Energy Absorption Contribution Deficits in Participants Following Anterior Cruciate Ligament Reconstruction: Implications for Second Anterior Cruciate Ligament Injury

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Context: Lower-extremity loading patterns change after anterior cruciate ligament reconstruction (ACLR). However, there is limited research regarding energy absorption contribution (EAC) of athletes following ACLR who reinjure their ACL and those who do not. EAC can be utilized as a measure of joint loading during tasks. Design: Cross-sectional study. Methods: Three groups of individuals (13 in each group) with matched age, sex, height, weight, and sports were enrolled. Data were collected at time of return-to-sport testing for the 2 ACLR groups. An 8-camera 3D motion capture system with a sampling rate of 120 Hz and 2 force plates capturing at 120 Hz were used to capture joint motions in all 3 planes during a double-limb jump landing. Results: Participants in the ACLR no reinjury and ACLR reinjury groups had significantly greater hip EAC (55.8 [21.5] and 56.7 [21.2]) compared with healthy controls (19.5 [11.1]), P < .001 and P < .001, respectively. The ACLR no reinjury and ACLR reinjury groups had significantly lower knee EAC (24.6 [22.7] and 27.4 [20.8]) compared with healthy controls (57.0 [12.2]), P < .001 and P < .001, respectively. However, the ACLR reinjury group had significantly lower ankle EAC (15.9 [4.6]) than healthy controls (23.5 [6.6]), whereas there was no statistical difference between the ACLR no reinjury group (19.7 [7.8]) and healthy controls. Conclusions: Athletes who had a second ACL injury after ACLR, and those without second ACL injury, appear to have similar hip, knee, and ankle joint loading of the surgical limb at return-to-sport testing. Nevertheless, joint loading patterns were significantly different from healthy controls. The study suggests that EAC as a measure of joint loading during a double-limb jump landing at time of return to sport may not be a strong predictor for second injury following ACLR.

Keywords: ACL, knee, rehab, EAC, jump

Nearly 200,000 anterior cruciate ligament (ACL) tears occur yearly in the United States, with up to 90% resulting in reconstructive surgery.1 Although various surgical methods and rehabilitation protocols have been utilized with the intention of improving patient outcomes following anterior cruciate ligament reconstruction (ACLR), poor outcomes and high retear rates remain prevalent.2,3 Research suggests that second ACL injuries (ACL graft rupture or contralateral ACL injury) occur at rates between 6% and 27% depending on the length of the time the cohort was followed.4 Given this high rate of second injury, it is imperative to continue to refine our understanding of potential risk factors for secondary ACL tears.

Previous research has identified several factors and altered biomechanics that put individuals at a higher risk for a second ACL tear. Paterno et al5 described that transverse plane hip kinetics, frontal plane knee kinematics, sagittal plane knee moments at landing, and deficits in postural stability all predicted second ACL injury. In addition, other factors such as high body mass index, short period from injury to ACL surgery, early resolution of impairments, and early reaching return-to-sport (RTS) criteria leave individuals at a higher risk of second ACL injury.6 Additionally, a recent study revealed that young athletes who returned to sport before 9 months postsurgery were nearly 7 times more likely to have a second ACL injury.7 In contrast, Grindem et al8 found that passing RTS criteria would reduce risk for a second ACL injury. Numerous RTS test batteries have been used to help identify when an athlete is ready to RTS following ACL surgery. Most test batteries include measures of range of motion, strength, functional assessments, movement quality, limb symmetry index, and patient’s self-reported outcomes.3,9 When examining walking performance at 6 months following ACLR, athletes who sustained a second ACL injury were found to have a more normal gait pattern (i.e., more symmetrical peak knee-flexion angles and less co-contraction of lower-extremity muscles) compared with those without reinjury.6 This finding suggests that a more challenging task other than walking, such as jumping or hopping, may be more appropriate to uncover the deficit and to allow clinicians to make an objective informed decision of RTS for these athletes. Furthermore, an impairment, such as altered joint loading, that occurs early in the rehabilitation process and persists during the continuum of care may be useful to assist in the RTS decision.

