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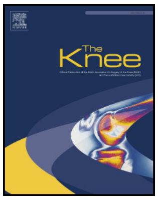

Participants at three months post-operative anterior cruciate ligament reconstruction (ACL-R) demonstrate differences in lower extremity energy absorption contribution and quadriceps strength compared to healthy controls[☆,☆☆]

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ABSTRACT

Background: The purpose of this study was to compare hip and knee energy absorption contribution (EAC) during a double limb squat (DLS) and quadriceps strength in patients three months post-operative ACL-R versus matched healthy controls.

Methods: Twenty-four ACL-R participants (Age = 15.5 ± 1.3 yrs; Ht = 1.66 ± .07 m; Mass = 66.3 ± 15.5 kg) were compared to 24 age, sex, limb, and activity-matched healthy controls (Age = 15.5 ± 1.2 yrs; Ht = 1.65 ± .08 m; Mass = 59.0 ± 9.8 kg). Lower extremity biomechanical data was collected at three months post-operative ACL-R during five consecutive DLS. EAC was calculated during DLS descent. Isokinetic quadriceps strength was collected at 60°/s. Normalized quadriceps peak torque (QUADS) was averaged across five trials. Independent t-tests examined differences in group hip and knee EAC during each task. Separate Pearson product–moment correlations examined the relationship between QUADS and hip and knee EAC during the DLS.

Results: ACL-R demonstrated greater injured limb hip EAC (46.4 ± 16.0) than Healthy (31.7 ± 11.0) during a DLS ($p = 0.001$). ACL-R demonstrated less injured limb knee EAC (42.7 ± 14.6) than Healthy (60.6 ± 8.9) during DLS ($p < 0.001$). No differences were seen between uninjured limb hip (ACL-R = 0.0 ± 14.2; Healthy = 33.4 ± 9.1, $p = 0.629$) or knee (ACL-R = 56.9 ± 15.6; Healthy = 59.1 ± 9.8, $p = 0.561$) EAC and matched limbs. ACL-R injured limb QUADS was decreased compared to Healthy (ACL-R = 1.1 ± 0.5; Healthy = 2.0 ± 0.5, $p < 0.001$). No differences were seen in QUADS on the uninjured and matched limbs (ACL-R = 2.0 ± 0.6; Healthy = 1.9 ± 0.5, $p = 0.894$). There was a weak, negative correlation between injured limb QUADS and hip EAC ($r = -0.471$, $p = 0.001$) and moderate, positive correlation between injured limb QUADS and knee EAC ($r = 0.615$, $p < 0.001$).

Conclusions: ACL-R participants demonstrate different eccentric loading strategies during a DLS at three months postoperative compared to matched healthy controls.

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1. Introduction

Lower extremity joint loading following anterior cruciate ligament reconstruction (ACL-R) has been studied across various different tasks and timeframes [1–10]. Alterations in joint loading as indicated by weight-bearing limb asymmetries after ACL-R have been demonstrated in patients during a squat at six and 12 months following surgery [11]. Similarly, significantly lower knee extension moments and smaller knee flexion and hip adduction angles are present during single-legged squats in patients who have undergone ACL-R when compared to healthy controls at approximately seven months post-operatively [1]. The primary focus of these investigations is on altered lower extremity loading strategies following ACL-R and the potential for re-injury to the ipsilateral limb or initial injury to the contralateral limb [12]. While these studies highlight the long-term joint loading effects of returning to functional activity following ACL-R, there is limited information in the literature that focuses on early stages of rehabilitation and its potential influence on future activity levels and outcomes.

