

Effects of Deficits in the Neuromuscular and Mechanical Properties of the Quadriceps and Hamstrings on Single-Leg Hop Performance and Dynamic Knee Stability in Patients After Anterior Cruciate Ligament Reconstruction

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Background: Understanding the role of neuromuscular and mechanical muscle properties in knee functional performance and dynamic knee stability after anterior cruciate ligament reconstruction (ACLR) may help in the development of more focused rehabilitation programs.

Purpose: To compare the involved and uninvolved limbs of patients after ACLR in terms of muscle strength, passive muscle stiffness, muscle activation of the quadriceps and hamstrings, hop performance, and dynamic knee stability and to investigate the association of neuromuscular and mechanical muscle properties with hop performance and dynamic knee stability.

Study Design: Cross-sectional study; Level of evidence, 3.

Method: The authors studied the quadriceps and hamstring muscles in 30 male patients (mean \pm SD age, 25.4 \pm 4.1 years) who had undergone unilateral ACLR. Muscle strength was measured using isokinetic testing at 60 and 180 deg/s. Passive muscle stiffness was quantified using ultrasound shear wave elastography. Muscle activation was evaluated via electromyographic (EMG) activity. Hop performance was evaluated via a single-leg hop test, and dynamic knee stability was evaluated via 3-dimensional knee movements during the landing phase of the hop test.

Results: Compared with the uninvolved limb, the involved limb exhibited decreased peak torque and shear modulus in both the quadriceps and hamstrings as well as delayed activity onset in the quadriceps ($P < .05$ for all). The involved limb also exhibited a shorter hop distance and decreased peak knee flexion angle during landing ($P < .05$ for both). Decreased peak quadriceps torque at 180 deg/s, the shear modulus of the semitendinosus, and the reactive EMG activity amplitude of the semimembranosus were all associated with shorter hop distance ($R^2 = 0.565$; $P < .001$). Decreased quadriceps peak torque at 60 deg/s and shear modulus of the vastus medialis were both associated with smaller peak knee flexion angle ($R^2 = 0.319$; $P < .001$).

Conclusion: In addition to muscle strength deficits, deficits in passive muscle stiffness and muscle activation of the quadriceps and hamstrings were important contributors to poor single-leg hop performance and dynamic knee stability during landing. Further investigations should include a rehabilitation program that normalizes muscle stiffness and activation patterns during landing, thus improving knee functional performance and dynamic knee stability.

Keywords: ACL; knee; muscle; rehabilitation

Anterior cruciate ligament (ACL) injury is commonly associated with knee instability and decreased activity level.⁶ Approximately two-thirds of ACL injuries occur via a noncontact mechanism such as jump landings.¹⁷ Return to play is highly desired and expected for athletes after ACL

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reconstruction (ACLR) and postoperative rehabilitation. Unfortunately, for some patients who return to their previous level of sports, the risk of subsequent ACL injury is 15-fold greater than that in the healthy population.⁴⁷

Despite restoration of passive knee laxity after ACLR, dynamic knee stability is often not fully restored, and this may partly explain the high risk of a secondary ACL injury.³⁵ Biomechanically, dynamic knee stability is considered as the ability to control the relative tibiofemoral movements during loading. The single-leg hop test has been used as a functional test to determine readiness to return to play,³¹ given that single-leg landings involve rapid deceleration, which is one of the mechanisms of ACL injury,⁴³ and hop test performance may be able to predict dynamic knee stability.¹⁴ Poor single-leg hop performance has been correlated with poor self-reported knee function 1 year after ACLR.³⁷ Recently, some research groups have suggested that measuring only hop distance during the single-leg hop test may mask any deficits in dynamic knee stability during landing.³¹ It has been reported that patients after ACLR exhibited altered lower limb biomechanics during a single-leg landing when compared with either the contralateral side or healthy control participants.²⁸ Aberrant knee biomechanics such as decreased knee flexion angle, reduced knee power absorption, and increased valgus movement are predictive of a second ACL injury.^{23,48}

