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Compensatory Strategies That Reduce Knee Extensor Demand During a Bilateral Squat Change From 3 to 5 Months Following Anterior Cruciate Ligament Reconstruction

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BACKGROUND: Decreased extensor moments in the surgical knee during bilateral squats can persist beyond 1 year following anterior cruciate ligament reconstruction (ACLR). This is accomplished using interlimb and intralimb compensations.

OBJECTIVES: This study sought to assess loading during squatting longitudinally, 3 and 5 months post ACLR, and to determine the extent to which interlimb and intralimb compensations contribute to reduced knee extensor moments.

METHODS: In this controlled, longitudinal laboratory study, 11 individuals (4 male) underwent 3-D motion analysis of a squat at 3 and 5 months post ACLR. A repeated-measures multivariate analysis of variance (limb by time) assessed differences in peak knee and hip flexion angles, knee extensor moment, vertical ground reaction force, and hip-to-knee extensor moment ratio. Stepwise linear regression analysis was used to determine the contribution of interlimb (between-limb vertical ground reaction force ratio) and intralimb (within-surgical-limb hip-to-knee moment ratio) compensations to the between-limb knee extensor moment ratio.

RESULTS: A significant effect of limb was observed for knee flexion angle, knee extensor moment, vertical ground reaction force, and hip-to-knee extensor moment ratio, while a significant effect of time was observed for knee extensor moment and hip-to-knee extensor moment ratio. At 3 months, the vertical ground reaction force ratio and hip-to-knee extensor moment ratio predicted the knee extensor moment ratio (R^2 = 0.854, P<.001). At 5 months, the hip-to-knee extensor moment ratio predicted the knee extensor moment ratio (R^2 = 0.584, P = .006).

CONCLUSION: Individuals used interlimb and intralimb compensations to reduce the knee extensor moment of the surgical limb at 3 months post ACLR. Similar reductions in the knee extensor moment at 5 months were accomplished with only intralimb compensations. *J Orthop Sports Phys Ther 2018;48(9):713-718. Epub 12 Jun 2018. https://doi.org/10.2519/jospt.2018.7977*

KEY WORDS: *anterior cruciate ligament reconstruction, interlimb compensation, intralimb compensation, knee extensor moment deficit, rehabilitation*

Following anterior cruciate ligament reconstruction (ACLR), individuals may adopt loading patterns that shift the mechanical demands away from the surgical knee during bilateral tasks.[2,5,6,12,13] Given the presence of joint-level impairments such as pain, decreased strength, and range of motion following surgery, the adoption of loading strategies that underload the knee is not surprising. However, despite the emphasis on restoring knee loading during rehabilitation,[4,8] these strategies appear to persist over time.[3,9,10] At 13 months post ACLR, individuals exhibited average knee extensor moments that were 17% smaller in the surgical limb compared to the nonsurgical limb during a bilateral squat against body-weight resistance.[12] Asymmetry of this magnitude would not be expected during what would be considered a submaximal task at a time when individuals are returning or have returned to sports and high-level activities.[5,6,12] The persistence of underloading is concerning, as asymmetrical limb loading during landing tasks has been linked to increased risk for anterior cruciate ligament (ACL) reinjury.[11]

Bilateral squatting tasks are incorporated into early rehabilitation to progressively load the knee as individuals progress to more demanding single-limb

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tasks.[14] However, the bilateral multijoint nature of a squat allows for compensations that can shift the task demands to the nonsurgical limb (interlimb compensation) or to adjacent joints within the surgical limb (intralimb compensation) to reduce knee extensor moments. While no study has evaluated squat mechanics during early rehabilitation, Labanca et al[5] found that individuals 1 month post ACLR performed bilateral sit-to-stand tasks with a 38% reduction in vertical ground reaction forces (vGRFs) in the surgical limb. This suggests that during early recovery, individuals depend on the nonsurgical limb to reduce demands on the surgical knee during bilateral tasks.