It is well documented that joint loading in the surgical limb after ACLR changes following surgery.10–13 Energy absorption contribution (EAC) is a calculation of joint loading during the eccentric phase of a given task integrating the negative part of the power curve where joint angular velocity and net joint moment are in opposite directions, indicating eccentric loading.12 Even in simple and routine tasks such as gait, significant changes in lower-extremity loading are observed up to and beyond 3 to 4 months following surgery.14,15 At a self-selected walking speed, subjects 3 to 4 months following ACLR demonstrated reduced vertical and posterior ground reaction forces.

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and shank angular velocity, and each of these variables were strongly associated with a reduced knee extensor moment. During more demanding tasks, such as a double-leg squat, individuals who were 3 months postoperation performed the squat using both interlimb and intralimb compensations to reduce the knee extension moment in the surgical limb. Similarly, Garrison et al showed that subjects 3 months following ACLR had significantly increased hip EAC and less knee EAC compared with healthy individuals during a double-limb squat. Likewise, during performance of the same double-leg squat task, subjects at 5 months postoperation continued to have intralimb compensations, resulting in an increase of the hip-to-knee extensor moment ratio. In addition to these early compensations, Roos et al found a decrease in knee extensor moments during a squat at 13 months post-ACLR, utilizing 2 strategies: (1) a shift toward hip and/or ankle moments and (2) a shift of support moment toward the nonsurgical limb. These findings support the notion that there are not only early compensations present in the surgical and nonsurgical limb following ACLR, but also these compensations persist throughout the continuum of care and beyond. At roughly 3 years post-ACLR, studies have shown that individuals continue to demonstrate decreased knee extensor moments and increased hip to knee joint power ratios in the surgical limb during tasks, such as single-leg squats, loaded squats, and double-leg jumps. Variations of these deficits in movement patterns can persist during functional tasks such as stair ascent as far as 10 years postsurgery. This early and continued underloading of the surgical limb following ACLR may be related to the underloading seen long term that may contribute to second ACL reinjury.

One variable relatively unexplored in ACL outcomes research is if underloading of the surgical knee that is present during less dynamic activities of daily living is more pronounced during sport-specific, complex tasks such as jumping, landing, or cutting. Specifically, does surgical limb underloading of the knee persist at time of RTS when these individuals are performing more complex activities? The long-term consequences of underloading is becoming more understood with Post-Traumatic Osteoarthritis; however, it is unknown whether this underloading contributes to the risk of second ACL injury. As we continue to better understand the complexity of ACL rehabilitation and given the continued high reinjury rate, this is another component that needs to be examined. EAC provides a measure of joint loading distribution during a task. This eccentric phase is critical to determine an individual’s loading pattern. Therefore, the purpose of this study was to examine if differences in EAC exist during a double-limb jump landing (JL) task between participants following ACLR who do not sustain a second injury, participants who do sustain a second injury, and a healthy control group. We hypothesized that those participants who sustained a second ACL injury would demonstrate altered EAC at hip, knee, and ankle at time of RTS compared with both the healthy control group and the ACLR no reinjury group. Previous studies have identified risk factors for second ACL injuries due to biomechanical deficits. It is thought that second ACL injury risk factors are complex and comprised of many variables, but we believed that a compensated movement pattern may leave individuals more susceptible to injury to either limb.

Methods

Participants

For all groups, participants were considered for the study if they were between the ages of 13 and 25 and if they were involved in a level 1 sport (eg, basketball, football, or soccer). For the ACLR groups, eligible participants were enrolled if they injured their ACL for the first time, and did not have any full thickness chondral injuries, or grades II or III medial collateral ligament, lateral collateral ligament, or posterior collateral ligament injuries. For the healthy 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 3 months. All participants following ACLR were those enrolled in a larger ongoing study examining clinical outcomes of ACLR across the continuum of care. The healthy controls were those enrolled in a separate ongoing study examining movement profiles of healthy athletes. All participants gave informed consent to participate 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. From the ACLR outcome study, 26 participants who met inclusion criteria were included in this study. Of these 26 ACLR participants, 13 went on to sustain a second ACL injury (ACLR reinjury group). Next, 13 participants following ACLR who did not go on to sustain a second ACL injury (ACLR no reinjury group) and 13 healthy controls, matched by age, gender, height, weight, and limb dominance and sport, were included in this EAC study. Table 1 displays the characteristics of the participants for these 3 groups.