To prevent a second ACL injury, the knee joint must be stabilized and protected by passive restraint (ligaments) and active restraint (muscles). However, decreased muscle strength of the quadriceps and hamstrings is a common consequence after ACL injury and ACLR.⁵⁶ Decreased quadriceps strength is thought to negatively affect dynamic knee stability by lowering the ability of the knee joint to dynamically absorb forces during loading.⁴⁵ However, recovery of muscle strength (>85% of limb symmetry) alone may not be sufficient to maintain dynamic knee stability.¹⁰ Altered muscle activation patterns during landing have been found in patients after ACLR even though they were considered fit for return to play.²⁰ Unfavorable muscle activation patterns (eg, increased preactivation of the lateral quadriceps and hamstrings) and low hamstrings to quadriceps coactivation during high-risk maneuvers (eg, single-leg landing, cutting, and deceleration) can cause exaggerated valgus and tibiofemoral shear forces, which are associated with ACL injury.^{21,46} Quadriceps activation increases the tensile force placed on the ACL, whereas higher hamstring activation helps to reduce reliance on the ACLR by providing additional passive resistance to anterior translation.^{18,25}

In addition to these neuromuscular properties, mechanical properties are a critical determinant of muscle performance.⁵⁰ Passive muscle stiffness measured via shear modulus contributes to rapid force production, which is a major determinant of muscle force that can be achieved during rapid limb movements.³ Decreased shear modulus of the vastus medialis (VM), associated with poor knee function, has been found in patients with ACLR when compared with healthy controls.¹⁹ Poor recovery of these muscle properties may lead to poor knee functional performance and even unfavorable knee biomechanics, which increases the risk of ACL reinjury. However, whether deficits in muscle stiffness and muscle activation affect knee functional performance and dynamic knee stability is not fully understood. Because muscular adaptations are modifiable by targeted muscular training,^{33,36} a clear understanding of the role of muscle properties in knee functional performance and dynamic knee stability may help clinicians to develop a more focused rehabilitation program after ACLR.

This study aimed to (1) compare the involved and uninvolved limbs of patients after ACLR regarding muscle strength, passive muscle stiffness, muscle activation of the quadriceps and hamstrings, single-leg hop performance, and dynamic knee stability during landing and (2) investigate the association of these muscle properties with hop performance and dynamic knee stability. We hypothesized that (1) compared with the uninvolved limb, the involved limb would show decreased muscle strength, decreased passive muscle stiffness, decreased muscle activation of the quadriceps and hamstrings, shorter hop distance, decreased knee flexion angle, and greater knee valgus torque and knee extension torque during landing and (2) decreased muscle strength, passive muscle stiffness, and muscle activation of the quadriceps and hamstrings would all be associated with shorter hop distance and poorer knee biomechanics.

METHODS

Study Patients

This was cross-sectional study. A total of 30 male patients who had undergone ACLR using hamstring tendon autograft were recruited from the Prince of Wales Hospital, Hong Kong, between August 2019 and January 2020. The inclusion criteria were (1) male sex; (2) age between 18 and 35 years; (3) preinjury Tegner activity level >6; (4) time since surgery between 6 and 18 months; and (5) no history

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of bone, ligament, meniscus, or muscle injury to the uninvolved limb. The exclusion criteria were (1) concomitant fracture, meniscal injury, or chondral lesion that needed surgical repair or additional postsurgical rehabilitation (diagnosis confirmed via magnetic resonance imaging and arthroscopy); (2) preparative radiographic signs of arthritis with Kellgren-Lawrence grade ≥ 1 ; (3) revision of ACL surgery; (4) previous spinal injury; or (5) hamstring strain during the previous 6 months. All reconstructions were performed by the same group of orthopaedic surgeons led by the same chief surgeon (P.S.H.Y.). All patients had regained full range of motion and had negative Lachman and pivot-shift tests. They were cleared to resume sports activity. The study protocol received ethics committee approval, informed consent was obtained from the patients, and all the procedures were conducted in accordance with the Declaration of Helsinki.

Isokinetic Muscle Strength

The isokinetic strength of the quadriceps and the hamstring muscles was tested using a Biodex dynamometer (Biodex System 4; Biodex Medical Systems Inc). Voluntary concentric contractions for both knee extension and flexion were tested at 60 deg/s for 5 repetitions and at 180 deg/s for 10 repetitions.⁴⁴ Patients were stabilized using straps placed over the trunk, the pelvis, and the tested thigh to isolate knee movement. A total of 3 submaximal voluntary concentric contractions were performed for familiarization. Patients were then instructed to move through their maximal knee flexion range and extension range to set the testing range of motion. The resulting peak torque values at 60 and 180 deg/s were collected for analysis.

