

Original Research

Analysis of Neuromuscular Control and Sensory and Psychological Anxiety Affecting Shock Absorption Capacity in Patients After Anterior Cruciate Ligament Reconstruction Surgery

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Background

Patients who have undergone anterior cruciate ligament (ACL) reconstruction surgery are at high risk of re-injury and osteoarthritis due to increased impact during landing. The characteristics of patients after reconstruction surgery include significant co-contraction of the knee joint antagonistic muscles, decreased proprioception of the knee joint, and psychological anxiety. However, it is unclear whether these factors are related to shock absorption capacity during landing. The purpose of this study was to investigate whether neuromuscular control and sensory and psychological anxiety are associated with shock absorption capacity during single-leg landing from a 30 cm platform in patients who had undergone ACL reconstruction. It was hypothesized that patients with significant knee co-contraction, knee proprioceptive impairment, and psychological anxiety would have reduced shock absorption capacity during landing.

Study Design

Descriptive Laboratory Study

Methods

This study included 16 patients who had undergone ACL reconstruction surgery after sustaining a sports-related ACL injury involving landing movements. Patients with concomitant meniscal or cartilage injuries were excluded. The subjects performed single-leg landings on a force plate from a height of 30 cm, and the shock absorption capacity and magnitude of co-contraction of the quadriceps and hamstrings were measured, and a co-contraction index (CCI) was calculated. In addition, the degree of knee joint proprioception impairment was measured using a Joint-Position Sense test (JPS test), and the level of psychological anxiety related to return to sport was assessed using the Anterior Cruciate Ligament–Return to Sport after Injury (ACL-RSI) scale. Multiple regression analysis was used to examine whether there was a relationship between outcomes and the shock absorption capacity during landing.

Results

The participants consisted of 16 patients (6 males and 10 females) with a mean age of 21.1 ± 2.4 years. Both the CCI and proprioceptive ability (JPS test) significantly influenced the loading rate during landing ($R^2 = 0.70$, $p < 0.01$), with a greater effect observed for

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CCI ($\beta > \text{JPS}$). No association was observed with the degree of psychological anxiety in the patients.

Conclusions

This study demonstrated that greater co-contraction of the knee joint antagonist muscles and reduced proprioceptive ability were associated with decreased shock absorption capacity during single-leg landing in patients after ACL reconstruction.

Level of Evidence

3

INTRODUCTION

Anterior cruciate ligament (ACL) injuries commonly occur during sudden deceleration movements, such as landing on one leg during sports activities.¹ ACL injuries occur approximately 40 milliseconds after foot contact during landing, which closely corresponds to the time when the vertical component of ground reaction force reaches its maximum during single-leg landing.² It has been reported that the tension on the ACL also reaches its peak at the moment of maximum impact.³ Autologous tendon transplantation for ACL reconstruction is the first-line treatment for ACL injuries; however, ACL injuries have a very high recurrence rate, with 15-35% of patients undergoing reconstruction experiencing re-injury.^{4,5} Additionally, patients who have sustained ACL injury are at increased risk of developing osteoarthritis of the knee, which is an important risk factor.⁶ Following ACL reconstruction, patients experience an increase in the vertical component of ground reaction force during movement,⁷ which can lead to increased interarticular forces in the knee joint and contribute to the early onset of osteoarthritis.⁸ Patients with higher peak vertical ground reaction forces during landing after ACL reconstruction have been reported to exhibit poorer cartilage matrix quality, as indicated by increased T2 relaxation times on quantitative MRI.⁹

Therefore, in rehabilitation, physical therapy is recommended to prevent excessive stress on the ACL and increased joint forces caused by large impacts during landing, as well as to promote the acquisition of landing techniques that provide sufficient shock absorption. However, the increase in the vertical component of the ground reaction force during landing is a challenge that cannot be improved through injury prevention programs,¹⁰ and there is currently limited research on the factors related to shock absorption capacity during landing.