Double-Limb JL

All participants following ACLR were tested at time of RTS testing as part of the study protocol. The healthy group was tested at a single point in time during the participation in the movement profile of healthy athletes study as mentioned above. An 8-camera Motion Capture System (Qualisys AB) with a sampling rate of 120 Hz was used to capture joint motions in all 3 planes during the double-limb JL. Thirty-three effective markers were adhered to each participant’s skin/clothing with double-sided tape. Two force plates capturing at 1200 Hz (Advanced Mechanical Technology, Inc) were used to obtain ground reaction forces and to allow accurate time sequencing during data collection and data processing. Each participant completed 3 trials of a JL task. Each trial began with the participant standing on top of a box that was placed at a distance of 50% of their height from the force plate. The JL task consisted of 2 double-limb jumps: one jump forward off a 30-cm box on to 2 legs, and then immediately into a vertical jump for maximal height. Energy absorption (EA) of the hip, knee, and ankle joints was calculated by integrating the negative area of the power curve (product of moment and angular velocity) during the loading phase of the double-limb JL. The loading phase is the period from initial toe contact with the force plate (vertical ground reaction forces [vGRF] > 10 N) to maximal knee flexion. See Figure 1 as reference. Energy absorption was normalized to the product of height and weight (Ht x BW) and averaged across 3 trials. EAC of each joint was calculated relative to the total EA (sum of hip, knee, and ankle EA) and reported as a percentage.

Data Analysis

All data analyses were performed using SPSS (version 25). To compare the descriptive characteristics of the participants between the 3 groups, a 1-way analysis of variance was used to examine age, height, weight, and International Knee Documentation Committee (IKDC) scores, and chi-square tests were used to examine sex and limb dominance between groups. Prior to statistical analyses, all
kinetic data were assessed for normality and outliers. A 3 (group) \times 3
(joint) repeated-measures analysis of variance with the alpha level
set at .05 was used to assess for differences in surgical limb hip, knee,
and ankle EAC between the 3 groups. If there was a signifi-
cant interaction, post hoc pairwise comparisons were performed.

Results

There was a significant interaction of group by joint, $F_{2,36,42.40} =
13.589$, $P < .001$. Post hoc tests revealed that there were no
differences present between the ACLR no reinjury group and
ACLR reinjury group at all 3 joints ($P > .05$). Both ACLR groups
had significantly greater hip EAC and lower knee EAC than the
healthy control group ($P < .001$). Although there was no differ-
ce in ankle EAC between the 2 ACLR groups, only ACLR
reinjury group had a significantly lower ankle EAC value (ACLR
reinjury: 15.9 [4.6] vs healthy controls: 23.5 [6.6]) than healthy
controls, whereas the ACLR no reinjury group (ACLR no-
reinjury: 19.7 [7.8]) did not. See Table 2 and Figure 2 for a
complete list of the results.

Discussion

The primary purpose of this study was to examine whether or not
EAC during a JL task was different between individuals who
underwent ACLR and sustained a second ACL injury compared
with those who did not sustain a second injury and healthy controls.
Our results indicated that there were significant differences in
surgical limb hip and knee EAC between athletes following
ACLR (regardless of reinjury) and healthy controls during a JL
task. At the knee joint, the results of our study indicated that there
were no significant differences between the ACLR no reinjury and
ACLR reinjury groups suggesting that surgical limb knee EAC
alone during a JL task is not an independent risk factor for a second
ACL injury.