Passive Muscle Stiffness

Passive muscle stiffness of the quadriceps and hamstrings was evaluated using the shear modulus of the VM, rectus femoris (RF), vastus lateralis (VL), semimembranosus (SM), semitendinosus (ST), and biceps femoris (BF) of both limbs for all patients in a temperature-controlled room set at 25°C. An Aixplorer ultrasound scanner (Supersonic Imagine) coupled with shear wave elastography mode and a linear transducer array (2-10 MHz; SuperLinear 10-2; Vermon) was used. Patients were asked to lie supine with hip and knee flexed to 30° for the measurements of the quadriceps and to lie prone with hip and knee flexed to 30° (measured via a goniometer) for the measurements of hamstring muscles, which is a method we previously established.¹⁹ The measurement locations were determined as follows: VM, 20% of the distance from the midpoint of the medial patellar border to the anterior superior iliac spine; RF, half of the distance from the anterior superior iliac spine to the midpoint of the superior tip of the patella; VL, one-third of the distance from the midpoint of the lateral patellar border to the anterior superior iliac spine; ST and SM, half of the distance from the ischial tuberosity to the medial femoral epicondyle; and BF, half of the distance from the ischial tuberosity to the lateral epicondyle of the

femur.⁵⁸ These positions have provided reliable readings in our previous work.¹⁹

For each muscle, images were taken after the transducer was held at the measurement site for <10 seconds in order to confirm that the shear elastic modulus in the region of interest (ROI) had a stable color distribution. The mean Young modulus (kPa) of a circle with the diameter of 11cm set near the center of the ROI was calculated.²⁶ The measurements were taken 3 times for each muscle, and the mean values were used for statistical analysis. Because skeletal muscle cannot be assumed to be isotropic, we report the shear modulus values as the Young modulus values divided by 3.²⁴ Electromyographic (EMG) amplitudes were monitored during the whole measurement to ensure a relaxed state. The surface EMG electrodes were placed over the bulk of the VL, VM, SM, and BF, which is close to the measurement points. The whole procedure was completed by the same researcher (X.H.) for all patients.

Single-Leg Hop Test

The single-leg hop test was performed according to a previous study.¹⁶ A 5-minute warm-up (stationary cycling exercise) was done before the test. Patients were asked to jump as far as possible, land on 1 leg with their hands placed on their hips, and maintain their balance for at least 2 seconds after landing. The hop distance was determined as the distance from the toe of the takeoff point to the toe of the final landing point. After sufficient practice of the test protocol, patients performed 3 successful trials, and the average value of 3 trials was used for analysis.

Knee Biomechanics

We quantified 3-dimensional knee kinematic and kinetic data using a skin marker-based motion analysis system (Vicon MX) with the lower limb marker set up following the standard protocol using 16 cameras and 16 reflective skin markers¹¹ (Figure 1). Before the single-leg hop test, calibration with patients in a standing position was performed to identify the centers of joints and create local coordinate systems for each body segment. From the single-leg hop task, the initial contact (IC) of landing was defined as the first time point at which the vertical ground-reaction force (vGRF) exceeded 10 N, and the landing phase was defined as the time from IC to peak knee flexion.³⁴ The kinematic variables, including peak value and value at IC, were collected from the 3-dimensional knee movements (knee flexion, knee valgus, and knee internal rotation). The kinetic variables including peak vGRF, peak knee valgus torque, and peak knee extension torque were evaluated via a synchronized force plate (0.60 × 0.40 m; model OR6-7; AMTI) at the center of the capture volume at 1500 Hz. Anthropometric measurements (height, body mass, limb length, and knee and ankle joint widths) were recorded and put into a Plug-in Gait model in Vicon Nexus software for estimating joint kinematics and kinetics. The vGRF was normalized to body mass, and torques were normalized to body mass × limb length. All kinematic and kinetic variables for both the

