healthy controls. Consistent with previously observed differences in internal knee/hip joint moments post-

ACL reconstruction compared to healthy controls and increased co-contraction observed with knee osteoarthritis, we hypothesized that the ACL reconstruction group would display 1) lower quadriceps muscle activity amplitudes, 2) higher hamstring muscle activity amplitudes, and 3) higher quadriceps:hamstring muscle co-contraction during stair ascent and descent.

2. METHODS

2.1 Participants

Eighteen participants greater than one year from unilateral ACL reconstruction and 17 healthy controls between 18 and 35 years old were recruited from a university setting. These individuals are included in a study focusing on kinematic and kinetic parameters that has been previously published (Hall et al., 2012). Participants were excluded if they had any history of musculoskeletal or neurological conditions precluding safe walking or stair ambulation. Healthy controls were excluded if they had a previous knee injury or surgery. This study was approved by the Institutional Review Board at Iowa State University, and all participants gave their written consent. The ACL group was on average 5 years from surgery (range 1 –18 years). The ACL reconstruction grafts included hamstring (n = 10), patellar tendon (n = 6), or a combination of hamstring and patellar tendon (n = 1), with one participant having an unknown graft.

2.2 Procedures

The experimental staircase consisted of three steps (step height 18.5 cm, tread depth 29.5 cm). Muscle activity signals were collected from a wireless EMG system (Delsys Myomonitor IV, Boston, USA). The surface EMG sensors contained dual bar contacts (1 mm x 10 mm with an intraelectrode distance of 10 mm) made from 99.9% Ag. These EMG sensors were single differential with a gain of 1000 V/V, channel noise <1.2 μV, and CMRR >80 dB. Force platform and EMG data were collected at a rate of 1600 Hz. Two portable force platforms on the first and second step of the stairs (AMTI, Watertown, USA) were used to determine the stance phases of stair ambulation. Previous studies have found inconsistent kinetic strategies between the first and second step during stair use (Hall et al., 2012; Kowalk et al., 1996; Vallabhajosula et al., 2012), highlighting the need to examine more than one step.

Participant age, height, weight, medical history, and physical activity levels (Tegner scale, Tegner and Lysholm, 1985) were recorded. The participant's skin was shaved (when needed), slightly abraded and cleaned with alcohol before surface electrodes were placed. For each participant, electrodes were placed on the affected leg of the post-ACL participants and on the right leg of the controls according to guidelines described by Cram et al. (1998). The electrodes were placed over the muscle belly in line with muscle fibers of the gastrocnemius, vastus lateralis, vastus medialis, rectus femoris, biceps femoris, semimembranosus, gluteus maximus and gluteus medius. A reference electrode was placed over the electrically neutral tissue of the right anterior superior iliac spine.

All participants performed three trials of 5-second maximum voluntary isometric contractions (MVIC) in order to normalize EMG data. Prior to MVIC, participants performed 2-3 warm-up sub-maximal and near maximal efforts for familiarization. Knee extension/flexion MVICs were acquired as manual resistance was applied anterior/posterior and proximal to the ankle joint centre as participants sat upright with the knee flexed to approximately 45°. Hip extensor MVIC was acquired as manual resistance was applied posteriorly to the distal thigh as participants stood upright with arm support. Hip abduction MVIC was acquired as manual resistance was applied lateral and proximal to the ankle joint centre as participants stood upright with arm support. Ankle plantar flexion MVIC was acquired against a wall as participants sat with their knee flexed approximately 45°. Participants were given verbal encouragement during all MVIC tests.

Participants performed two tasks: stair ascent and stair descent. Individuals descended and ascended the stairs using a step-over-step technique at a self-selected pace. Participants performed three trials leading with right and left leg, for a total of six trials for each task. All data were analyzed during the stance phase of walking on the first and second step of both stair ascent and descent. For analyses, step detection was initiated at 5% of body weight (BW) and terminated when the vertical ground reaction force dropped below 5% BW.