An indicator of shock absorption capacity during landing is the loading rate, calculated by dividing the peak value of the vertical component of ground reaction force by the time from foot contact to reaching the peak value of the vertical component of ground reaction force.¹¹ A smaller value indicates superior shock absorption, while a larger value indicates insufficient shock absorption, resulting in a hard landing and high stress on the lower limbs over a short period of time.¹¹ Previous studies have reported that patients after ACL reconstruction demonstrate increased loading rates during landing compared to healthy individuals, indicating reduced shock absorption capacity.¹² Pre-

vious studies have suggested associations between landing shock absorption and knee joint extension moment,¹³ hip joint compensation,^{14,15} and ankle joint range of motion restrictions.¹⁶ However, there are no reports on factors related to patients' neuromuscular control mechanisms or psychological states. Patients following ACL reconstruction often show altered neuromuscular control strategies, such as increased co-contraction around the knee joint, as well as reduced proprioceptive acuity.^{17,18} Moreover, psychological factors, especially anxiety and reduced confidence during return-to-sport decision-making, have been associated with increased risk of a second ACL injury.¹⁹

While increased simultaneous activity of knee joint antagonist muscles provides joint stability, it also increases interarticular forces, raising concerns about the risk of promoting the onset or progression of osteoarthritis of the knee joint.²⁰ In a study of healthy individuals,²¹ it was found that increased simultaneous activity of the quadriceps and hamstrings affects shock absorption capacity during landing, but the relevance to patients after ACL reconstruction surgery remains unclear. The authors hypothesized that increased co-contraction would impair efficient shock absorption by the quadriceps and increase the loading rate. Additionally, proprioceptive dysfunction is considered a risk factor for reinjury and osteoarthritis of the knee,^{22,23} but its impact on shock absorption capacity during landing has not been demonstrated. The authors further hypothesized that patients with proprioceptive dysfunction may struggle with precise knee joint control during landing, leading to increased loading rates. Furthermore, psychological changes in patients undergoing ACL reconstruction often include fear of re-injury, which not only hinders return to sports but has also been reported as a risk factor for re-rupture.^{19,24} Patients with psychological anxiety tend to have smaller lower limb flexion angles during landing,²⁵ leading to insufficient shock absorption during landing and an increase in the loading rate. Therefore, the purpose of this study was to investigate whether neuromuscular control and sensory and psychological anxiety are associated with shock absorption capacity during single-leg landing from a 30 cm platform in patients who have undergone ACL reconstruction.

METHODS

PARTICIPANTS

This study recruited 16 patients who had undergone ACL reconstruction surgery. The required sample size was determined by an a priori power analysis using G*Power (version 3.1.9.7). Based on a previous study that investigated the correlation between a co-contraction index and loading rate in a similar landing task, an effect size of $r=0.65$ was referenced.²¹ With a specified two-tailed significance level of $\alpha=0.05$ and a desired statistical power of $1-\beta=0.80$, the minimum required sample size for the correlation analysis was calculated to be 15 participants. Since this study included 16 participants, the minimum requirement was satisfied. Participants were patients who had sustained an ACL injury during sports involving landing movements and subsequently underwent ACL reconstruction. All participants had been cleared by their surgeons to return to sport, including landing tasks. As part of the general return-to-sport criteria, quadriceps and hamstring strength of the reconstructed limb were required to reach at least 90% of the strength of the contralateral limb. Therefore, all participants had satisfied this criterion. The exclusion criteria were a history of orthopedic conditions or central nervous system disorders other than ACL injuries that required cessation of sports activities. In addition, we excluded those with meniscal injuries, injuries to other knee ligaments, articular cartilage lesions, or a prior history of ACL injury.

All participants underwent ACL reconstruction using an autologous hamstring tendon double-bundle technique. Although surgeries were performed by multiple surgeons, the graft type and surgical procedure were consistent. The two most common surgical procedures performed for ACL reconstruction are autologous hamstring tendon grafting and bone-in patellar tendon grafting. Because differences in pain incidence and knee flexor strength have been reported between the two procedures,^{26,27} subjects were selected for this study based on whether they had undergone autologous hamstring tendon grafting, which is more common in Japan. All participants were informed of the protection and rights of the participants, freedom to participate or withdraw, and details of the study in writing and verbally under the Declaration of Helsinki. Written informed consent was obtained from all the participants. This study was approved by the Institutional Review Board of the Graduate School of International University of Health & Welfare (approval number: 23-Ig-137). All participants were evaluated on the same day to ensure consistency across assessments. The examinations were conducted in the following order: motion analysis, proprioception test, and psychological assessment. All examinations were conducted by a single physical therapist with experience in orthopedic rehabilitation.