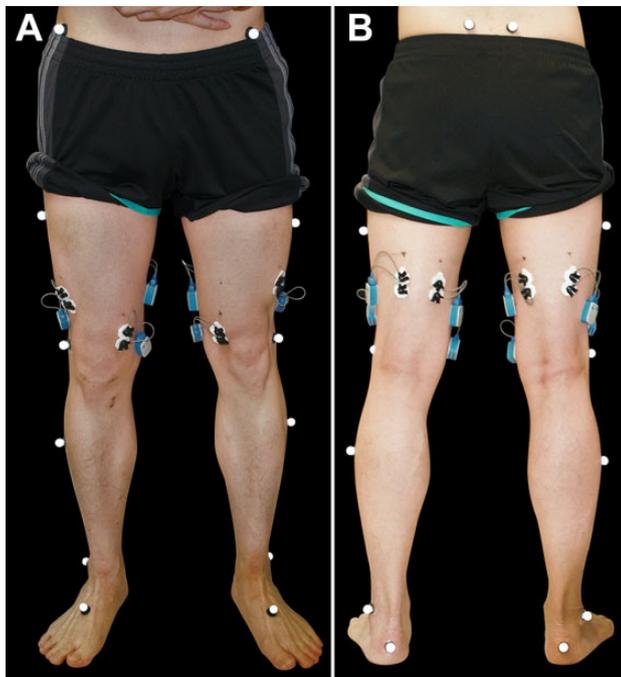


Figure 1. Marker placements with respect to the Vicon Plug-In Gait model: (A) anterior view, (B) posterior view.

involved and uninvolved limbs were calculated for data analysis.

Muscle Activation

Muscle activation was assessed using an electromyography instrument with a wireless telemetry system (Noraxon Inc) during single-leg hop landing with a sampling rate of 1500 Hz on the VM, VL, SM, and BF. The skin over these muscles was carefully shaved, abraded, and cleaned with alcohol before electrode placement. Bipolar surface electrodes with a 2-cm interelectrode distance were applied to the skin in the middle part of the muscle bellies on both limbs according to the recommendations from SENIAM by the same researcher (X.H.).²² EMG data were time synchronized with the kinematic and kinetic data. Raw EMG data were band-pass filtered using a fourth-order, zero-lag Butterworth filter with high- and low-pass cutoff frequencies of 10 and 500 Hz, respectively. The data were then full-wave rectified and processed using a root-mean-square algorithm. The following parameters were analyzed: (1) onset time, the time interval from muscle activity onset to IC; (2) mean preparatory EMG activity, the magnitude of muscle activity 100 milliseconds before IC; and (3) mean reactive EMG activity, the magnitude of muscle activity 250 milliseconds after IC.⁵⁴ The muscle onset was determined via the rising of linear envelopes representing each muscle burst.⁵ We performed 3 trials of 3-second maximal voluntary contraction with the knee and hip flexed at 30° for each muscle group to provide EMG normalization criteria. The quadriceps-to-hamstrings ratio was determined separately for the preparatory (before landing) and reactive (during

landing) phases by calculating the mean of the normalized VM and VL EMG data and then dividing this number by the normalized SM and BF EMG data.

Subjective Knee Function and Knee Laxity

The subjective knee function was evaluated using the International Knee Documentation Committee (IKDC) scoring system, which consists of 10 questions about symptoms and activity, with the score ranging from 0 to 100.²⁷ Knee laxity (anterior displacement of the tibia) was measured using a KT-1000 arthrometer (MEDmetric Corp) at 134 N with the knee flexed at around 20°.⁵¹ The side-to-side difference was recorded as anterior knee laxity difference.

Statistical Analysis

The study sample size was calculated based on the effect size of 0.155 in VM shear modulus between limbs from the first 10 patients. With an alpha level of .05 and a statistical power of 0.80, we determined that a sample size of 27 patients was needed.

Data normality was determined using a histogram and the Shapiro-Wilk test. Mean and SD were calculated for normally distributed variables, whereas median and interquartile range were calculated for variables that were not normally distributed. Given the small number of missing values, we used the listwise exclusion method to deal with the missing data. Because the involved limb was assumed to be the same as the uninvolved side, comparisons of muscular and knee biomechanics measures between limbs were conducted using the paired-samples *t* test or Wilcoxon rank sum test. Associations among all the variables were first assessed using Pearson correlation.