Recent studies [13–15] have examined joint loading during the initial phases of rehabilitation after ACL-R and have identified potential alterations in movement patterns that may impact future functional performance. Patients who had undergone an ACL-R demonstrated a 62% limb symmetry index (LSI) of vertical ground reaction forces (vGRF) during a sit-to-stand task at one month following surgery [13]. Furthermore, LSI of the sit-to-stand task at one month post-operative ACL-R predicted LSI of a countermovement jump at six months after ACL-R. Early knee loading patterns of patients following ACL-R have also been examined during gait at one month, three months, and at time of beginning to jog [15]. The surgical limb presented with reductions in knee flexion angles and negative work compared to the non-surgical limb at each of the time points. Likewise, altered knee asymmetries during gait at one month post-operative ACL-R were related to knee asymmetries at time of return to jogging in these individuals [15]. The results from the aforementioned studies suggest that participants who have experienced an ACL-R demonstrate a diminished capacity to absorb loads across the reconstructed knee when compared to either the uninjured limb or those of healthy controls. While this information is beneficial to the clinician, it does not provide insight into potential movement compensation strategies employed by the other joints of the reconstructed or contralateral limbs.

Energy absorption (EA) has previously been described in healthy individuals as a means of estimating lower extremity muscle activity that produces movement during landing activities [16, 17]. When healthy, physically active participants were classified into high, moderate, and low sagittal plane EA groups, those in the high group demonstrated landing strategies (increased knee extension moment, peak anterior tibial shear force, etc.) during initial ground contact (i.e., 1st 100 ms) that could potentially place greater stress on the ACL [16]. In a similar study, participants in the high frontal plane EA group exhibited greater knee valgus angle at initial contact and peak valgus angle, peak knee varus moment and greater knee valgus angle at peak knee varus moment than those in the low frontal plane EA group [17]. These studies point to the fact that individuals who use larger eccentric muscle actions (EA) in order to dissipate kinetic energy as a means to decelerate the body during the initial phase of landing do so in a manner that may increase the load to the ACL [16, 17]. Energy absorption findings suggest that high demands are placed on the lower extremity during landing and thus sufficient quadriceps strength is necessary. Limited information regarding EA or the contribution of individual joints within the limb (energy absorption contribution (EAC)) in the ACL-R population exists, and in particular during the early phases of early rehabilitation.

Initiation of running following ACL-R often occurs around the three to four month mark [15, 18, 19] and assumes the participant has sufficient quadriceps strength to efficiently absorb energy during lower extremity loading. Isometric quadriceps strength LSI values of 67 ± 23% at 30° knee extension and 56 ± 26% at 90° knee extension have previously been reported in 58 patients at two months following ACL-R [13]. Furthermore, the isometric strength deficits at 90° measured at two months post-operative ACL-R were significantly related to functional testing at the six month time point. While these results indicate that quadriceps strength deficits are present during the early phases of rehabilitation following ACL-R, there is limited information in the literature in regard to early quadriceps strength measures and how this might play a role in the ability to appropriately load the involved limb through energy absorption. Therefore, the aim of this study was to compare EAC of the hip and knee during a double limb squat (DLS) and quadriceps strength in patients who were three months post-operative ACL-R versus matched healthy controls. It was hypothesized that participants in the ACL-R group would demonstrate deficits in EAC of the hip and knee on the involved limb and no differences in EAC on the uninvolved limb when compared to the limbs of matched healthy controls. Additionally, ACL-R individuals will demonstrate lower normalized quadriceps strength measures on the involved limb compared to the matched limb of healthy controls.

Table 1
Participant demographics.

	ACL-R (24)	Healthy (24)	p-Value
Age	15.5 ± 1.3	15.5 ± 1.2	0.91
Height (cm)	166.0 ± 6.8	165.8 ± 8.0	0.90
Weight (kg)	66.3 ± 11.5	58.9 ± 9.8	0.02[a]

[a] Indicates significant difference between the groups.