2.3 Data Reduction

As an initial step, non-physiological EMG signals consistent with loss of sensor contact with the skin or loss of wireless signal were removed from the analysis. Raw EMG data for the MVICs and stair ascent/descent were bandpass filtered between 10-450 Hz and notch filtered at 60 Hz with a fourth order, dual-pass Butterworth filter. The data were then rectified and filtered using a low-pass filter at 10 Hz to create a linear envelope. MVIC amplitudes were defined as the maximum 30ms moving window with overlap during the MVICs. Individual muscle EMG amplitudes were calculated as the average linear envelope for 1-50% stance and 51-100% stance during the first and second steps of stair ascent/descent, then normalized to the peak MVIC amplitudes.

Based on the equation described by Rudolph et al. (2001), co-contraction indices (CCI) were calculated:

$$CCI_{m1:m2} = avg\left\{\sum_{i=initial}^{i=final} \frac{min\{EMG_{m1}(i), EMG_{m2}(i)\}}{max\{EMG_{m1}(i), EMG_{m2}(i)\}}\left(EMG_{m1}(i) + EMG_{m2}(i)\right)\right\}$$

In this equation, *m1/m2* represent the two muscles being analyzed, *initial/final* were set to 1-50% or 51-100% of stance, *min* represents the EMG linear envelope values from the less active muscle group, and *max* represents the EMG linear envelope values of the more active muscle group at each time step. CCI was calculated during the first and second steps of stair ascent and stair descent. CCIs were calculated for (m1:m2): vastus lateralis:biceps femoris, vastus medialis:semimembranosus, vastus lateralis:vastus medialis and biceps femoris:semimembranosus. All data were processed using custom code written in Matlab^{TM} version 9.0 (The Mathworks Inc., Natick, MA, USA).

2.4 Statistical Analysis

Independent t-tests and chi-square tests were used to determine differences in group characteristics as appropriate. Muscle activity amplitudes were assessed for normality. In the event where muscle amplitudes did not conform to normal distribution, data were squared and log-transformed prior to analysis. Univariate ANOVA was used to test for between group (ACL vs. control) differences for subject characteristics, EMG amplitudes, and CCIs. All data are reported as means and standard deviations. Statistical analyses were performed using SPSS for Windows (Version 21, SPSS Chicago, IL, USA). The statistical significance level was set at $p < 0.05$.

RESULTS

There were no significant differences in subject characteristics ($p > 0.05$) when comparing the ACL group (10 females; 8 males; age 26±6 years; height 1.73±0.14 m; mass 75±16 kg; Tegner score 7±2) to the control group (10 females; 7 males; age 26±4 years; height 1.70±0.12 m; 68±12 kg; Tegner score 6±1).

3.1 EMG Activity Amplitudes during Stair Ascent

The ACL group had a significantly higher gluteus maximus activity amplitude compared to the control group during 1-50% stance ($p = 0.02$) during stair ascent (Table 1). Ensemble curves of muscle activity amplitudes during stair ascent are shown in Figure 1.

3.2 EMG Activity Amplitudes during Stair Descent

The ACL group had a significantly higher gluteus maximus activity amplitude compared to the control group during 1-50% stance ($p = 0.01$) and 51-100% stance ($p < 0.001$) of stair descent (Table 1). The ACL group also had significantly higher semimembranosus amplitude during 1-50% stance ($p =0.01$) and significantly higher gluteus medius amplitude during 51-100% stance. In contrast, the control group had significantly higher rectus femoris amplitude during 1-50% stance ($p =0.04$). Ensemble curves of muscle activity amplitudes during stair descent are shown in Figure 2.

3.3 CCIs during Stair Ascent

The ACL group had a significantly higher vastus lateralis:biceps femoris CCI compared to the control group during 51-100% stance ($p = 0.01$) of stair ascent (Table 2). The ACL group also had a significantly higher vastus lateralis:vastus medialis CCI during 51-100% stance ($p = 0.05$).