Factors with $r > 0.3$ and $P < .05$ were subsequently included in multivariate regression analysis (stepwise method) until the model with the greatest adjusted R^2 was obtained. Other factors, including limbs (involved/uninvolved), age, body mass index, time since surgery, preinjury activity level (Tegner), and knee laxity, were also included in the regression model for the adjustment. Collinearity tests were performed to determine whether the correlation among the predictor variables may have negatively influenced each regression model via variable suppression. We examined the variance inflation factor for each regression model to assess its multicollinearity. A variance inflation factor >10.0 is thought to indicate multicollinearity within a regression model.⁴ Statistical significance was defined as $P < .05$. The power for regression analysis was adequate (power >0.80) based on the power calculation with an alpha level of .05, number of independent variables of 3, and observed multiple correlation coefficient of 0.56.⁷ All analyses were performed using SPSS (Version 26.0; SPSS Inc).

RESULTS

The characteristics of the 30 study patients are reported in Table 1. All patients were able to accomplish all tests except for 2 patients who refrained from performing the single-leg

TABLE 1
Characteristics of the Study Patients (N = 30)^a

Variable	Mean ± SD
Age, y	25.4 ± 4.1
Body mass index	23.3 ± 2.0
Preinjury activity level, Tegner	8.0 ± 1.1
Current activity level, Tegner	6.3 ± 1.4
Time from surgery, mo	9.9 ± 2.6
Time from injury, mo	13.1 ± 3.6
Knee laxity, side-to-side difference, mm	1.8 ± 4.4
Single-leg hop distance LSI, %	86.2 ± 13.6
IKDC score	81.9 ± 10.4

^aIKDC, International Knee Documentation Committee; LSI, limb symmetry index.

hop test on the involved limb because of fear of the knee giving way and pain. The side-to-side difference in knee laxity for these 2 patients was 2 and 4 mm. The knee biomechanics data of the uninvolved limb of 1 patient failed to be analyzed due to invisible markers.

For the between-limb comparison, the involved limb exhibited decreased peak torque in the quadriceps and hamstrings at both 60 and 180 deg/s when compared with the uninvolved limb (quadriceps peak torque at 60 deg/s: $r = -5.228$, $P < .001$; hamstring peak torque at 60 deg/s: $r = -2.998$, $P = .006$; quadriceps peak torque at 180 deg/s: $r = -5.204$, $P < .001$; hamstring peak torque at 180 deg/s: $r = -3.466$, $P = .002$). The shear modulus of VM, SM, and ST was significantly lower in the involved limb when compared with the uninvolved limb (VM shear modulus: $r = -2.931$, $P = .007$; SM shear modulus: $r = -2.337$, $P = .027$; ST shear modulus: $r = -6.688$, $P < .001$). The shear modulus was not significantly different for VL, RF, and BF. The EMG activity onset for VM was significantly delayed in the involved limb compared with the uninvolved limb ($r = 2.335$; $P = .030$). The other muscles did not have significant difference in EMG activity onset, and none of the muscles showed differences in preparatory or reactive amplitudes between limbs. The involved limb exhibited a significantly shorter hop distance and decreased peak knee flexion angle when compared with the uninvolved limb ($r = -5.194$, $P < .001$ and $r = -2.750$, $P = .011$, respectively). The details are presented in Table 2.

The regression model showed that decreased quadriceps peak torque at 180 deg/s, ST shear modulus, and reactive EMG amplitude of SM and shorter time since ACLR were associated with shorter hop distance ($R^2 = 0.565$; $P < .001$). Decreased quadriceps peak torque at 60 deg/s and VM shear modulus were associated with a smaller peak knee flexion angle ($R^2 = 0.319$; $P < .001$). An increased reactive EMG amplitude of SM was associated with greater peak knee valgus torque ($R^2 = 0.128$; $P = .005$). An increased preparatory EMG amplitude of VM was associated with greater peak knee extension torque ($R^2 = 0.112$; $P = .010$). For all regression models, the variance inflation factor never exceeded 2.0, and therefore we are confident that

multicollinearity did not influence the results. The details are presented in Table 3.

DISCUSSION

The study results indicated that in addition to decreased quadriceps and hamstring strength, the involved limb exhibited delayed VM activity onset and decreased shear modulus of VM, SM, and ST together with a shorter hop distance and decreased peak knee flexion angle during landing when compared with the uninvolved limb. Decreased muscle strength, passive muscle stiffness, and muscle activation of the quadriceps and hamstrings were found to be associated with poorer single-leg hop performance and dynamic knee stability.