Data evaluating squat mechanics at 1 to 2 years post ACLR suggest that individuals continue to reduce sagittal plane knee loading, not only by compensating with the contralateral limb, but also by shifting the demands within the limb to the hip.[12] Specifically, reduced knee extensor moments have been found along with increased hip extensor moments, in combination with[7] and in the absence of[13] between-limb differences in ground reaction forces, during squat tasks. Together, these studies suggest that individuals may rely on interlimb compensations to unload the knee during early rehabilitation but adopt intralimb compensations as they progress through rehabilitation. However, evaluation of squat performance over time is needed to determine whether a shift in compensatory strategies occurs.

Understanding the mechanisms used to underload the knee in the sagittal plane, particularly during rehabilitation, when bilateral squats are introduced and progressed, will inform clinicians and help develop strategies to prevent long-term persistence. The purpose of this study was to (1) assess loading patterns during a bilateral squat task in individuals longitudinally at 3 and 5 months post ACLR, and (2) determine how interlimb and intralimb compensations contribute to reduced knee extensor moments at these time points.

METHODS

Participants

Participants were included in the study if they were between the ages of 14 and 40 years, had undergone ACLR, and were currently receiving physical therapy treatment. They were excluded if they had a current injury to the contralateral limb that would influence function or had concurrent knee pathology that limited their weight-bearing status. Participants were recruited from a single physical therapy clinic, and the researchers did not control for specific interventions. However, 4 treating physical therapists agreed that their treatments followed standard rehabilitation protocols that emphasized early restoration of range of motion and progression off crutches when patients demonstrated gait without observable deviations.

Balance and lower extremity strengthening exercises were progressed based on the individual patient's ability.[1,15] Participants were assessed longitudinally at 2 time points: 3 and 5 months after surgery. All procedures were explained to each participant, and informed consent was obtained as approved by the Institutional Review Board of the University of Southern California Health Sciences Campus. Parental consent and youth assent were obtained for all participants under the age of 18 years.

Procedures

Testing took place at the Human Performance Laboratory in the Division of Biokinesiology and Physical Therapy at the University of Southern California, located at the Competitive Athletes Training Zone (Pasadena, CA). Kinematic data were collected using an 11-camera motion-capture system at 250 Hz (Qualisys AB, Gothenburg, Sweden). Ground reaction forces were obtained using two 1.20 × 0.60-m force platforms at 1500 Hz (Advanced Mechanical Technology, Inc, Watertown, MA). Kinematic and kinetic data were collected synchronously using Qualisys Track Manager Version 2.8 (Qualisys AB).

Prior to biomechanical testing, participants rode a stationary bike to warm up for 5 minutes before placement of the reflective markers. The reflective markers (25-mm spheres) were placed on the following anatomical landmarks to define body segments: the L5-S1 junction, and bilaterally on the end of second toes, first and fifth metatarsal heads, medial and lateral malleoli, medial and lateral epicondyles of femurs, greater trochanters, posterior superior iliac spines, and iliac crests. Reflective markers were affixed to the participant's skin using 5-mm circular double-sided tape and reinforced with Transpore tape (3M, St Paul, MN). Tracking marker clusters mounted on semi-rigid plastic plates were secured to the thighs, shanks, and heel plates of shoes using flexible fabric bands and duct tape. A static calibration trial was collected with all markers attached. Tracking marker clusters, as well as markers on the end of the second toe, iliac crests, posterior superior iliac spines, and the L5-S1 junction, remained on the participant throughout the entire testing, while other markers were removed after the static calibration trial.

Participants were asked to perform squats with each foot on an individual force platform, with feet shoulder-width apart and arms crossed over the chest. No additional weight or resistance was added. Participants were instructed to squat down as low as possible without pain and to return to the standing position between each squat. After practice, they performed 2 trials of 5 consecutive squats at a self-selected comfortable pace. A 3-minute break between each trial was provided to prevent fatigue. The self-selected rate of squatting (squats per second) was calculated to determine whether it differed between individuals.