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2. Material and methods

2.1. Participants

Forty-eight individuals who met the inclusion criteria were enrolled into this study to include 24 participants who underwent ACL-R and 24 age, sex, limb, and activity-matched healthy controls. The ACL-R participants were tested at three months post-operatively as part of a larger ongoing study examining clinical outcomes across the continuum of care. Table 1 details participant demographics. For both groups, participants were considered eligible for this study if they were between the ages of 13 and 25 and were involved in a level 1 (e.g. basketball, football or soccer) or 2 (softball, baseball) sport [20]. For the ACL group, eligible participants were enrolled if they injured their ACL for the first time, but did not experience any of the following: full thickness chondral injuries, grade II or III medial collateral ligament (MCL), lateral collateral ligament (LCL) or posterior collateral ligament (PCL) injuries, or a meniscal tear that required repair. For the control group, eligible participants were enrolled if they were not experiencing an active lower extremity orthopedic injury and had not been injured within the last three months. Following the screening process, if the participants were eligible, they were invited to participate in the study. All participants gave informed consent for the study and the rights of each person were protected. If the participant was a minor, parental consent and child assent were attained. The Institutional Review Board of Texas Health Resources approved the research procedures. Following enrollment in the study, each participant completed a demographic information sheet that included injury history and sports participation.

2.2. Instrumentation

A 10-camera Qualisys Motion Capture System (Qualisys AB, Göteborg, Sweden) with a capture rate of 120 Hz was used to capture joint motions in all three planes during the double limb squat task. Thirty-three reflective markers were adhered to participants' skin/clothing with double-sided tape (Figure 1). Marker placement included bilateral posterior superior iliac crest, bilateral superior sacral poles, inferior sacrum, bilateral greater trochanters, bilateral mid-thigh, bilateral medial and lateral femoral


[redacted]

Figure 1. Participant performing a DLS with marker placement.

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condyles, bilateral mid tibia, bilateral medial and lateral malleoli, bilateral first and fifth metatarsal heads, and bilateral calcaneus. Two Advanced Mechanical Technology, Inc. (AMTI, Watertown, MA) force plates capturing at 1200 Hz were used during data collection to allow accurate time sequencing during data collection and processing, and capture joint kinetics.

2.3. Squat task

Participants were asked to stand with feet shoulder width apart, one foot on each force plate and were instructed to perform a DLS as if they were sitting down into a chair while keeping their hands raised overhead and their feet flat on the floor (Figure 2). A metronome set at 60 bps was used to ensure consistent pace across testing as participants completed five double limb squats.

2.4. Isokinetic testing

The Biodex Multi-Joint Testing and Rehabilitation System (Biodex Medical Systems, Shirley, NY) was used for testing extensor peak torque. For the purpose of this study, extensor peak torque will be referred to throughout the manuscript as quadriceps strength. Participants were seated on the Biodex system and secured with padded straps around the thigh, pelvis, and torso to minimize accessory and compensatory movements during testing [21, 22]. The test limb femoral condyle was aligned with the Biodex axis of rotation as per the manufacturer instructions. Participants performed five submaximal knee extension/flexion repetitions to familiarize themselves with the testing motion. To measure quadriceps strength at 60°/s, participants performed five consecutive concentric contractions [23]. All participants began testing on their uninjured limb followed by the injured limb and the average of the five trials for each limb was normalized to body weight and used for data analysis.

2.5. Data analysis and statistics

All measurements were collected bilaterally and limb dominance (side used to kick a ball) was defined prior to testing. The injured limb of the ACL-R group was matched to the limb of the control group based upon the side of dominance. Data was exported from the Qualisys system to Visual 3D for data processing. Kinematic and kinetic data were filtered with a Butterworth filter with a cutoff frequency of 12 Hz. Energy absorption of the hip and knee joints was calculated by integrating the negative part of the net power (Watts) curve during the descent phase of the DLS and normalized to the product of height and weight ($Ht * BW$) and averaged across the middle three trials. EAC of each joint was calculated relative to the total EA (sum of hip, knee, and ankle EA) and expressed as a percentage. Ankle joint EAC was not included as it was not the variable of interest in this study. Independent T-tests were used to assess for differences between the two groups for EAC of the hip and knee and for quadriceps strength (QUADS). Separate Pearson product–moment correlations were performed to examine the relationship between QUADS and EAC of the hip and knee during the DLS. Alpha level was set at $p < 0.05$.