Our findings are consistent with previous studies that reported significantly decreased quadriceps and hamstring muscle strength⁵⁶ and decreased knee flexion angle during landing for ACL-reconstructed limbs.²⁸ As well, we found decreased shear modulus in VM, SM, and ST, which indicates that the muscles become less stiff. Interventions that help to increase muscle stiffness, such as eccentric exercise training and cryotherapy, may be necessary for rehabilitation.^{33,49} The altered passive muscle stiffness may be caused by the impaired gamma loop function, which regulates muscle stiffness around the knee joint.³⁰ Besides decreased muscle perimysium thickness,⁵³ altered muscle internal structures are considered as possible mechanisms for altered passive muscle stiffness.¹ Significantly reduced volume of SM has been reported in patients even 2 years after ACLR, regardless of graft type.⁵² It has been found that muscle and tendon stiffness are affected after harvesting hamstring muscle for graft.⁵⁵ This probably explains the significant decrease in ST muscle shear modulus, as hamstring muscle atrophy and shortening were obvious after ACLR using ST tendon.⁴¹ For the quadriceps muscles, we found a significant decrease only in VM. The VM is more challenging to be trained because it achieves maximum contraction during full extension and because VM weakness is frequently found even after completion of a rehabilitation program.^{8,39} In contrast to our study, McPherson et al⁴⁰ found a decrease in shear modulus of VL in patients 6 months after ACLR and an increase in shear modulus of VM of the involved limb when compared with the uninvolved limb 12 months after ACLR. Kawai et al²⁹ reported no significant difference in shear modulus of the quadriceps muscles between the involved and the uninvolved limb in patients at an early stage after ACLR. It should be noted that these 2 studies included patients with bone–patellar tendon–bone or hamstring tendon graft, whereas all of the patients in our study underwent reconstruction using hamstring tendon graft. In addition, the characteristics of their patients and joint position were different from ours. We included only male and active young patients in order to make this sample more homogeneous. Muscle stiffness was measured with knees and hips flexed to 30° in our study, which is commonly observed during landing.³⁵ Contrary to a previous study¹⁶ that reported a trend of earlier VM onset, we found a delayed VM onset in the involved limb

TABLE 2
Difference in Hop Performance, Knee Kinematics, Knee Kinetics, Muscle Strength, Passive Muscle Stiffness, and Muscle Activation During Landing Between the Involved and Uninvolved Limbs^a

	Involved Limb	Uninvolved Limb	P
Hop performance			
Hop distance, cm	101.4 ± 26.3	117.6 ± 23.8	<.001 ^b
Kinematics, deg			
Flexion			
IC	16.1 ± 7.8	17.5 ± 8.5	.488
Peak	48.1 ± 12.9	54.6 ± 13.9	.011 ^c
Valgus			
IC	4.4 (−0.3 to 8.4)	5.9 (−0.6 to 8.4)	.904
Peak	−3.4 ± 6.1	−2.1 ± 9.4	.506
Internal rotation			
IC	−5.6 ± 19.6	1.7 ± 18.6	.286
Peak	4.5 ± 14.1	10.3 ± 13.2	.210
Kinetics			
Peak vGRF, %BM	2.6 ± 1.2	2.4 ± 1.1	.213
Peak valgus moment, N-cm/kg	177.8 (87.4 to 370.0)	187.3 (89.0 to 389.2)	.701
Peak extension moment, N-cm/kg	607.0 (471.2 to 918.0)	522.2 (417.3 to 888.4)	.442
Muscle strength, N-cm			
Quadriceps peak torque at 60 deg/s	149.1 ± 41.8	178.2 ± 35.7	<.001 ^b
Quadriceps peak torque at 180 deg/s	113.8 ± 28.1	132.6 ± 26.7	<.001 ^b
Hamstring peak torque at 60 deg/s	64.9 ± 19.1	71.3 ± 19.7	.006 ^b
Hamstring peak torque at 180 deg/s	52.2 ± 18.9	57.4 ± 17.8	.002 ^b
Passive muscle stiffness, kPa			
VM shear modulus	3.2 ± 0.5	3.4 ± 0.4	.007 ^b
RF shear modulus	3.8 ± 0.7	3.3 ± 0.6	.661
VL shear modulus	3.3 ± 0.5	3.2 ± 0.4	.124
SM shear modulus	4.7 ± 0.9	5.4 ± 1.9	.027 ^c
ST shear modulus	3.7 ± 1.1	5.7 ± 1.6	<.001 ^b
BF shear modulus	3.9 ± 1.1	4.0 ± 0.8	.456
Muscle activity			
EMG onset, ms			
VM	−144.9 ± 75.8	−190.4 ± 79.7	.030 ^c
VL	−172.1 ± 88.5	−181.3 ± 66.3	.722
SM	−175.0 (−192.4 to −78.0)	−161.1 (−187.8 to −97.1)	.447
BF	−160.6 ± 73.1	−183.4 ± 63.5	.198
Preparatory EMG amplitude, %MVC			
VM	25.2 (15.0 to 40.9)	27.6 (18.6 to 32.5)	.145
VL	20.3 (13.7 to 33.7)	22.8 (14.0 to 41.1)	.128
SM	12.2 (5.1 to 26.0)	8.9 (6.3 to 16.5)	.798
BF	7.4 (4.7 to 14.9)	6.9 (4.9 to 11.5)	.620
Reactive EMG amplitude, %MVC			
VM	27.4 (21.9 to 52.6)	25.0 (20.3 to 47.6)	.689
VL	26.2 (13.6 to 36.0)	21.1 (14.0 to 40.0)	.144
SM	13.0 (5.1 to 23.2)	9.9 (6.3 to 29.6)	.925
BF	6.4 (4.5 to 10.4)	5.2 (3.4 to 10.0)	.238