3.4 CCIs during Stair Descent

The ACL group had a significantly higher vastus medialis:semimembranosus CCI compared to the control group during 1-50% stance ($p = 0.02$) of stair descent (Table 2).

DISCUSSION

Those with established knee osteoarthritis are reported to have altered muscle activity and increased levels of muscle co-activation (Childs et al., 2004; Hortobagyi et al., 2005; Hubley-Kozey et al., 2009; Lewek et al., 2004), which are thought to affect knee joint loading and function. However, little is known about muscle activity alterations during daily tasks in cohorts at risk to develop knee osteoarthritis, such as individuals with ACL reconstruction. Previously, reduced internal knee extensor moments (Hall et a., 2012; Hooper et al., 2002; Kowalk et al., 1997) and increased internal hip extensor moments (Hall et al., 2012) have been found during stair use in ACL reconstructed individuals compared to healthy controls. In the current study, our purpose was to test whether or not EMG activity amplitudes and CCI were different when comparing ACL reconstructed individuals with healthy controls during stair ascent and stair descent movements.

Our first hypothesis was that quadriceps muscle activity amplitudes would be lower in ACL reconstructed individuals as compared to healthy controls. This hypothesis was not supported since there were no significant differences in vastus lateralis or vastus medialis amplitudes during stair ascent or descent. Reduced vastus medialis activity has been reported in the post-ACL reconstruction injured leg compared to the non-injured leg during counter-movement jumps (Nyland et al., 2010). However, no limb-to-limb difference in vastus lateralis muscle activity was observed during walking or jogging in those with ACL reconstruction (Lewek et al., 2002). Taken together, these studies suggest that more functionally demanding tasks may be required to detect alterations in quadriceps muscle activity. Instead of reduced quadriceps activity, a significantly lower rectus femoris amplitude was observed during the current study for the ACL group during the first half of stair descent. Albeit speculative, this may partially explain the reduced internal knee extensor moments during stair use that have been reported in ACL reconstructed individuals (Hall et al., 2012; Hooper et al., 2002; Kowalk et al., 1997). Reduced rectus femoris activity would also be consistent with increased net internal hip extensor moments during stair use.

Our second hypothesis was that hamstring muscle activity amplitudes would be higher in ACL reconstructed individuals as compared to healthy controls. This hypothesis was partially supported by a significantly increased semimembranosus amplitude for the ACL group during the first half of stair descent. Higher hamstring activity in the ACL group may partially explain the reduced internal knee extensor moment and increased internal hip extensor moment that have been reported in ACL reconstructed individuals (Hall et al., 2012; Hooper et al., 2002; Kowalk et al., 1997; Lewek et al., 2002). Studies on ACL injury (Boerboom et al., 2001; Limbird et al., 1988) and arthroscopic partial meniscectomy patients (Sturnieks et al., 2011; Thorlund et al., 2012) also suggest increased hamstring activity during functional tasks. The increased hamstring activity could intensify compressive loads and alter the patterns of shear in the tibiofemoral joint (MacWilliams et al., 1999). The altered loading patterns likely affect articular cartilage morphology and potentially contribute to cartilage degeneration. In addition to potential impairment of cartilage integrity, increased hamstring activity has been associated with poorer knee function in people 1-2 years following ACL reconstruction (Perraton et al., 2013).

In terms of muscle activity, the gluteus maximus appeared to show the greatest differences between the ACL group and controls. Gluteus maximus activation was higher in the ACL group compared to the control group for both stair ascent (1-50% stance) and stair descent (1-50% and 51-100% stance). These findings are consistent with increased internal hip extensor moments that have been previously reported in ACL reconstructed individuals during stair negotiation (Hall et al., 2012) and during a counter movement jump (Nyland et al., 2010). Combined with decreased rectus femoris activity and higher hamstring muscle activity, we speculate that increased gluteus maximus activity in the ACL group may be a neuromuscular adaptation that shifts the dependence of moment generation from the knee joint to the hip joint. This proposed strategy is likely to result in similar or reduced knee joint internal forces even when increased co-contraction may be needed to improve joint stability. In addition, gluteus medius activation was higher in the ACL group compared to the control group during stair descent (51-100% stance). This is a potentially interesting observation as a greater hip abduction moment during gait has been suggested to be protective against ipsilateral medial knee osteoarthritis progression (Chang et al., 2005). We are not aware of other studies reporting gluteus medius activity for individuals following ACL reconstruction. However, our results are similar to a recent study reporting higher gluteus medius activation for individuals with early signs of medial knee osteoarthritis during one-leg standing (Duffell et al., 2014).

