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Gait Analysis Post Anterior Cruciate Ligament Reconstruction: Knee Osteoarthritis Perspective

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ABSTRACT

Individuals with anterior cruciate ligament (ACL) reconstruction are at increased risk to develop knee osteoarthritis (OA). Gait analysis describing kinetics of the lower extremity during walking and stair use (stair ascent and stair descent) can provide insight to everyday dynamic knee joint loading. In this study, we compared lower extremity gait patterns of those with ACL reconstruction (>1 yr) to a control group. Fifteen ACL reconstructed individuals and 17 healthy controls participated in this study. Knee extensor and flexor strength were assessed. Using inverse dynamics, lower extremity moments were calculated during the stance phase of walking and during two steps of stair ascent and descent. Univariate ANOVA was used to test for main effects between 1) injured leg and control group and 2) non-injured leg and control group. Student paired t-tests were used to determine differences between the injured and non-injured leg. Those with ACL reconstruction exhibited reduced knee extension moments during stair descent and stair ascent (second step) and increased hip extension moments during stair ascent (second step) and walking as compared to controls. Knee flexor strength was significantly reduced in the ACL group, but no differences were found in knee extensor strength. No kinetic differences were observed between the injured and non-injured leg of the ACL group. However, the injured leg had reduced knee flexion angles during stair use as compared to the non-injured leg. Walking and stair ambulation highlight altered joint loading in those with ACL reconstruction surgery. Individuals appeared to compensate for lower knee extension moments by increasing hip extension moments. Furthermore, the load distribution on the articular cartilage is likely shifted as evidenced by reduced knee flexion angles in the ACL reconstructed leg.

Keywords: anterior cruciate ligament reconstruction, knee osteoarthritis, gait analysis, biomechanics, stair ambulation
Introduction

Anterior cruciate ligament (ACL) injuries are among the most common musculoskeletal injuries, occurring frequently in young adults, especially women. Individuals younger than 30 years old sustain ACL ruptures more often as compared to the general population [1, 2]. ACL ruptures are often concurrent with meniscal injuries [2] and where combined injury has occurred, 48% of cases have evidence of knee osteoarthritis (OA) within 5-20 years after initial ACL injury [2, 3]. Therefore, individuals between 35-40 years old are at increased risk of knee OA following ACL rupture [1].

Structural changes associated with ACL injury combined with long-term changes in dynamic loading contribute to the development of knee OA [2]. As a measuring tool, gait analysis is considered a practical and reliable technique to indirectly assess dynamic loads on the lower extremity [4]. Investigating lower extremity kinetics during walking and stair negotiation can provide insight into everyday repetitive loads placed on the knee joint.

Arguably, external knee varus moments have the greatest clinical consequence when considering potential knee OA risk factors. Knee varus moments are associated with medial compression, the compartment most often affected with OA. Miyazaki et al. [5] established that the risk of knee OA progression increased by a factor of 6 with each 1% increase in knee varus moments. Attention has also focused on the role of the hip abductors in protecting against knee OA. Impaired hip abduction moment generation causes contralateral pelvis drop, increasing knee varus moments and compression in the medial knee [6, 7]. Hooper et al. [8] observed no differences in knee varus moments while walking or using the stairs when comparing the injured and non-injured leg one year post-ACL reconstruction. However, Butler et al. [9] observed 21% greater knee varus moments during walking in individuals five years following ACL reconstruction when compared to a control group. Increased knee varus moments may not be present within the first year of ACL rupture, but medial knee loading may increase as time progresses. Further study is required to assess whether dynamic knee joint loading is greater for individuals post-ACL surgery during walking and stair ambulation.
Sagittal lower extremity kinetic accommodations at the knee [8, 10, 11] and hip [8, 11, 12] have been reported following ACL reconstruction. Individuals 6-12 months post-ACL reconstruction have altered walking patterns as compared to controls, including reduced knee flexion angles at mid-stance [8, 11] and reduced internal knee extension moments during early stance [10, 11]. These gait adaptations may lead to degenerative changes in the articular cartilage by altering the loading patterns on the knee joint. Decreased knee flexion angles and internal knee extension moments have been associated with quadriceps weakness in individuals up to one year post-ACL surgery [13, 14]. Large cross-sectional studies have established strong relationships between quadriceps weakness and the onset of knee OA [15, 16]. Persistent quadriceps weakness developed through arthrogenic inhibition leads to altered kinetics and kinematics after knee injury [17]. Despite ACL reconstruction and aggressive rehabilitation regimes, weakness in quadriceps musculature exists up to one year post-ACL reconstruction surgery [18]. Theoretically, weak quadriceps musculature reduces the ability to generate the necessary force to provide efficient eccentric control during the loading phase of gait [17]. It has yet to be determined if quadriceps weakness along with reduced knee extension moments and knee flexion angles persist long-term (greater than one year after ACL reconstruction).