^aValues are expressed as mean ± SD for normally distributed variables and median (interquartile range) for nonnormally distributed variables. BF, biceps femoris; BM, body mass; EMG, electromyographic; IC, initial contact; MVC, maximal voluntary contraction; RF, rectus femoris; SM, semimembranosus; ST, semitendinosus; vGRF, vertical ground-reaction force; VL, vastus lateralis; VM, vastus medialis.

^bSignificant difference between involved and uninvolved limbs ($P < .01$).

^cSignificant difference between involved and uninvolved limbs ($P < .05$).

when compared with the uninvolved limb in this study. The previous studies defined the muscle onset as the first muscle burst in EMG activity before landing, whereas we defined the onset as the rising of linear envelopes representing muscle burst, which may have led to the different results. Different rehabilitation protocols may also affect the muscle activation pattern during landing. The earlier

VM onset reported in a previous study¹⁶ was suggested to be a compensatory adaptation to stabilize the knee, which allows the muscles to have enough time to generate force, providing less impact force on the knee during landing.

Quadriceps strength, passive hamstring stiffness, and hamstring activation during landing were found to be associated with single-leg hop distance after adjustment for

TABLE 3

Summary of Stepwise Multiple Linear Regression Analysis for Muscle Properties That Predict Hop Performance and Peak Knee Flexion, Valgus Moment, and Extension^a

Predictor Variable	Standardized β	β (95% CI)	<i>t</i>	<i>P</i>
Predictors of Single-Leg Hop Performance ($R^2 = 0.565$; $P < .001$)				
Quadriceps peak torque at 180 deg/s	0.485	0.487 (0.297-0.677)	5.160	<.001
ST shear modulus	0.317	1.545 (0.626-2.464)	3.377	.001
Reactive SM EMG amplitude	0.211	16.710 (2.046-31.374)	2.290	.026
Time since surgery	0.312	3.024 (1.230-4.818)	3.388	.001
Predictors of Peak Knee Flexion During Landing ($R^2 = 0.319$; $P < .001$)				
Quadriceps peak torque at 60 deg/s	0.348	0.134 (0.042-0.226)	2.923	.005
VM shear modulus	0.385	3.803 (1.439-6.167)	3.231	.002
Predictor of Peak Knee Valgus Moment During Landing ($R^2 = 0.128$; $P = .005$)				
Reactive SM EMG amplitude	0.380	336.015 (108.287-563.744)	2.961	.005
Predictor of Peak Knee Extension Moment ($R^2 = 0.112$; $P = .010$)				
Preparatory VM EMG amplitude	0.361	187.186 (46.979-327.393)	2.684	.010

^aEMG, electromyographic; SM, semimembranosus; ST, semitendinosus; VM, vastus medialis.

confounding factors. It seems that dynamic knee stability is influenced by passive muscle stiffness and muscle activation in addition to muscle strength. Previous researchers have found positive correlations between hop performance and knee muscle strength.¹³ Because muscle force generation capacity is determined by the muscle's mechanical function and neuromuscular efficiency,² changes in knee muscle stiffness and muscle activation pattern may affect hop performance. In this study, we included patients within 6 to 18 months after ACLR because this is the time when most patients are likely to complete their rehabilitation program and return-to-sports activities. However, we found a shorter time since ACLR to be associated with poor hop performance, indicating that muscle recovery may be time-related or affected by the progress of rehabilitation.