Data Analysis

Marker coordinate data were labeled and digitized using Qualisys Track Manager Version 2.8 (Qualisys AB). Lower extrem-

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ity kinematics and net joint moments were calculated using Visual3D (C-Motion, Inc, Germantown, MD) software. Data were filtered using a fourth-order, zero-lag, 12-Hz Butterworth low-pass filter. Local coordinate systems of the pelvis, thighs, shanks, and feet were derived from the standing calibration trial, and the 6 degrees of freedom of each segment were determined from the segment's triad of reflective markers. Ankle, knee, and hip sagittal plane kinematics were calculated by determining the transformation from the triad of markers to the position and orientation of each segment determined from the standing calibration trial, using a joint coordinate system approach. Body mass was calculated by dividing the average vGRF over 5 seconds during the static trial by 9.81 N/kg. Body mass, kinematics, and ground reaction force were used to calculate sagittal plane net joint moments at the knee and hip, using standard inverse dynamics equations. Moments, reported as internal moments, were normalized to body mass.

Peak sagittal plane moments at the knee and hip, peak vGRF, and peak knee and hip flexion angles were identified during the deceleration phase of the squat. The deceleration phase was defined as the time from standing (highest position of L5-S1 marker) to peak knee flexion angle. To characterize knee extensor moment deficits in the surgical knee, a ratio of peak knee extensor moments was calculated between limbs (ie, surgical limb divided by nonsurgical limb). To characterize the distribution of forces between the limbs, a between-limb ratio of peak vGRFs was calculated in the same way. For these ratios, 1 indicates symmetry between limbs, less than 1 indicates that the nonsurgical limb is greater than the surgical limb, and greater than 1 indicates that the surgical limb is greater than the nonsurgical limb.

To characterize the relative contributions of hip and knee moments to deceleration, a within-limb ratio of hip extensor moment to knee extensor moment was calculated for each limb. For this ratio, 1 indicates symmetry between hip and knee extensor moments within the limb, less than 1 indicates that the knee moment is greater than the hip moment, and greater than 1 indicates that the hip moment is greater than the knee moment. Variables were averaged across 3 repetitions (middle 3 out of 5 repetitions) from 2 trials for each participant.

Statistical Analysis

Descriptive statistics (mean, standard deviation, and Cohen's *d* effect size) were calculated for all variables. The rate of squatting was compared across time using a paired *t* test. To determine whether differences exist between limbs or across time in peak knee and hip extensor moments, peak vGRF, peak knee and hip flexion angles, and within-limb hip-knee ratio during deceleration, a 2-way (limb by time) repeated-measures multivariate analysis of variance was performed. In the case of a main effect of limb or time, paired *t* tests were performed.

Separate stepwise linear regressions were used to determine the independent contribution of interlimb (vGRF ratio) and intralimb (hip-knee moment ratio) compensations to knee extensor moment deficits (between-limb knee extensor moment ratio) in the surgical limb at each time point (3 and 5 months). The criterion of probability of F to enter of .05 or less was used to enter a variable into the model, and the criterion of probability of F to remove of .10 or greater was used to remove a variable from the model. Significance levels were set at $\alpha \leq .05$. All analyses were performed using PASW Statistics Version 18 (IBM Corporation, Armonk, NY).

RESULTS

Eleven eligible individuals (mean ± SD age, 22.9 ± 9.5 years; 7 female, 4 male; height, 171.5 ± 9.7 cm; weight, 67.5 ± 10.1 kg) participated in this longitudinal observational study. Allograft (n = 4) and bone-patellar tendon-bone (n = 6) and hamstring (n = 1) autograft procedures were performed by 4 different surgeons. Seven participants reported concurrent injuries: meniscal tear (n = 6) and medial collateral ligament injury (n = 1). None of these concurrent injuries were treated surgically. None of the participants reported weight-bearing restrictions following surgery. Three participants reported previous ACLR to the contralateral (n = 2) and ipsilateral knees (n = 1) at least 2 years prior to reinjury, and all had returned to presurgical levels of physical activity.