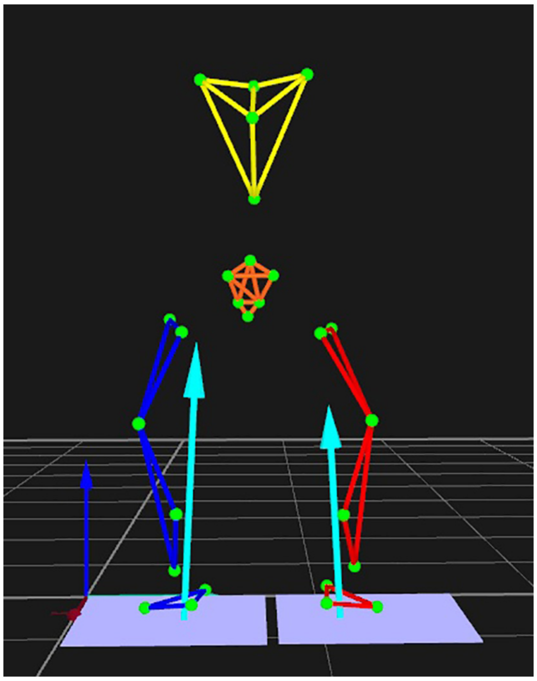

Figure 2. 3D motion capture of DLS with representative ground reaction forces.

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3. Results

ACL-R participants demonstrated significantly greater EAC at the hip (46.4 ± 16.0%, $p = 0.001$) of the injured limb than the hip of the matched limb of the healthy controls (31.7 ± 11.0%) during a DLS (Figure 3a). In contrast, ACL-R participants demonstrated significantly less EAC at the knee (42.7 ± 14.65%, $p < 0.001$) of the injured limb than the knee of the matched limb of the healthy controls (60.6 ± 8.9%) during DLS (Figure 4a). There were no significant differences between hip (ACL-R = 34.0 ± 14.2%; Healthy = 33.4 ± 9.1%, $p = 0.629$) or knee (ACL-R = 56.9 ± 15.6%; Healthy = 59.1 ± 9.8%, $p = 0.561$) EAC on the un-injured and matched limbs (Figures 3b and 4b). QUADS of the injured limb of the ACL-R group was significantly decreased compared to the matched limb of the healthy controls (ACL-R = 1.1 ± 0.5 BW; Healthy = 2.0 ± 0.5 BW, $p < 0.001$). No significant differences were seen in QUADS on the uninjured and/or matched limbs between groups (ACL-R = 2.0 ± 0.6 BW; Healthy = 1.9 ± 0.5 BW, $p = 0.894$). Table 2 demonstrates the between group differences for EAC and strength on the injured and uninjured limbs. Finally, there was a weak negative correlation between QUADS of the injured limb and injured limb hip EAC ($r = -0.471$, $p = 0.001$) and a moderate positive correlation between QUADS of the injured limb and knee EAC of the injured limb ($r = 0.615$, $p < 0.001$).

4. Discussion

The results of this study demonstrate that participants who are at the three month mark following ACL-R utilize altered eccentric loading strategies during a DLS compared to matched healthy controls. The finding of decreased EAC of the injured knee in ACL-R participants when compared to the healthy group is in line with the initial hypothesis. In contrast, there was an increase in EAC of the hip of the injured limb in ACL-R participants which was not expected. Likewise, deficits in QUADS were present in the injured limb of the ACL-R group compared to the healthy controls which is consistent with the second hypothesis of this study. No differences in EAC or strength were found on the uninjured limb. The combination of these findings suggests that an altered movement strategy on the side of the injured limb may have been employed by ACL-R participants in which there was an increased gluteal contribution with a simultaneous decrease in quadriceps contribution during the DLS.