MOTION ANALYSIS

Landing motion analysis was performed using a three-dimensional motion analysis system with ten infrared cam-

eras (Vicon Motion Systems, Oxford, UK), two force plates (Kistler, Winterthur, Switzerland), and a surface electromyography system (Biometrics, Newport, RI, USA). The sampling frequency was set to 100 Hz for the infrared cameras and floor reaction force sensors, and 1000 Hz for the surface electromyography. The three-dimensional motion analysis system was synchronized with the force plates and surface electromyography. The measurement software used was the VICON NEXUS ver.1.7.1 (Vicon Motion Systems, Oxford, UK). Kinematic data were obtained by attaching infrared reflective markers with a diameter of 14 mm to various parts of the subjects' bodies and capturing the coordinates of the markers using 10 infrared cameras. The attachment positions of the infrared reflective markers were based on the Plug-In-Gait Model, with additional markers placed on the medial side of the knee joint, medial malleolus, and first metatarsophalangeal joint of the foot.

Surface electromyography (EMG) electrodes were used to acquire muscle activity data using a dry reusable stainless steel EMG amplifier (Biometrics, Newport, NJ, US). The electrodes were placed on five muscles in the thigh that could be measured using surface EMG: the rectus femoris, vastus lateralis, vastus medialis, biceps femoris, and semitendinosus. The attachment sites were placed at the locations recommended by the Surface EMG of Non-Invasive Assessment of Muscle (SENIAM) for each muscle.²⁸ The electrodes were attached by the same researcher using a tape measure, relying on bony landmarks, to ensure consistent positioning, and were placed along the direction of the muscle fibers. Prior to electrode placement, the skin was prepared to minimize artifacts. Hair was shaved when necessary, and the skin surface was cleaned using a dedicated skin preparation agent (Skin Pure, Nihon Kohden, Japan) to remove dirt and superficial keratin. After wiping the area with an alcohol swab and confirming that the skin was dry, the electrodes were attached using an adhesive tape (T350, Biometrics Ltd., UK).

The subjects performed a single leg drop landing movement from a 30 cm platform in a manner that felt comfortable and natural. The participants stood on the platform with both hands on their hips, using this as the starting position, and landed on the force plate with the affected limb without jumping upward, allowing themselves to fall. After practicing several times beforehand, measurements were obtained, and trials in which the subjects could maintain a static posture for 3 seconds after landing were considered successful. The movement measurements were terminated after five successful trials.

After completing the landing movement measurement, the maximum voluntary contraction (MVC) of the quadriceps and hamstrings was measured to normalize muscle activity during the landing movement. MVC measurement was performed twice using a method consistent with manual muscle testing,²⁹ involving isometric exercise at maximum effort for 3–5 seconds, and the higher value was used for data analysis. Based on previous studies,^{30,31} the averages of the rectus femoris, vastus lateralis, and vastus medialis were defined as the quadriceps %MVC (%MVCQuad),

while the averages of the biceps femoris and semitendinosus were defined as the hamstring %MVC (%MVCHam).

In this study, shock absorption capacity was defined as the ability to attenuate ground reaction forces during single-leg landing. The loading rate (N/kg/s) was used as the quantitative indicator of shock absorption capacity. To calculate the loading rate, the peak value of the vertical component of the ground reaction force was divided by body weight and normalized. The formula is as follows:

$$\text{loading rate} \left(\frac{\text{N/kg}}{\text{s}} \right) = \frac{\text{peak } F_z(\text{N}) / \text{bodyweight}(\text{kg})}{\text{time to peak } F_z(\text{s})}$$

In addition, to evaluate the co-contraction of the quadriceps and hamstrings during the landing phase, the co-contraction index (CCI) recommended by Falconer et al.³² was calculated using the following formula: the proportion of muscle activity that is simultaneous with the total muscle activity of the quadriceps and hamstrings within the analysis interval.

The activity of the quadriceps and hamstrings during the landing phase (%iEMGQuad and %iEMGHam) were calculated by integrating %MVCQuad and %MVCHam over time within the analysis interval. The analysis interval was defined as the deceleration phase, which spans the initial ground contact to the moment at which the maximum knee joint flexion angle was recorded. Initial ground contact was defined as the moment when the vertical component of the vertical ground reaction force first exceeded 10 N.³³

$$\text{CCI}(\%) = 2 \times \frac{\%iEMGQuad \cap \%iEMGHam}{\%iEMGQuad + \%iEMGHam} \times 100$$