Our third hypothesis was that quadriceps:hamstring muscle co-contraction would be higher in ACL reconstructed individuals. This hypothesis was partially supported as we observed higher vastus lateralis:biceps femoris co-contraction during 51-100% stance of stair ascent and higher vastus medialis:semimembranosus co-contraction during 1-50% stance of stair descent in the ACL group. Our findings likely reflect a neuromuscular adaptation to protect the reconstructed ACL from excessive strain and to stabilise the knee joint. Cadaver studies have reported that during loaded isometric flexion, hamstring co-contraction reduces strain on the ACL, preventing anterior tibial translation and internal rotation of the knee (MacWilliams et al., 1991). In addition, higher co-contraction indexes between vastus medialis and medial hamstrings have been reported in people with knee osteoarthritis and have been shown to discriminate between knee osteoarthritis severities (Hubley-Kozey et al., 2009).

The ACL group also displayed increased vastus lateralis:vastus medialis co-contraction during 51-100% stance of stair ascent. Data from static and dynamic experiments suggest that increased lateral-to-medial quadriceps co-contraction may reflect a neuromuscular adaptation to counteract an external knee varus moment (Lloyd et al., 2001; Pandy et al., 2010). However, results are inconclusive whether external knee varus moments for those with ACL reconstruction are higher (Butler et al., 2009) or not different (Hall et al., 2012) when compared to healthy controls. Interestingly, it has been reported that individuals with osteoarthritis have greater lateral relative to medial co-contraction compared to controls (Heiden et al., 2009). It must be acknowledged that the specific effect of altered neuromuscular strategies on the health of articular cartilage remain unknown. Nonetheless, altered loading likely affects the morphology of the articular cartilage and may contribute to cartilage degeneration (Arokoski et al., 2000). Longitudinal studies are needed to determine the role of increased co-contraction in the development of cartilage degeneration (Zeni et al., 2010).

There are several limitations of this study that warrant consideration. First, as this was an exploratory study, a sample size calculation was not performed a priori and we did not correct for the multiple statistical comparisons performed (Nakagawa, 2004). As such, our findings should be interpreted with caution. Second, due the cross-sectional study design, the potential implications of our findings for early post-traumatic knee osteoarthritis onset remain speculative. While we aimed to investigate long-term muscle activation amplitude of those with ACL reconstruction, the time range from surgery (2-18 years) was expansive. Prospective studies following ACL reconstruction are needed to solidify possible associations between muscle activation and early onset post-traumatic knee osteoarthritis. Third, differences in quality of individual MVICs may inflate or reduce group differences in muscle activity during the tasks and in co-contraction calculations (Zeni et al., 2010). Despite all participants being pain-free and encouraged to maximally contract their muscles during multiple trials, inconsistencies in effort and neuromuscular control may have been introduced during the MVIC collection. In support of using MVICs, previous research has found no differences in voluntary activation as determined using burst superimposition knee extensor strength in persons with previous ACL reconstruction at approximately three months post-surgery (Lewek et al., 2002). Fourth, it should be noted that MVICs in this study were performed against manual resistance similar to a clinical setting. However, MVICs are ideally performed using an isokinetic dynamometer where participants are firmly secured in seated position, similar to Lewek et al., (2002). Fifth, a limitation was the absence of information regarding any concurrent meniscus repair/resection and physical therapy/rehabilitation performed following ACL reconstruction.