Descriptive statistics (mean ± SD) are reported in the **TABLE**. No significant difference in the rate of squatting was observed over time ($P = .598$). No significant limb-by-time interaction was observed, while a main effect of limb was present ($F = 6.59$, $P = .028$). Post hoc paired *t* tests were performed to compare between limbs, collapsed across time for each variable of interest. Compared to the nonsurgical limb, the surgical limb exhibited a significantly lower peak knee flexion angle (2.4° ± 2.6°; $P = .013$; effect size, 0.95), lower peak knee extensor moment (0.37 ± 0.18 Nm/kg; $P<.001$; effect size, 2.16), less peak vGRF (0.09 ± 0.06 N/kg; $P<.001$; effect size, 1.69), and greater hip-knee ratio (0.68 ± 0.55; $P = .002$; effect size, 1.28) (**FIGURE**). No significant difference was noted between limbs for hip flexion angle ($P = .504$) and extensor moment ($P = .383$).

At 3 months, the between-limb vGRF ratio and within-limb hip-knee extensor moment ratio (surgical limb) together predicted the knee extensor moment ratio ($R^2 = 0.854$, $P<.001$). The vGRF ratio entered the regression equation first and was the largest predictor of the knee extensor moment ratio ($R^2 = 0.624$, $P = .004$, $\beta = 0.790$). The hip-knee extensor moment ratio entered second ($R^2 = 0.230$, $P = .007$, $\beta = -0.492$). Smaller vGRF ratios and larger hip-knee extensor moment ratios predicted smaller knee extensor moment ratios. At 5 months, the hip-knee extensor moment ratio (surgical limb) was the only variable to enter the regression equation ($R^2 = 0.584$, $P =$

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.006, $\beta = -0.765$). Larger hip-knee extensor moment ratios predicted smaller knee extensor moment ratios.

DISCUSSION

Substantial deficits in knee extensor moments were observed in the surgical limb at both time points. On average, a 38% decrease in knee extensor moment was observed in the surgical compared to the nonsurgical knee at 3 months. While the deficits appear to decrease to 30% at 5 months post ACLR, the absence of a significant interaction between limb and time suggests that these deficits did not significantly improve over time. Studies have reported deficits of smaller magnitudes at later time points following surgery, suggesting that further improvements are likely past 5 months, but their persistence at any magnitude during submaximal tasks is of concern.[5,12] Moreover, the underloading strategies reported in this study are present at a time when rehabilitation is focused on more demanding single-limb exercises and progression to running.

Differences between limbs with respect to vGRF and the hip-knee extensor moment ratio at 3 and 5 months suggest that both between- and within-limb compensations are present. On average, vGRF was 13% lower under the surgical compared to the nonsurgical limb, indicating that individuals were underloading their surgical limb. The hip-knee extensor moment ratio was, on average, 40% larger in the surgical limb, indicating that individuals shifted the extensor demands away from the knee and toward the hip in the surgical limb. At 3 and 5 months post ACLR, the hip-knee extensor moment ratio in the nonsurgical limb was close to 1, indicating that peak hip and knee extensor moments were relatively equal during the squat. In contrast, the hip-knee extensor moment ratio in the surgical limb was well above 1 at both time points, indicating that the peak hip extensor moment was larger than the knee extensor moment. The absence of a limb-by-time interaction suggests that these deficits were not different between 3 and 5 months post ACLR.

However, further analyses of their contributions to knee extensor moment deficits at each time point suggest that the underlying mechanics for underloading the knee may differ with time. At 3 months post surgery, both vGRF ratio and surgical-limb hip-knee extensor moment ratio predicted knee extensor moment deficits. Together, they accounted for 85% of the variance in the between-limb knee extensor moment ratio. The vGRF ratio, however, was the largest predictor, explaining 62% of the variance. The hip-knee extensor moment ratio accounted for the remaining 23%. Lower vGRF and larger hip-knee extensor moment ratios predicted smaller knee extensor moments in the surgical limb. These data suggest that at 3 months post ACLR, individuals appear to utilize both interlimb and intralimb compensations but rely more heavily on an interlimb compensation as they shift their weight to the opposite limb. At 5 months post ACLR, only the hip-knee extensor moment ratio predicted knee extensor moment deficits in the surgical limb, indicating that individuals preferentially utilized an intralimb compensation to underload the knee extensors at 5 months. Despite the similarity in the magnitude of knee extensor moment deficits in the surgical limb, it appears that individuals alter the underlying compensatory strategy from 3 to 5 months following surgery.