Significant differences in surgical limb hip EAC were present
between both the ACLR no reinjury and ACLR reinjury groups

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Table 1 Characteristics of Participants for the ACLR No Reinjury Group, ACLR Reinjury Group, and Healthy Controls

<table>
<thead>
<tr>
<th></th>
<th>ACLR no reinjury (n = 13)</th>
<th>ACLR reinjury (n = 13)</th>
<th>Healthy controls (n = 13)</th>
<th>P (ACLR no reinjury vs ACLR reinjury)</th>
<th>P (ACLR no reinjury vs healthy controls)</th>
<th>P (ACLR reinjury vs healthy control)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, y</td>
<td>15.4 (0.9)</td>
<td>15.2 (1.2)</td>
<td>15.2 (1.1)</td>
<td>.932</td>
<td>.853</td>
<td>.982</td>
</tr>
<tr>
<td>Height, cm</td>
<td>164.8 (6.8)</td>
<td>165.7 (9.6)</td>
<td>165.8 (6.8)</td>
<td>.947</td>
<td>.934</td>
<td>.999</td>
</tr>
<tr>
<td>Weight, kg</td>
<td>68.2 (12.9)</td>
<td>63.7 (14.0)</td>
<td>60.5 (13.2)</td>
<td>.672</td>
<td>.315</td>
<td>.811</td>
</tr>
<tr>
<td>Sex (male/female)</td>
<td>2/11</td>
<td>2/11</td>
<td>2/11</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>IKDC (0–100)</td>
<td>92.3 (10.3)</td>
<td>95.5 (3.8)</td>
<td>99.5 (1.4)</td>
<td>.423</td>
<td>.018*</td>
<td>.256</td>
</tr>
<tr>
<td>VAS (0–10)</td>
<td>1.4 (2.0)</td>
<td>0.5 (0.8)</td>
<td>N/A</td>
<td>.172</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Injured limb (R/L)</td>
<td>5/8</td>
<td>6/7</td>
<td>N/A</td>
<td>.691</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Limb dominance (R/L)</td>
<td>11/2</td>
<td>12/1</td>
<td>12/1</td>
<td>.539</td>
<td>.539</td>
<td>1.000</td>
</tr>
<tr>
<td>Time of return-to-sport testing postsurgery, months</td>
<td>6.8 (1.5)</td>
<td>7.0 (1.2)</td>
<td>—</td>
<td>.884</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

Abbreviation: ACLR, anterior cruciate ligament reconstruction; IKDC, International Knee Documentation Committee; L, left; N/A, not applicable; R, right; VAS, visual analog scale. *Statistically significant difference between groups ($P < .05$).
compared with healthy controls. These findings reaffirm our knowledge of surgical limb intralimb compensations that occur in those following ACLR.\textsuperscript{15,24} This study highlights that these impairments remain toward the end of the rehabilitation continuum even as athletes are preparing to RTS. It has been hypothesized that the increased EAC at the hip provides a compensatory strategy for these individuals to avoid loading their knee during functional tasks.\textsuperscript{15,24} Previous research has shown that individuals offload their knee in favor of their hip following ACLR across a variety of tasks.\textsuperscript{15,16} We found no differences between ACLR no reinjury and ACLR reinjury groups, but both utilized a significantly greater hip strategy than the healthy group. This finding is unique in that there is currently limited research that examines EAC changes following ACLR and its potential effects on reinjury. Prior to an ACL injury, landing with decreased hip flexion during a drop jump has been found to be a risk factor for primary ACL injury.\textsuperscript{25} This study was performed in a healthy population, and these same kinematic risk factors may not apply once an individual has undergone ACLR.