To summarize, the results of our study indicate that individuals with ACL reconstruction exhibit higher gluteus maximus, semimembranosus, and gluteus medius activity, but lower rectus femoris activity during stair negotiation. In addition, those with ACL reconstruction displayed higher vastus lateralis:biceps femoris, vastus medialis:semimembranosus, and vastus lateralis:vastus medialis co-contraction during stair negotiation. Overall, these adaptations may reflect compensatory strategies to maintain knee joint stability and reduce internal knee extensor moments. The overall effect remains unknown, since internal knee joint loads may be increased by higher co-contraction, reduced by lower internal knee extensor moments, or the net balance could remain unchanged. Our findings suggest neuromuscular adaptations are present in people at least one year from ACL reconstruction and further research is warranted to determine the effects of these alterations on physical function and long-term joint health.

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None

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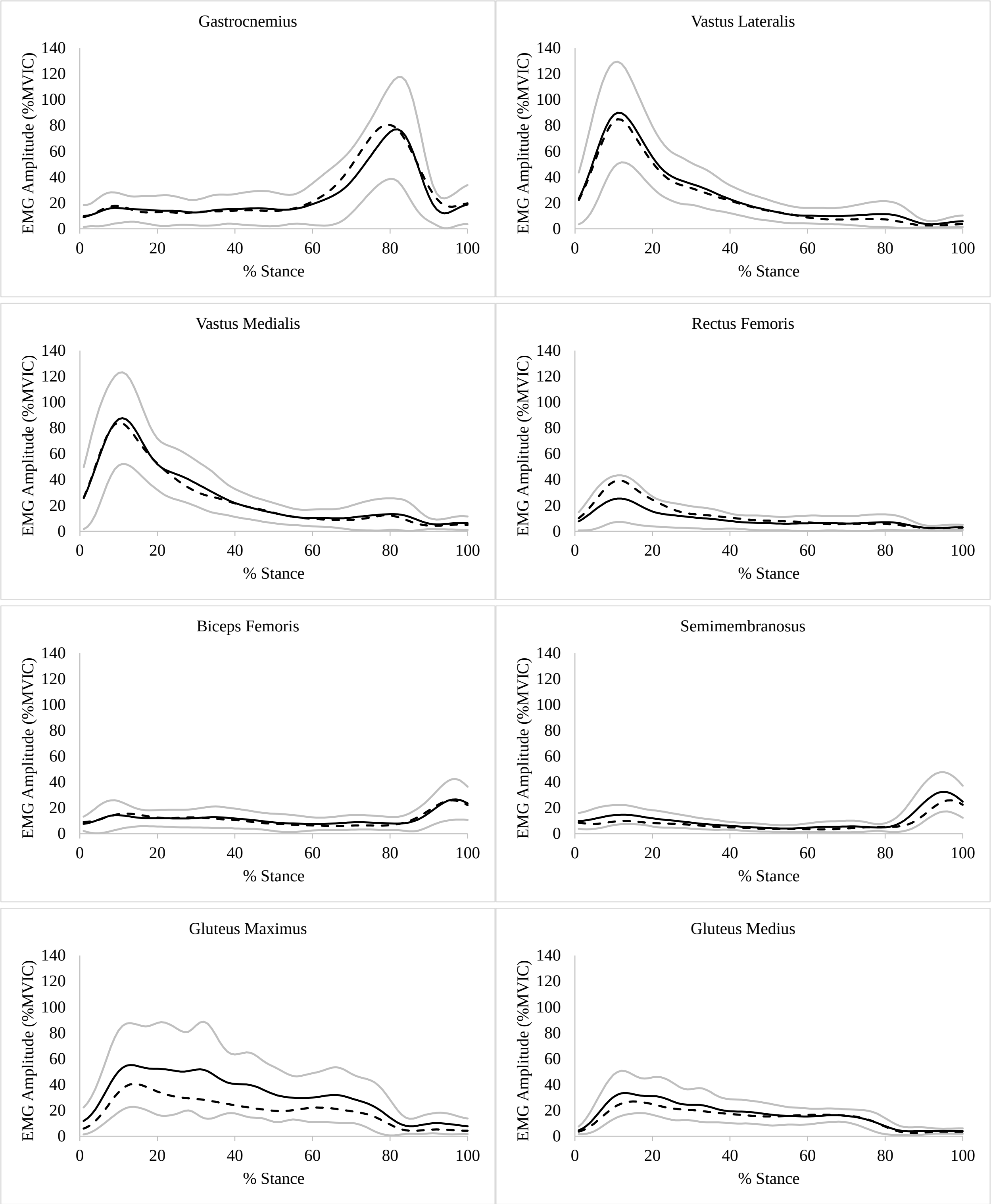