Interestingly, this change in strategy was observed in the absence of significant

TABLE Descriptive Statistics*

Variable/Time	Surgical Limb	Nonsurgical Limb
Peak knee flexion, deg		
3 mo	101.5 ± 12.9†	103.7 ± 12.6
5 mo	104.3 ± 14.8	106.7 ± 15.0
Peak hip flexion, deg		
3 mo	92.1 ± 17.7	91.1 ± 18.6
5 mo	88.5 ± 15.9	88.6 ± 16.0
Peak knee extensor moment, Nm/kg		
3 mo	0.67 ± 0.24†	1.08 ± 0.18
5 mo	0.78 ± 0.22	1.11 ± 0.25
Peak hip extensor moment, Nm/kg		
3 mo	1.11 ± 0.24	1.05 ± 0.22
5 mo	1.11 ± 0.35	1.06 ± 0.36
Peak vertical ground reaction force, N/kg		
3 mo	0.58 ± 0.08†	0.68 ± 0.06
5 mo	0.62 ± 0.09	0.70 ± 0.12
Hip-knee extensor moment ratio		
3 mo	1.81 ± 0.68†	1.00 ± 0.26
5 mo	1.50 ± 0.60	0.96 ± 0.28
Peak vertical ground reaction force between-limb ratio		
3 mo	0.86 ± 0.11	
5 mo	0.89 ± 0.07	
Rate of squatting, squats/s		
3 mo	0.57 ± 0.04	
5 mo	0.55 ± 0.06	

*Values are mean ± SD.
†Significant main effect of limb.

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changes in hip extensor moments or vGRFs over time. Only the contribution of these variables to knee extensor moment deficits changed over time. The absence of a significant contribution from the vGRF ratio at 5 months suggests that individuals may become more comfortable loading the surgical limb at 5 months, leaving only the intralimb compensation to explain underloading of the knee.

These findings have several implications for rehabilitation following ACLR. Substantial decreases in knee extensor moments were observed during the performance of a submaximal task at a time of rehabilitation when patients are expected to be capable of meeting the mechanical demands of the task. Loading impairments may be difficult to identify clinically, as they were observed along with small differences between limbs in peak knee flexion and no differences between limbs in peak hip flexion. This presents a clinical challenge, given that between-limb differences in knee angle as small as 3° are difficult to detect clinically. During early rehabilitation, strategies for restoring symmetrical weight bearing during bilateral tasks should be emphasized and reinforced even during submaximal tasks. In addition, efforts should be made to continue to focus on sagittal plane knee loading and avoid compensation with the hip extensors. These efforts may be more important in later rehabilitation. Finally, efforts must be made to identify mechanisms for identifying these deficits in the clinic.

While these data longitudinally describe knee sagittal plane underloading strategies following ACLR at 2 rehabilitation time points, interpretation of the data in the present study may be limited due to the small sample size recruited. Two participants included in the analyses had previous contralateral ACLR. Given that ratio calculations compare the surgical limb to what is considered a healthy nonsurgical limb, unresolved impairments may influence the ratio calculations, making these individuals appear less impaired. However, analyses of these data without the 2 participants revealed the same results, suggesting that they were not behaving differently.

Determination of factors that underlie underloading of the knee in the sagittal plane cannot be made based on the current data. In the absence of strength data, it is not known whether individuals can meet the mechanical demands of the task. The fact that the tasks were performed within a self-selected, pain-free range and that there were no complaints of pain suggests that pain did not factor heavily into task performance. No electromyography was collected, thus limiting the authors' ability to determine the presence of hamstring cocontraction during the task. If present, then knee extensor moments may have been underestimated, as inverse dynamics calculate net joint moments. Surgical reconstruction techniques, surgeons, and treating physical therapists varied across participants, making it difficult to attribute deficits or compensatory strategies to a type of surgery or rehabilitation. Despite the large and medium effect sizes observed, a larger sample size would allow for improved generalization to a typical population of patients treated in a physical therapy clinic.