PROPRIOCEPTION TEST

To assess proprioceptive ability of the knee joint, the Joint-Position Sense test (JPS test) was conducted. The JPS test is measured by actively or passively reproducing the target joint angle.³⁴ A systematic review demonstrated that the JPS test has sufficient validity to distinguish between ACL-injured knees and asymptomatic knees.³⁵ For this test, the subject sat on the Biodex System 4 (Biodex Medical System, New York, US) wearing shorts and bare feet, with their eyes covered. JPS test was assessed at 30° knee flexion using a passive-active reproduction method. Specifically, the examiner passively positioned the participant's knee at the target angle (30°) and held this position for 5 seconds. The participant was then asked to actively reproduce this angle without visual feedback. The passive-active reproduction method has been reported to be appropriate for evaluating proprioception after ACL reconstruction, as it minimizes the confounding influence of muscle strength and motor planning on angle reproduction.³⁶ In a previous study,³⁷ it was reported that five repetitions of the active knee JPS test are necessary to ensure consistent proprioceptive scores; therefore, this measurement was performed five times, and the average absolute error between the target angle and the reproduced angle was calculated. The following formula was used for calculation, with θ target set to 30° and $n=5$.

$$\text{JPS}(\circ) = \frac{1}{n} \sum_{i=1}^n |\theta_{\text{reproduced},i} - \theta_{\text{target}}|$$

PSYCHOLOGICAL MEASURE

The Japanese version of the Anterior Cruciate Ligament-Return to Sport after Injury scale (ACL-RSI scale) was administered as a psychological anxiety test. The ACL-RSI scale is a psychological assessment tool for patients with ACL injuries developed in 2008 and consists of a 12-item questionnaire on “emotions,” “confidence in performance,” and “risk assessment.” risk assessment.³⁸ The maximum possible score is 100 points, with higher scores indicating a better psychological status. The ACL-RSI scale has been shown to be associated with persistent alterations in landing muscle activation patterns after ACL reconstruction and is also used to predict the likelihood of returning to sport.^{39,40} This evidence supports the decision to use ACL-RSI in examining psychological anxiety in relation to landing mechanics. The ACL-RSI scale has demonstrated good validity and reliability in clinical guidelines and its validity has been confirmed in the Japanese version.^{41,42}

STATISTICAL ANALYSES

Statistical analysis was performed using multiple regression analysis to clarify the relationship between the loading rate and the CCI, JPS test, and ACL-RSI scale in the single-leg landing movements of ACL reconstruction patients. The dependent variable was the loading rate, and the independent variables were the CCI, JPS test results, and ACL-RSI scale scores. Before analysis, the normality of the variables was confirmed using the Shapiro-Wilk test, and the shape of the distribution was examined using histograms. None of the variables deviated significantly from a normal distribution or exhibited a frequency bias. Therefore, dummy variables and transformations are not applied. Additionally, a correlation matrix was examined, and no variables with $|r| > 0.9$ were identified; therefore, all variables were included in the analysis. The significance level for all statistical analyses was set at $p < 0.05$. IBM SPSS Statistics 22 (SPSS Japan Inc., Tokyo, Japan) was used as the statistical software.

RESULTS

The mean age of the subjects was 21.1 ± 2.4 years, and the mean postoperative follow-up period was 35.7 ± 11.9 months (Table 1). Among the 16 subjects, six were male and 10 were female, and the affected limb was on the right side in five subjects and the left side in 11 subjects.

The results of the loading rate, CCI, JPS test, and ACL-RSI scale during the single-leg stance are shown in Table 2. The mean loading rate was 532.1 ± 138.7 N/kg/s, the mean CCI was $61.12 \pm 6.6\%$, the mean JPS test results were $5.6 \pm 1.9^\circ$, and the mean ACL-RSI scale results were 58.2 ± 9.7 points.

The results of the multiple regression analysis examining the effects of the CCI, JPS test, and ACL-RSI scale on the loading rate are shown in Table 3. Variable selection was performed using the stepwise method (variable addition/subtraction method), and the ACL-RSI scale was excluded from the variables. Several regression models were

Table 1. Characteristics of the participants (n = 16)

	Mean ± SD
Age (years)	21.1 ± 2.4
Sex (male/female)	6 / 10
Height (cm)	166.4 ± 7.0
Weight (kg)	65.5 ± 12.3
BMI (kg/m ²)	23.6 ± 3.8
Injured side (right/left)	5 / 11
Postoperative lapse period (months)	35.7 ± 11.9

SD, standard deviation
BMI, Body Mass Index

Table 2. Mean values of each measurement

	Mean ± SD
Loading rate (N/kg/ms)	532.1 ± 138.7
CCI (%)	61.2 ± 6.6
JPS test (°)	5.6 ± 1.9
ACL-RSI scale (points)	58.2 ± 9.7