The purpose of this study was to analyse the gait of those with ACL reconstruction and a comparable healthy group during three tasks: stair ascent, stair descent, and level walking. The primary focus was to determine if factors associated with the development and/or progression of knee OA were observed in the ACL reconstructed limb when compared to the non-injured limb and healthy counterparts. We hypothesized that the ACL reconstructed leg would display: 1) increased external knee varus moments, 2) reduced knee extensor strength, 3) reduced knee flexion angles, and 4) reduced knee extension moments when compared to the non-injured limb and control group.
Participants

Individuals >1 year from unilateral ACL reconstruction and healthy controls between 18-35 years old were recruited from a university setting. Exclusion criteria included history of any other musculoskeletal or neurological conditions precluding safe walking and stair negotiation. Control participants were excluded if they had a previous knee ligament injury or surgery. Our study aimed to match participants (i.e., age and sex) at group level. This study was approved by the Institutional Review Board at XXXX XXXX XXXX. The ACL group was on average 6 years from reconstruction surgery (range 2-18 years). The reconstruction type varied: 41% hamstring graft, 41% patellar tendon, 12% combination of cadaver and hamstring, and 6% cadaver. Most of the ACL group sustained meniscal damage at time of ACL rupture (71%), and 59% of the ACL ruptures were considered non-contact in nature.

Methods

A 6 m walkway and a three-step staircase (step height 18.5 cm, tread depth 29.5 cm) were used. Kinematic data were collected using an 8-camera, three-dimensional motion analysis system (Vicon Nexus, Los Angeles, CA). Kinetic data were recorded using two portable force platforms positioned on the first and second step of the stairs and one in-ground force platform for level walking (AMTI, Watertown, MA). Kinematic data were collected at a sampling rate of 160Hz, while force platform data were collected at a rate of 1600Hz.

After informed consent was obtained, age, height, weight, medical history, and physical activity levels (Tegner scale) were recorded. Knee extensor and knee flexor strength data were acquired by two testers using a hand-held dynamometer (Lafayette Instrument Company, Lafayette, IN). While maintaining a seated upright position with the knee flexed approximately 90°, participants performed three maximal knee flexion and knee extension contractions against matched manual resistance. Participants were pain-free and received standardized instructions and verbal encouragement during the strength tests. High inter-rater reliability and good intra-rater reliability was achieved (ICC = 0.89-0.97, ICC = 0.76,
respectively). The peak dynamometer force used for analysis was normalized to body mass using an allometric model [19].

Retro-reflective markers (1.9 cm diameter) were placed bilaterally on the medial and lateral malleoli, heel, fifth metatarsal head, dorsal foot, anterior shank, medial and lateral femoral condyles, anterior thigh, greater trochanter, anterior superior iliac spine, posterior superior iliac spine, and acromion process. Individual markers were placed on the sacrum and cervicale. Following a static trial, markers on the heels, medial malleoli, medial femoral condyles, and posterior superior iliac spines were removed. Removed markers were recreated during dynamic trials using transforms derived from the static trial. Participants performed three trials leading with each leg for a total of six trials for each task: stair ascent, stair descent, and level walking. Individuals wore preferred shoes, performed tasks at a self-selected pace, and used a step-over-step technique to complete stair tasks.

Data were analysed from the stance phase of walking and the first and second step of both stair ascent and descent. For stair negotiation, stance phase was defined as the period from when vertical ground reaction force reached 20% of body weight (BW) to the point when vertical ground reaction force dropped below 20% BW. Stance phase for walking was initiated at 5% BW and terminated when vertical ground reaction force dropped below 5% BW. Stance time was calculated for each of the three tasks. Gait analysis was performed on both legs of all participants. Noise was reduced in kinematic and kinetic data using a fourth order, symmetric Butterworth filter with a cutoff frequency of 6Hz. Using inverse dynamics, maximum internal ankle plantar flexion, knee extension, hip extension, hip abduction, and external knee varus moments were calculated during each stance phase, transformed to the distal segment coordinate system, and normalized by body mass. Peak moments were averaged across the three trials of each task. Kinetic and kinematic data were processed using custom code written in Matlab™ (The Mathworks Inc., Natick, MA).

Between group (post-ACL versus control) differences for age, height, body mass, physical activity levels, and stance time were compared using t-tests. Univariate ANOVA was used to test for main effects between 1) injured leg and control group and 2) non-injured leg and
control group. Student paired t-tests were used to determine differences between the injured and non-injured leg. Statistical analyses were performed using SPSS for Windows (SPSS, Chicago, IL). A statistical significance level was set at $p \leq 0.05$. An average of right and left leg was determined for the control group and used to compare with the injured and non-injured leg of the ACL group.