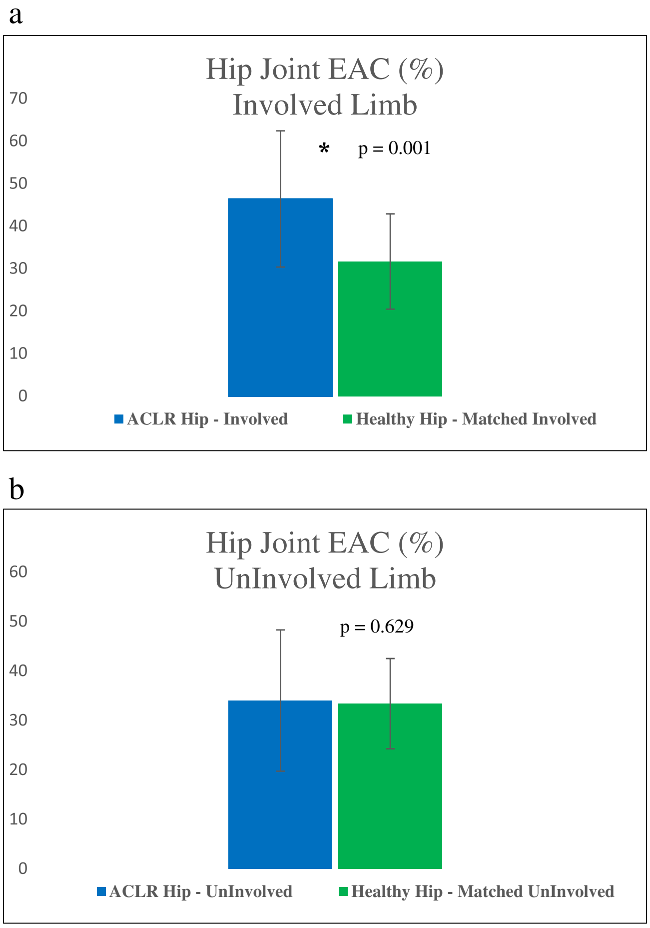

Figure 3. a — Hip Joint Energy Absorption Contribution — Involved Limb ACL-R versus Involved Limb Healthy. b — Hip Joint Energy Absorption Contribution — UnInvolved Limb ACL-R versus UnInvolved Limb Healthy.

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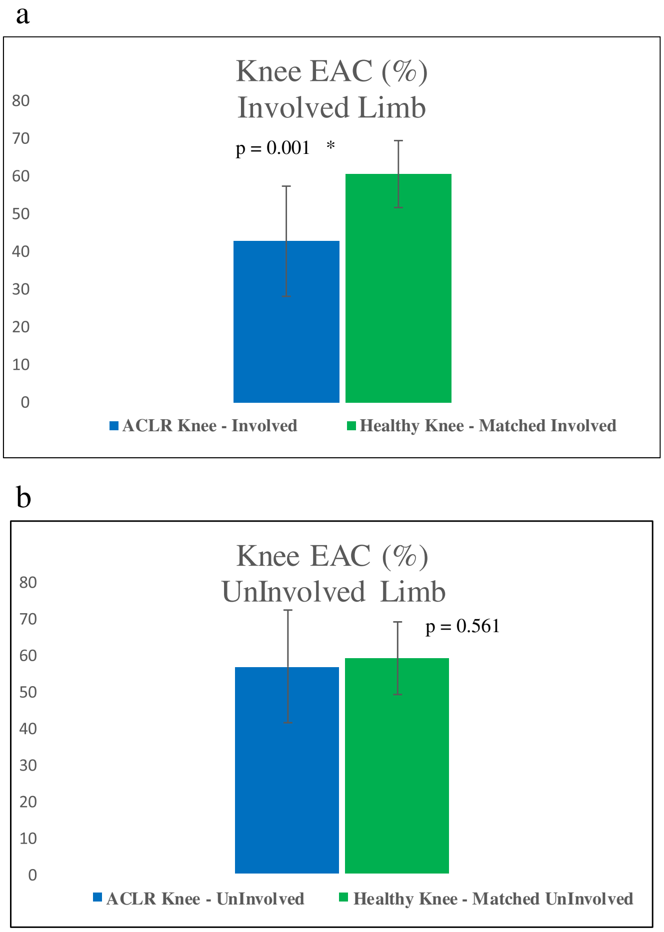