The findings at the knee joint are consistent with previously published research that showed significantly lower surgical limb knee loading during a variety of tasks such as a squat and single-limb vertical hop following ACLR.\textsuperscript{15,26} Although knee joint EAC did not discriminate between those who sustained a second ACL injury and those who did not, previous work has identified multiple biomechanical factors that help to predict a second ACL injury. Paterno et al\textsuperscript{5} examined a drop vertical jump and determined predictive risk factors for second ACL injury, including nonsurgical limb hip internal rotator moment impulse, increased frontal plane (valgus) knee motion, asymmetries in internal knee moments at initial contact, and deficits in single-leg postural stability. In the current study, we examined surgical limb knee joint loading as measured by EAC which is a measure of the negative portion of the power curve (eccentric loading) but is measured over the duration of the loading response (ie, initial contact to maximum knee flexion). In contrast, earlier documented risk factors for second ACL injury such as asymmetry in internal knee extensor moment were measured at initial contact.\textsuperscript{5} Thus, the current variable of knee EAC may not be sensitive enough to detect risk of reinjury or to differentiate between groups during a JL task. Previous research would suggest lower-extremity interlimb compensations may leave individuals at increased risk for reinjury due to over reliance on the nonsurgical limb or the surgical limb not prepared to react to complex movements.\textsuperscript{27} As such, the combination of these findings suggests that identification of risk factors for second ACL injury is multifactorial in nature and might be dependent upon timing of when the loading occurs during the task. Further research is needed to fully understand the consequences of knee “under” or “over” loading on reinjury risk.

At the ankle joint, our data suggest that surgical limb EAC in the ACLR no reinjury group (19.7 [7.8]) was closer to healthy controls (23.5 [6.6]) than those who sustained the second ACL injury (15.9 [4.6]). Although there was no difference in knee and ankle EAC between the 2 ACLR groups, the ACLR reinjury group

<table>
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<th>P ACLR no reinjury vs healthy controls</th>
<th>P ACLR reinjury vs healthy controls</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip</td>
<td>55.8 (21.5)</td>
<td>56.7 (21.2)</td>
<td>19.5 (11.1)</td>
<td>1.000</td>
<td>&lt;.001*</td>
<td>&lt;.001*</td>
</tr>
<tr>
<td>Knee</td>
<td>24.6 (22.7)</td>
<td>27.4 (20.8)</td>
<td>57.0 (12.2)</td>
<td>1.000</td>
<td>&lt;.001*</td>
<td>.001*</td>
</tr>
<tr>
<td>Ankle</td>
<td>19.7 (7.8)</td>
<td>15.9 (4.6)</td>
<td>23.5 (6.6)</td>
<td>.414</td>
<td>.441</td>
<td>.015*</td>
</tr>
</tbody>
</table>

Figure 2 — Surgical limb EAC. ACL indicates anterior cruciate ligament; EAC, energy absorption contribution. * Statistically significant difference between groups (P < .05).
surprisingly had a slightly higher knee EAC but lower ankle EAC than the ACLR no reinjury group. These results may imply that the ACLR reinjury group appeared to shift loading from the ankle to the knee, which could have contributed to their second injury. Perhaps there is benefit in future work examining the load-sharing concept of knee to ankle EAC ratio as a predictor of ACL reinjury.

We hypothesized that there would be a statistical significance between our ACLR reinjury and ACLR no reinjury groups across joints. However, our findings did not support this, and this may be due to the low number of ACL reinjuries (n = 13) in this cohort. This limited our ability to stratify our reinjuries based on graft rupture (ipsilateral) and contralateral limb tear. Paterno et al. previously reported that female athletes are 6 times more likely than males to tear the contralateral ACL compared to an ipsilateral graft rupture. A systematic review by Wiggins et al. determined the percentage of ACL graft rupture was 11.1% while a contralateral tear was 14.1% in young adults. When considering the impact of graft choice on quadriceps strength and our understanding of how deficits in quadriceps strength can affect EAC, further studies that include larger data points are needed to subanalyze the potential role of EAC on reinjury.

Intralimb compensations, like those found in our study, result in an underloading of the surgical knee following ACLR. The lack of loading exposure of the surgical limb knee during both simple and complex movements may place it at risk when it is required to perform a knee dominant movement. Previous studies have demonstrated high numbers of second injury following primary ACLR. A possible explanation as to why contralateral ACL tears occur at a high rate may be due to the increased dependence on the contralateral knee as a result of the underloaded surgical knee.