SD, standard deviation
CCI, Co-Contraction Index
JPS test, Joint Position Sense test, JPS > 5°= dysfunction
ACL-RSI scale, Anterior Cruciate Ligament-Return to Sport after Injury scale

Table 3. Results of multiple regression analysis

Predictor	B (Unstandardized)	SE	β (Standardized)	t	95% CI (Lower–Upper)	p-value
CCI	942.09	159.38	0.78	5.91	597.78 - 1286.39	<0.001*
JPS	-27.44	8.17	-0.44	-3.36	-45.08 - -9.80	0.005*
Model fit						
R ² = 0.77, F= 22.2, p < 0.001*						

* p<0.01
CCI, Co-Contraction Index
JPS test, Joint Position Sense test

estimated, but the model with the lowest Akaike information criterion (AIC) was adopted, resulting in the following equation:

$$\text{loading rate} = 346.23 + 942.09 \times \text{CCI} - 27.44 \times \text{JPS}$$

The significance of the regression equation was confirmed via analysis of variance, with a p-value below 0.01, indicating statistical significance. Furthermore, the coefficient of determination was 0.70, indicating high goodness of fit and predictive accuracy. There were no outliers where the predicted values exceeded $\pm 3\text{SD}$ of the observed values. The results clarified that the CCI and JPS influenced the magnitude of the loading rate. Additionally, since the standardized partial regression coefficient (β) was higher for CCI than for JPS, the influence of CCI was particularly significant.

DISCUSSION

These results indicate that increased quadriceps–hamstrings co-contraction and impaired knee joint proprioception are associated with reduced shock absorption capacity during single-leg drop landing after ACL reconstruction. One possible explanation for this is that greater co-contraction of the quadriceps and hamstrings increases knee joint stiffness. When joint stiffness increases, the knee joint range of motion during landing becomes restricted, limiting the ability to eccentrically absorb impact forces and resulting in a higher loading rate. Increased impact during landing is a known risk factor for ACL injury and knee osteoarthritis.^{3,8} Therefore, increased co-contraction of the knee muscles, which reduces shock absorption capacity, may elevate the risk of ACL re-injury and knee osteoarthritis. Furthermore, when knee joint proprioception is impaired, the ability to accurately perceive joint position decreases, making it difficult to perform the fine lower-limb

motor control necessary to attenuate impact during landing. In the present study, impaired proprioception was associated with a higher loading rate, suggesting that reduced proprioceptive function may contribute to insufficient shock absorption.

The average error in the JPS test for healthy individuals is approximately 3° ,⁴³ but the average error for patients who had undergone ACL reconstruction in this study was 5.6° . Previous studies have determined that a JPS test score of 5° or higher indicates proprioceptive dysfunction in patient who had undergone ACL reconstruction,⁴⁴ and approximately half of the participants in this study had positional error at that level, suggesting they had dysfunction. When the ACL is damaged, afferent input from mechanoreceptors within the ligament is reduced, which may lead to diminished ability to finely regulate and stabilize the knee joint, even though other proprioceptors in surrounding tissues such as the musculotendinous structures remain active. This leads to inadequate motor control that relies on the proprioceptive sensation of the surrounding tissues. Proprioceptive dysfunction is thought to increase the risk of reinjury and osteoarthritis of the knee,^{22,23} and this study suggests that it may also be a potential risk factor from the perspective of shock absorption capacity.

Scores on the ACL-RSI scale did not affect the loading rate. No significant association was observed between ACL-RSI and shock absorption capacity. This negative finding should be interpreted with caution. The landing task involved a 30-cm single-leg drop landing, which has been widely used in previous ACL studies due to its safety and standardization. However, given that participants in this study were evaluated an average of 36 months postoperatively, this task may have been relatively easy for them. Consequently, a ceiling effect may have occurred, potentially masking the association between psychological anxiety and loading rate. If a similar study was conducted using subjects whose postoperative recovery period is more limited and who are nearing a full competitive return, different results may be obtained. Furthermore, the ACL-RSI scale primarily measures readiness to return to sport rather than general psychological anxiety, which may limit its sensitivity to landing-related psychological influences.

This study revealed that the shock absorption capacity during landing was associated with quadriceps–hamstrings co-contraction and knee joint proprioceptive dysfunction following ACL reconstruction. These findings suggest that when excessive co-contraction or impaired proprioception is present, landing mechanics may be altered in a manner that reduces the ability to attenuate impact. Although this study did not directly examine rehabilitation interventions, clinical strategies that aim to optimize muscle activation patterns and enhance proprioceptive function may be considered in patients who demonstrate insufficient shock absorption during functional assessments.