Figure 4. a — Knee Joint Energy Absorption Contribution — Involved Limb ACL-R versus Involved Limb Healthy. b — Knee Joint Energy Absorption Contribution — UnInvolved Limb ACL-R versus UnInvolved Limb Healthy.

Previous studies have examined the loading strategies during the early stages of rehabilitation following ACL-R across tasks such as walking [15], jogging [14, 15], single limb hop [14], and sit-to-stand [13]. In patients who had recently undergone an ACL-R, smaller knee flexion angles of the reconstructed limb were demonstrated during gait at one month, two months and again during running at approximately four months following surgery [15]. In addition, these same participants utilized lower negative work (eccentric loading) values in the ACL-R limb across all three time points as well. Similarly, asymmetrical lower limb loading has been confirmed at one month post-operative in a group of 58 athletic patients with unilateral isolated ACL-R [13]. When participants were instructed to perform a sit-to-stand task at one month following ACL-R, vGRF LSI values were measured at 62% ± 14%. These LSI values at one month post-operative ACL-R were predictive of vGRF LSI of a countermovement jump (CMJ) performed at six months ACL-R [13]. At time of initiation for return to running (4.6 ± 1.4 months) following ACL-R, the surgical limb demonstrates significantly greater deficits in variables that demand loading at the knee during a single limb hop task and running [14]. Decreased knee extensor moments, knee flexion angular velocities, rates of knee extensor moment development, and knee power absorptions were noted in the ACL-R limb of surgical patients when compared to healthy controls while

Table 2
Joint energy absorption contribution (EAC) and quadriceps (QUADS) strength differences of the injured and uninjured limbs between groups.

Variables	ACL-R (injured)	Healthy (matched)	p-Value	ACL-R (uninjured)	Healthy (matched)	p-Value
Hip joint EAC (%)	46.4 ± 16.0	31.7 ± 11.0	0.001[a]	34.0 ± 14.2	33.4 ± 9.1	0.629
Knee joint EAC (%)	42.8 ± 14.6	60.6 ± 8.9	0.001[a]	56.9 ± 15.6	59.1 ± 9.8	0.561
QUADS (BW)	1.1 ± 0.5	2.0 ± 0.5	<0.001[a]	2.0 ± 0.6	1.9 ± 0.5	0.894

[a] Indicates significant difference between the groups.

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performing the tasks. The results of these studies suggest that lower extremity loading patterns following ACL-R may transfer across similar tasks (gait and running) and remain over time [13, 15].

Although the aforementioned studies [13–15] did not directly measure EAC during gait, jogging, hopping, or sit-to-stand, each demonstrated altered lower extremity loading patterns during the early stages of rehabilitation in patients who had undergone ACL-R. These asymmetrical patterns are similar to findings of the current study in which ACL-R participants utilized greater contribution of the hip and lesser contribution of the knee on the injured limb compared to healthy controls during a squatting task at the three month mark. This finding appears to be directly related to deficits in quadriceps strength of the injured limb ($r = 0.615$). Likewise, the outcome of decreased quadriceps strength on the involved limb after ACL-R is consistent with earlier data from this institution in which there was a 17% decline in quadriceps strength from the pre-operative time point to the three month mark [24]. Previous data has shown that patients who were at two months following ACL-R had a quadriceps strength LSI of 56 ± 26% [13]. This quadriceps strength deficit at two months was found to be related to the ability of the participant to perform a counter-movement jump at six months following ACL-R. The current study only measured quadriceps strength at three months following ACL-R, and thus was not predictive of future participant performance. However, the significant relationship between the inability of the participants to employ an appropriate knee loading strategy during a squat and the lack of quadriceps strength compared to the healthy control group does hint at an underlying foundational strength issue which could lead to future limitations in functional performance. This should be taken into consideration when clinicians are assessing an individual's capacity to begin a jogging progression at three to four months following surgery [15, 18, 25].