Although we reported fairly symmetrical ground reaction force symmetry percentages with the JL task (88%), this can be misleading as both the surgical and nonsurgical limbs may be completing the task with intralimb compensations. In addition, the inability for impairments to resolve at the time of RTS most likely requires an asymmetrical amount of stress and reliance on the nonsurgical limb to carry out sport-specific movements.

One unexpected finding in our results is that the ACLR no reinjury group had a significantly lower IKDC score compared with the healthy controls. There was no statistical difference between the ACLR reinjury group and healthy controls. Although the IKDC does not assess psychological readiness as the Anterior Cruciate Ligament Return to Sport after Injury Scale does, there is some level of confidence associated with higher scores. As the IKDC is a self-reported outcome measure utilized to assess knee function, we can infer that these subjects who had higher scores perceived their knee were doing extremely well. In contrast, one may conclude that their higher IKDC scores may suggest engaging in activity with increased risk for ACL tears. Similar to our findings, recently published research revealed that those who had higher confidence based on Knee Injury and Osteoarthritis Outcome Score quality of life subscale question 3 (“How much are you troubled with lack of confidence in your knee?”) were at an increased risk of second ACL injury. While this knee confidence at RTS is based on a single question, the “confident” group was more likely to sustain a second ACL injury.

There is currently no published research regarding the most effective methods of addressing this well-documented movement compensation of intralimb load sharing in those who have undergone ACLR. It has been established that surgical limb knee loading improves during a double-leg squat across the continuum of care. It has not yet been defined which rehabilitation interventions provide a sufficient stimulus to optimize knee joint loading and carry over to functional activity. However, clinically those prescribing rehabilitation interventions may be able to implement targeted exercise with specific external cueing to decrease these stark deficits in movement patterns. In addition to deficits in neuromuscular control following ACLR, quadriceps strength contributes to one’s ability to attenuate load.

Future research is needed to examine the effects of time of RTS and knee loading. Sigward et al. reported peak knee extensor moment increases in a double-leg squat between 3 and 5 months post-ACLR. Interestingly, Welling et al. found that athletes continue to struggle to pass objective RTS testing even past 9 months post-ACLR. Testing did not consist of analysis of intralimb compensations, but with the proven literature, it can be inferred that maladaptive movement patterns were most likely utilized during functional testing. With only 11.3% of participants passing RTS testing, objective measures that can analyze intralimb compensations must be applied to understand the status of the entire individual.

**Limitations**

The current study looked at participants with an average age of 15.6 (1.8) years and had 4 males in the ACLR groups. These results may not be able to be extrapolated for individuals out of this age range, as further data need to be analyzed for individuals in a different age range. This composition of females and males does not represent the typical population that is reported in the literature. The Multi-center Orthopedic Outcomes Network group has reported females to comprise 48% and the Norwegian Knee Ligament Registry 43% in their ACLR cohorts.

In addition, our findings of JL EAC may not be applicable to tasks, such as hopping or single-leg activities. This is an important aspect to consider, as the mechanism of injury for ACL is commonly in single-leg stance positions. Our data analyze the entire eccentric phase of the landing; however, initial contact may be more relevant to the time when the ACL would tear. Peak elongation of the ACL is thought to occur within the first 70 milliseconds, whereas the EAC accounts for a longer phase (initial contact to maximum knee flexion), thus this variable may not be sensitive enough to identify the time frame in which ACL injury is likely to occur.

**Conclusions**

The results from our study revealed a significant difference of hip and knee EAC between the ACLR groups and healthy controls. Regardless of a second ACL injury, both groups utilize an increased hip strategy at time of RTS testing. This knee offloading has been previously confirmed but never examined in regard to second ACL injury. This affirms the belief that they have not achieved “normal” biomechanics at the time of RTS testing. The ACLR reinjury and ACLR no reinjury groups showed no statistical significance differences in EAC across all joints. Due to the complexity of ACL injury, utilizing EAC as a single predictor for second ACL injury may be unrealistic. More research between graft retears versus contralateral tears will be imperative to discover whether joint EAC is a risk factor for a second ACL injury.

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