Figure 1: EMG ensemble curves during stair ascent. The black solid lines indicate average values for post-ACLR participants, while the black dashed lines indicate average values for control participants. The grey solid lines represent plus and minus one standard deviation for post-ACLR participants.

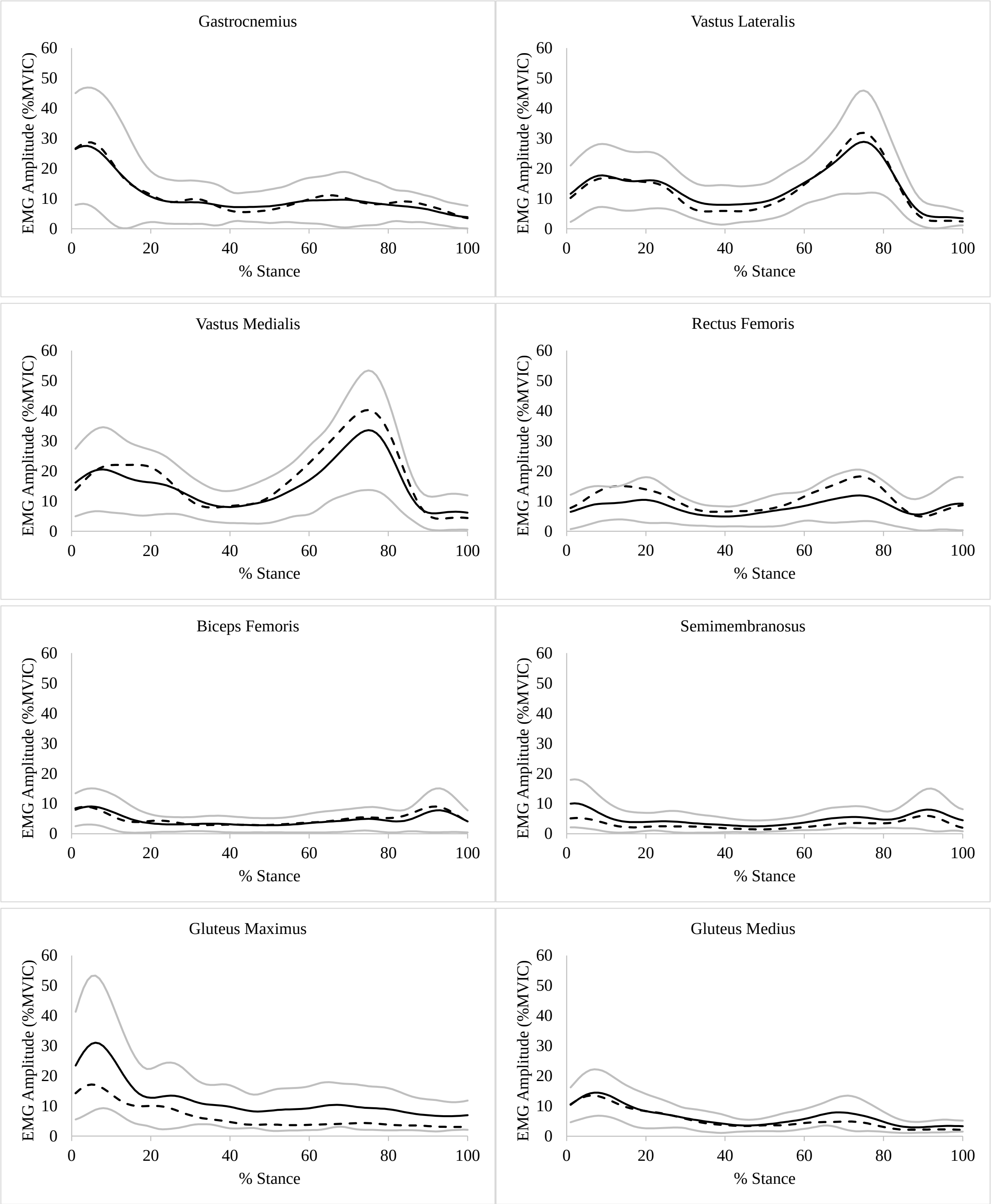

Figure 2: EMG ensemble curves during stair descent. The black solid lines indicate average values for post-ACLR participants, while the black dashed lines indicate average values for control participants. The grey solid lines represent plus and minus one standard deviation for post-ACLR participants.

Table 1. Mean muscle amplitude for the first and second half of stance during stair ascent and star descent. Values are in mean ± SD.

	Stair Ascent					Stair Descent				
	ACL % MVIC	**Control** % MVIC	**ACL - Control** [95% CI]	**F-value**	**p-value**	**ACL** % MVIC	**Control** % MVIC	**ACL - Control** [95% CI]	**F**	**p-value**
Gastrocnemius										
1-50% stance	15.4 ± 8.8	14.2 ± 7.5	[-5.1, 7.4]		0.99†	12.2 ± 6.3	12.6 ± 5.2	[-4.7, 3.9]		0.85
51-100% stance	37.5 ± 17.5	40.4 ± 14.9	[-15.3, 9.4]		0.63	7.3 ± 3.1	8.3 ± 5.1	[-4.1, 2.1]		0.51
Vastus Lateralis										
1-50% stance	44.5 ± 13.7	42.8 ± 22.5	[-11.7, 15.2]		0.80	13.1 ± 5.1	10.9 ± 6.1	[-1.7, 6.2]		0.11†
51-100% stance	9.1 ± 4.4	7.0 ± 3.7	[-0.8, 5.0]		0.15	15.7 ± 4.3	15.0 ± 6.2	[-3.0, 4.5]		0.69
