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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.

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, 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, 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

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demonstrated changes in lower limb muscle control and muscle activation while wearing a knee brace (Rebel and Paessler, 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 × 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 fibres 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-s 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 and 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 30 ms 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:

$$\mathrm{CCI}_{m1:m2} = avg\left\{ \sum_{i=initial}^{i=final} \frac{min\{\mathrm{EMG}_{m1}(i), \mathrm{EMG}_{m2}(i)\}}{max\{\mathrm{EMG}_{m1}(i), \mathrm{EMG}_{m2}(i)\}} (\mathrm{EMG}_{m1}(i) + \mathrm{EMG}_{m2}(i)) \right\}$$

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