**Results**

Overall, 19 people with unilateral ACL reconstruction and 17 healthy controls were examined. Due to equipment malfunction and numerical outliers, a subset of the cohort are presented for stair analysis (ACL = 14; control =13) and walking analysis (ACL = 15; control = 17). There were no differences between the ACL group and controls for age, height, and body mass (Table 1). Furthermore, no differences in Tegner scores were found between the groups, verifying that all post-ACL individuals had returned to typical physical activity levels. No differences were found between the ACL and control group for stance time during stair ascent, stair descent, or walking. This variable was excluded as a possible confounder in our subsequent results.

Knee extensor strength did not significantly differ between the injured leg (21.5 ± 7.3 N/kg$^{0.67}$), non-injured leg (21.5 ± 7.7 N/kg$^{0.67}$), and controls (22.9 ± 6.2 N/kg$^{0.67}$). There were no differences for knee flexor strength between the non-injured leg and controls. However, knee flexor strength was weaker in the injured leg (13.9 ± 2.1 N/kg$^{0.67}$) as compared to controls (15.9 ± 2.4 N/kg$^{0.67}$, $p = 0.021$) and approached significance when compared to the non-injured limb (14.6 ± 2.1 N/kg$^{0.67}$, $p = 0.058$).

Differences were observed in initial knee flexion angles between the injured leg, non-injured leg and controls (Table 2). The injured limb had reduced initial knee flexion compared to the non-injured leg on both steps during stair ascent ($p = 0.020$ and $p = 0.005$; step one and two, respectively) and stair descent ($p = 0.002$ and $p = 0.002$). Additionally, the injured leg had significantly reduced initial knee flexion angles compared to controls during stair
descent on step one ($p = 0.022$) and approached significance on step two ($p = 0.059$). These reductions in knee flexion angles were observed throughout stance phase (Fig. 1).

No significant differences between the legs of the ACL group were found for any kinetic variables examined during any of the tasks (Table 2). However, there were significant differences in peak hip extension and knee extension moments between the injured leg and non-injured leg as compared to controls. Hip extension moments were significantly increased for the injured leg and the non-injured leg as compared to the controls during the second step of stair ascent ($p = 0.029$, $p = 0.029$; injured and non-injured leg, respectively) and during walking ($p = 0.018$, $p = 0.017$). Peak hip extension moments for the injured leg were 26% greater during the second step of stair ascent (Fig. 2a) and 31% greater during level walking (Fig. 2b) as compared to controls. Increased peak hip extension moments approached significance for the non-injured limb during stair descent for step two ($p = 0.051$) as compared to controls.

In contrast, peak knee extension moments were significantly decreased for the injured leg during the second step of stair ascent ($p = 0.024$) as compared to controls. Peak knee extension moments were also reduced during both steps of stair descent for the injured leg ($p = 0.035$ and $p = 0.002$) and the non-injured leg ($p = 0.028$ and $p = 0.004$) as compared to controls. In comparison to controls, the injured leg displayed 22% lower peak knee extension moments on the second step of stair ascent (Fig. 3a), 17% lower during step one of stair descent, and 25% lower during step two of stair descent (Fig. 3b). Ankle plantar flexion moments, external knee varus moments, and hip abduction moments did not differ between the injured leg, non-injured leg, and controls during any of the three tasks.

**Discussion**

This study aimed to determine if established biomechanical parameters associated with the development and/or progression of knee OA existed >1 year post-ACL reconstruction. Knee injuries, including ACL ruptures, increase the risk for early-onset knee OA by 10-fold as compared to the general, uninjured population [20]. Focusing on repetitive movements such
as stair use and walking in a post-ACL reconstruction cohort provides a good model to investigate the early onset of knee OA pathogenesis.

Contrary to our first hypothesis, the injured leg did not display increased knee varus moments during any of the tasks as compared to the non-injured limb or controls. Knee varus moments, closely associated with knee OA, have been reported to increase up to 21% in the injured limb during walking [9]. The average time from surgery was similar to that of this previous study [9], suggesting that additional factors may have influenced knee joint kinetics. For example, type of ACL reconstruction surgery, rehabilitation program, time from injury to surgery, and physical activity level may influence knee OA risk factors.

During walking, the injured leg demonstrated increased hip extension moments despite not having reduced knee extension moments. Increased hip extension moments during the stance phase of walking have also been found in those 6-months post-ACL reconstruction [21]. The injured leg also produced greater hip extension moments during the second step of stair ascent, likely as a compensation for reduced knee extension moments. Studies have found increased hip extension moments combined with decreased knee extension moments during closed-chain exercises in individuals within and following one year post-ACL reconstruction [22, 23]. The ratio of hip:knee extension moments is significantly related to the magnitude of anterior tibia shear in those at least one year from ACL reconstruction surgery [22]. Specifically, higher hip:knee extension moment ratios are associated with reduced anterior tibia shear. Thus, to avoid placing strain on the repaired ACL, individuals may increase hip extension moments and decrease knee extension moments. How this compensatory strategy influences internal knee joint loading is unclear, but we speculate this adaptation likely increases hamstring:quadriceps co-contraction and results in higher compressive loading on the articular cartilage, which may relate to the initiation of knee OA.