Vastus Medialis										
1-50% stance	44.5 ± 12.9	42.0 ± 13.4	[-7.4, 12.3]		0.61	14.2 ± 7.3	15.5 ± 7.7	[-6.5, 4.0]		0.64
51-100% stance	10.4 ± 5.8	9.0 ± 4.8	[-2.6, 5.4]		0.36†	17.9 ± 6.8	22.3 ± 11.4	[-10.9, 2.0]		0.22†
Rectus Femoris										
1-50% stance	14.0 ± 9.2	18.1 ± 11.6	[-11.6, 3.5]		0.34†	**7.3 ± 3.1**	**10.4 ± 5.0***	**[-5.9, -0.2]**		**0.04**
51-100% stance	5.7 ± 3.8	5.0 ± 2.7	[-1.7, 3.1]		0.57	8.7 ± 4.0	11.6 ± 7.5	[-7.1, 1.2]		0.40†
Biceps Femoris										
1-50% stance	12.3 ± 6.6	11.9 ± 4.8	[-3.9, 4.6]		0.97†	4.5 ± 1.8	4.4 ± 1.9	[-1.2, 1.4]		0.88
51-100% stance	11.9 ± 4.7	10.8 ± 4.4	[-2.3, 4.4]		0.52	4.6 ± 2.1	5.4 ± 2.3	[-2.4, 0.8]		0.31
Semimembranosus										
1-50% stance	9.6 ± 3.6	7.4 ± 3.9	[-0.6, 5.0]		0.12	**4.3 ± 1.8***	**2.8 ± 1.2**	**[0.4, 2.6]**		**0.01**
51-100% stance	11.5 ± 3.4	9.0 ± 3.6	[-0.1, 5.1]		0.06	5.0 ± 2.3	3.8 ± 1.6	[-0.2, 2.7]		0.10
Gluteus Maximus										
1-50% stance	**44.1 ± 21.0***	**28.2 ± 13.3**	**[3.3, 28.7]**		**0.02**†	**15.9 ± 7.4***	**9.9 ± 5.9**	**[1.4, 10.7]**		**0.01**†
51-100% stance	20.9 ± 11.6	13.4 ± 5.2	[1.0, 13.9]		0.07†	**9.1 ± 5.3***	**3.8 ± 2.2**	**[2.5, 8.2]**		**<0.001**†
Gluteus Medius										
1-50% stance	23.8 ± 8.0	19.6 ± 8.1	[-1.4, 9.8]		0.14	8.0 ± 1.6	7.6 ± 3.1	[-1.3, 2.0]		0.69
51-100% stance	11.1 ± 3.8	10.7 ± 4.5	[-2.5, 3.4]		0.56†	**4.9 ± 1.3***	**3.5 ± 1.6**	**[0.4, 2.4]**		**0.01**