However, there are some points to be considered when considering the rehabilitation for co-contraction. In the early stages after ACL reconstruction surgery, the reconstructed ligament is unstable and the knee joint is unstable, and it is said that co-contraction of the hamstrings com-

pensates for stability.⁴⁵ On the other hand, in patients like those in this study, where the reconstructed ligament is stable and sports return is permitted, excessive co-contraction can counteract internal torque on the joint, leading to increased energy costs and reduced performance.^{46,47} Therefore, when considering interventions to address excessive co-contraction in ACL reconstruction rehabilitation, it is important to take into account the recovery process of the reconstructed ligament. The level of co-contraction should be evaluated over time beginning pre-operatively, and if elevated quadriceps–hamstrings co-contraction persists even after the reconstructed ligament has stabilized, targeted intervention may be appropriate. For example, biofeedback training has been reported to be effective in reducing excessive quadriceps–hamstrings co-contraction around the knee joint.⁴⁸ Interventions that address proprioceptive deficits such as vibration therapy and neuromuscular training using balance boards have been shown to improve joint position sense.^{49,50} For ACL-injured patients with insufficient shock absorption, interventions targeting antagonist muscle co-contraction and proprioceptive deficits, when present, may contribute to safer landings.

LIMITATIONS OF THE STUDY

In this study, the factors related to neuromuscular control, proprioception, and psychological state were examined related to the ability to absorb impact upon landing. from the perspective of the risk of ACL reinjury and the potential for developing post-traumatic osteoarthritis of the knee. However, because ACL tensile stress or joint forces were not directly measured, the recommendations are solely based on the biomechanical risks of landing. The small sample size of this study limits the generalizability of the findings and the statistical power. The a priori power analysis was based on an effect size ($r=0.65$) derived from a prior study involving healthy individuals, which may not accurately reflect the true effect size and variance within an ACL-reconstructed patient population. While this sample size met the minimum requirement for a strong correlation, a larger sample size is generally warranted for the multiple regression analysis that served as the primary analysis for this study. Therefore, the results should be interpreted with caution and regarded as preliminary. This study was conducted as a single-group, descriptive study without a control group, therefore direct comparison regarding whether the measured values in the ACL-reconstructed patients were statistically or clinically different from a non-ACLR population are not able to be performed. The interpretation of these observed metrics relies solely on comparison with existing literature, which is a limitation of the current design. Future studies should incorporate an appropriate control group to facilitate comparative analyses and provide a more robust understanding of the characteristics specific to the ACL-reconstructed population. Another limitation of this study is the timing of evaluation. Participants were assessed at an average of 36 months postoperatively, which is later than the typical 9–12 months commonly used for return-to-sport assessments. This delay may have affected

the outcomes, and future studies should investigate patients at earlier and standardized postoperative time points. The rehabilitation process and duration varied among individuals, making it impossible to rule out the influence of different rehabilitation programs on these results. Furthermore, estimated pre-injury capacity (EPIC) levels were not assessed in this study, which should be addressed in future research. In addition, although all study subjects underwent ACL reconstruction using a standard autologous hamstring tendon double-bundle technique, other commonly used procedures, such as bone–patellar tendon–bone grafting, may yield different results. Surface electromyography was used to measure the muscle activity of the thigh muscles to calculate the CCI as an indicator of co-contraction; however, other knee joint muscles, such as the intermediate vastus muscle, the short head of the biceps femoris, and the gastrocnemius muscles, which, although primarily ankle plantar flexors, also acts as a two-joint muscle influencing knee flexion, were not measured.

However, shock absorption capacity is likely influenced by a variety of factors, including hip and ankle joint function future studies should incorporate these variables in more comprehensive analyses.

In addition, although a 100-Hz sampling rate is commonly used and considered sufficient in clinical biomechanics studies, the use of a higher sampling frequency could have provided more detailed kinematic data.

CONCLUSION

The degree of quadriceps–hamstrings co-contraction and knee joint proprioceptive function appear to be associated with shock absorption capacity during single-leg landing in individuals following ACL reconstruction. Increased co-contraction may contribute to greater knee joint stiffness, and impaired proprioception may reduce the ability to perform finely controlled lower-limb movements, both of which were associated with a higher loading rate in this study. In contrast, no association was observed between psychological readiness (ACL-RSI scale scores) and shock absorption capacity.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

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