Despite our second hypothesis, no differences in isometric knee extensor strength were found. Possibly, isometric tests are less discriminating as a measure of strength compared isokinetic strength tests. This observation has been made in those with partial
meniscectomies [24], which had been performed on many of our participants. Interestingly, we found reduced knee flexor strength in the injured limb as compared to controls.

The third hypothesis was partially supported as the injured leg had reduced knee flexion angles compared to the non-injured leg during stair ascent/descent and the controls during step one of stair descent. While the clinical relevance of these small alterations in knee flexion angles is unclear, it is widely believed that a spatial shift in the location of load contact will lead to degeneration of the articular cartilage [25]. In the current study, reduced initial knee flexion angles during stair use singly discriminates the ACL-reconstructed limb from the non-injured leg. Strength and proprioception affect knee position, and despite no differences in isometric extensor strength, it remains possible that strength deficits at the end of range of motion are present. Weak knee flexors are likely to contribute to reduced initial knee flexion angles. In addition, proprioception impairments have been observed in those up to one year post ACL reconstruction [26].

Our fourth hypothesis was also partially supported, as reduced knee extension moments were found in the injured leg during stair descent and the second step of stair ascent. It is likely that reduced knee extensor moments are an adaptation to reduce stress on the injured ACL and to reduce pain related to compressive forces [27]. Decreased knee extension moments have been observed in ACL reconstructed limbs up to one year post surgery during stair ascent [8, 28], stair descent, and walking [14]. Our findings suggest this strategy continues long-term when surgical recovery is complete, individuals are pain-free, and normal physical activity levels return. Knee extension moments are indicative of quadriceps and hamstring neuromuscular function [17] and have been attributed to reduced quadriceps strength [13, 14] and reduced knee flexion angles in those with ACL injury [14].

Our findings suggest that changes in sagittal moments precede potential changes in frontal moments in those considered at high risk to develop knee OA. However, changes in direction and magnitude of internal loads on the knee joint cannot be determined using only moment data. For example, internal knee extension moments are a net joint moment calculation [29] that does not account for quadriceps and hamstring contributions separately.
A reduced knee extension moment in the injured leg may be the result of increased hamstring activity, in which case knee joint loading would increase. Regardless of deviation, changes in the position of load to areas that were previously unloaded are likely to initiate degeneration [25].

Limitations of this cross-sectional study exist. The kinetic and kinematic differences we found may have existed prior to the ACL injury and perhaps even contributed to the injury occurring. Therefore, the timing of the observed changes and their effect on knee OA pathogenesis remains unknown [30]. While we aimed to investigate long-term gait patterns of those with ACL reconstruction, the range of time from surgery (2-18 years) was wide. Future studies with narrower time ranges from surgery are needed to assess ACL-reconstructed gait patterns to solidify possible causative factors (e.g., reduced knee flexion angles and knee extensor moments) for early knee OA onset. Indeed, longitudinal studies are warranted to investigate the onset of frontal plane adaptations, in particular knee varus moments that are closely associated with knee OA.

In conclusion, our findings suggest that biomechanical changes associated with knee OA persist even after an average of six years post-ACL reconstruction. To our knowledge, this is the first study to determine long-term ACL group reductions in knee flexion angles and knee extensor moments during stair use. We speculate that it is a coupling of hip and knee kinetic changes along with reduced knee flexion angles that contribute to the initiation of knee OA.
Table 1. Descriptive statistics comparing ACL reconstruction individuals and healthy controls.

Table 2. Lower extremity kinematics and kinetic during stair ascent, stair descent, and walking. Compared to control: *p<0.05. Compared to ACL non-injured: †p<0.05. Results are in mean ± SD.

Figure 1. Ensemble curves for knee flexion angle during step two of stair ascent and stair descent; injured vs. non-injured of ACL group.

Figure 2. Ensemble curves for hip extension moments during the stance phase of (a) step two of stair ascent and (b) walking; injured vs. control.

Figure 3. Ensemble curves for knee extension moments during the stance phase of the second step of (a) stair ascent and (b) stair descent; injured vs. control.
<table>
<thead>
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<th>Variable</th>
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<th>Control ((n=17))</th>
<th>(p)-value</th>
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<td>7M/10F</td>
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<td>Height (cm)</td>
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<td>Body Mass (kg)</td>
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<td>Stair Descent</td>
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<tr>
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References