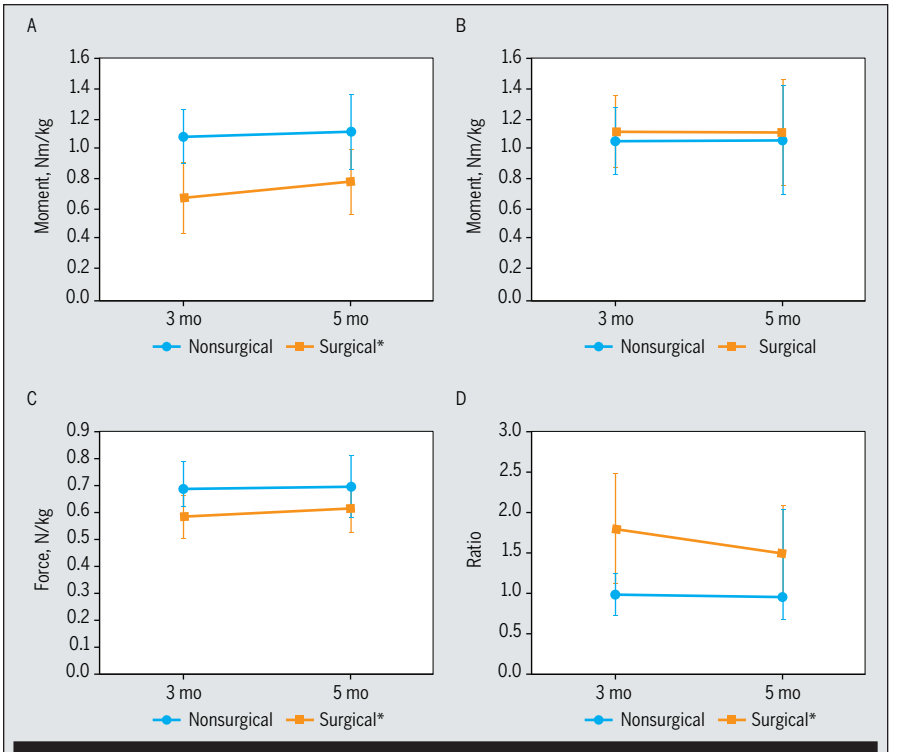


FIGURE. Mean ± SD (A) peak knee extensor moment, (B) peak hip extensor moment, (C) peak vertical ground reaction force, and (D) hip-knee extensor moment ratio between surgical (orange line) and nonsurgical (blue line) limbs during the deceleration phase of a bilateral squat at 3 and 5 months post anterior cruciate ligament reconstruction. *Main effect of limb.

CONCLUSION

Substantial deficits in knee extensor moments in the surgical limb exist at 3 and 5 months post ACLR during a squat against body-weight resistance to a self-selected depth. These deficits do not improve between 3 and 5 months, but the compensatory strategies that contribute to reduced knee extensor moments change across this time interval. At 3 months, individuals relied more heavily on a between-limb compensation, shifting weight to the other limb while also shifting the demand to the hip

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extensors within the surgical limb. By 5 months post ACLR, decreased knee extensor moments in the surgical limb were primarily driven by an intralimb shift to the hip extensors. Despite a difference between limbs in vGRF, a shift away from the nonsurgical limb did not explain knee extensor moment deficits at 5 months post ACLR.

KEY POINTS

FINDINGS: After anterior cruciate ligament reconstruction, individuals exhibited deficits in sagittal plane loading of the knee during bilateral squats at 3 and 5 months following surgery. While these deficits did not improve during this time, the strategy used to compensate for reduced knee extensor moments shifted from a combined interlimb and intralimb compensatory strategy at 3 months to an intralimb strategy at 5 months.

IMPLICATIONS: During rehabilitation of individuals following anterior cruciate ligament reconstruction, efforts should be made to encourage equal distribution of loads between the limbs and avoid compensation with the hip extensors during bilateral squats. An increased focus on the restoration of knee sagittal plane loading during double-limb tasks in early rehabilitation may be needed to limit the persistence of underloading after rehabilitation.

CAUTION: This study did not determine which factors underlie impairments in knee extensor moments. The effectiveness of any recommendations for improving such impairments is speculative.

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