Bold denotes significant difference ($p < 0.05$); * denotes significantly larger at $p < 0.05$; † denotes log transformed values; MVIC: maximum voluntary isometric contraction

Table 2. Co-contraction indices (CCI) for the first and second half of stance during stair ascent and descent. Values are in mean ± SD.

Stair Ascent

	ACL % MVIC	**Control** % MVIC	**ACL - Control** [95% CI]	**F-value**	**p-value**
Vastus Lateralis:Biceps Femoris					
1-50% stance	12.1 ± 6.6	11.6 ± 4.9	[-3.8, 4.8]		0.83
51-100% stance	**6.8 ± 3.4***	**4.2 ± 2.2**	**[0.5, 4.8]**		**0.01**†
Vastus Medialis:Semimembranosus					
1-50% stance†	8.6 ± 3.7	6.2 ± 3.7	[-0.4, 5.3]		0.09
51-100% stance	4.8 ± 2.0	3.6 ± 1.7	[-0.2, 2.6]		0.10
Vastus Lateralis:Vastus Medialis					
1-50% stance	46.3 ± 14.2	41.7 ± 16.8	[-7.0, 16.2]		0.42
51-100% stance	**9.0 ± 4.7***	**6.0 ± 3.5**	**[-0.1, 6.1]**		**0.05**†
Biceps Femoris:Semimembranosus					
1-50% stance	8.9 ± 4.7	6.4 ± 3.5	[-0.7, 5.7]		0.12
51-100% stance	9.6 ± 3.8	7.4 ± 3.5	[-0.6, 5.0]		0.13

Stair Descent

	ACL % MVIC	**Control** % MVIC	**ACL - Control** [95% CI]	**F-value**	**p-value**
Vastus Lateralis:Biceps Femoris					
1-50% stance	4.2 ± 2.8	3.7 ± 2.0	[-1.4, 2.5]		0.50†
51-100% stance	3.3 ± 2.1	3.2 ± 1.8	[-1.5, 1.6]		0.92
Vastus Medialis:Semimembranosus					
1-50% stance†	**3.8 ± 2.4**	**2.0 ± 1.0**	**[0.5, 3.3]**		**0.02**†
51-100% stance	3.7 ± 2.0	2.4 ± 1.1	[0.0, 2.5]		0.15†
Vastus Lateralis:Vastus Medialis					
1-50% stance	11.4 ± 4.9	8.8 ± 3.5	[-0.6, 5.8]		0.10
51-100% stance	14.8 ± 5.8	15.5 ± 7.1	[-5.4, 4.0]		0.76
Biceps Femoris:Semimembranosus					
1-50% stance	3.5 ± 3.1	2.3 ± 1.1	[-0.6, 2.9]		0.20†
51-100% stance	3.9 ± 3.4	3.1 ± 1.1	[-1.1, 2.7]		0.93†