Quadriceps strength is routinely assessed as a marker for readiness to return to play following ACL-R [7, 8, 18, 19, 22, 26] and can influence a patient's self-reported function for return to sport (RTS) [27]. Information regarding quadriceps strength and the relationship to the individual's ability to appropriately load the injured joint during a functional task in the early stages of rehabilitation following ACL-R is limited. Atrophy of the quadriceps muscle at four weeks has been shown to significantly contribute to quadriceps muscle weakness in individuals who were tested for strength at 12 weeks postoperative ACL-R [28]. The current study did not examine the effect of muscle atrophy on subsequent quadriceps weakness, therefore an association between the two variables cannot be made. On the surface, the deficit in QUADS of the injured limb appears to be a major contributor to this compensatory movement pattern; however, it is unclear if there are underlying motor control issues that may be playing a role as well. Previous studies have suggested that a rehabilitation focus of motor control be implemented into the early stages of the program as a means to re-establish symmetrical lower extremity loading in tasks such squatting and walking [12, 13, 15]. By restoring normal loading during these tasks, it may provide the stimulus needed for quadriceps strength development [12, 14].

Participants in the current study used a greater hip contribution of the injured limb when compared to the healthy group during squatting at three months. Hip muscle strength has previously been studied pre-operatively in a cohort of adolescent athletes who were preparing for ACL-R [29]. No strength differences were seen for hip extensors, abductors, or external rotators in the injured limb of the ACL group when compared to the matched limb of the control group. Similarly, hip abductor strength was found to be greater in the participants who had been released for return to activity (average of approximately seven months) following ACL-R, while no differences were seen in hip extensor strength when compared to healthy, matched controls [30]. In contrast, deficits in hip external rotation strength have been demonstrated at 8.3 ± 2 months post-operative ACL-R when compared to healthy controls [31]. While these studies [29–31] were conducted at different time points during the rehabilitation process, the results suggest that hip strength may play an important role in the outcomes of rehabilitation after injury to the ACL. Results from the current study seem to propose that the ACL-R group utilized a compensatory pattern of eccentric gluteal activity on the injured side as a means to perform a double limb squat; yet, the lack of hip muscle strength measures preclude the authors from making a direct correlation.

4.1. Limitations

The results from the current study demonstrate altered loading patterns during a squat maneuver in the injured limb of adolescent athletes at three months following ACL-R. These results may not be transferable to other populations, different time points, or across more dynamic tasks such as gait or jogging. The fact that EAC was measured at three months after ACL-R in these participants gives insight into one point in time during the early stages of rehabilitation. It is possible that the EAC of participants following ACL-R may not look the same when measured pre-operatively or at time of RTS. Future research regarding loading strategies as measured by EAC across different time points and tasks is warranted. The current findings help to establish that movement deficiencies of the involved limb are present at three months post-operative ACL-R and sets the stage to further study how these deficiencies might influence movement patterns at time of return to sport. In addition, quadriceps strength was tested at a time in which most individuals who have undergone an ACL-R are experiencing less pain and becoming more functional with less restriction during their activity levels. Despite this fact, there is a possibility that pain could have limited participant performance during quadriceps strength testing. Participants were instructed to stop all testing if they experienced pain and/or discomfort in their knee during the isokinetic testing; however, all participants were able to complete testing without complaints of pain.

5. Conclusion

Participants who are at three months following ACL-R demonstrate different eccentric loading strategies during a DLS compared to matched healthy controls. Quadriceps strength deficits may contribute to avoidance of the knee joint and greater

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usage of the hip during the squat. Increasing strength of the quadriceps may improve loading symmetry between hip and knee joint EAC strategy.

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