We found quadriceps strength and passive stiffness of VM to be associated with peak knee flexion angle during single-leg landing. It has been reported that quadriceps strength deficits are often associated with a more extended knee during jump landing after ACLR.⁴² As well, the ability of the muscle to achieve sufficient force in a limited time is important because most ACL injuries occur within 40 milliseconds after IC.³² Passive muscle stiffness was found to contribute to rapid force production,³ and decreased muscle stiffness could result in a decreased muscle reaction time,³⁸ thus affecting joint stability. This probably explains why patients with decreased quadriceps stiffness in the ACLR limb tend to land with smaller peak knee flexion angles, suggesting a reduced ability to attenuate energy through the lower limb joints. VM weakness is frequently found in patients with ACLR, as the VM achieves maximum contraction during full extension, which is more difficult to be strengthened, especially at an early stage after surgery.⁸ Despite a lack of significant differences between limbs for

EMG activity amplitude, several significant relationships were identified between EMG activity amplitude and knee biomechanics. It seems that patients with greater knee valgus moment and knee extension moment tend to have increased muscle activity of the medial quadriceps and hamstring muscles. Theoretically, increased hamstring activity can limit frontal-plane knee loading, and high preparatory muscle activity helps to stabilize the knee by increasing the sensitivity of the muscle spindle, which reduces the time to produce sufficient muscle tension so as to prevent joint injury.⁹ It has been found that patients who have undergone ACLR tend to use increased quadriceps and hamstring coactivation by increasing the hamstring activity during landing when compared with healthy people.³ It may be that patients with weaker SM and VM have adopted a compensatory strategy by increasing their muscle activity to "tense up" in an attempt to increase knee stability.

To the best of our knowledge, this is the first study investigating the combined effects of muscle strength, muscle activation, and passive muscle stiffness as possible underlying mechanisms of dynamic knee stability after ACLR. However, there were several limitations in this study. First, this cohort was evaluated at only a single time point after ACLR, limiting applicability of the finding. Further studies with longitudinal evaluations can provide a more precise picture and perhaps affect rehabilitation strategies. Second, muscle stiffness was measured in a passive way. The utility of shear wave elastography in patients with ACL injury remains limited due to the limited capabilities of this technology and data quality during active muscle contraction.⁴⁰ Improved methodological capabilities and data quality for active muscle stiffness will allow for a better understanding of a muscle's mechanical performance,

particularly during athletic movements such as jump landing. Third, we focused only on the muscles of the quadriceps and hamstrings because they are the key dynamic stabilizers around the knee joint. However, a previous study⁵⁷ found that the other lower limb muscles, such as gluteus maximus and gluteus medius, were associated with knee biomechanics during landing, which should be considered in future studies. Fourth, we included only male patients to reduce the effect of sex. The results might not be applicable to female patients given that hormonal fluctuations in women can affect muscle stiffness and joint laxity.¹² Fifth, because all of the patients underwent reconstruction using hamstring tendon graft, the results might not be applicable to other graft types. The effect of different graft types on changes in muscle elasticity and muscle coordination warrants further investigation. Sixth, the dynamic evaluation of knee stability is multifactorial, and the variations in the lesion itself, limb axis, type of sport, and rehabilitation protocol were difficult to control. It is also unknown whether changes in rehabilitation can affect muscle activation and stiffness (independent of strength) and thus affect performance on the hop test. Therefore, further studies are needed to confirm our findings.

CONCLUSION

In addition to muscle strength deficits, deficits in passive muscle stiffness and muscle activation of the quadriceps and hamstrings contributed to poor single-leg hop performance and dynamic knee stability during landing. Given that muscle activation can be enhanced via neuromuscular training³⁶ and muscle stiffness can be modified via stretching exercises, cryotherapy, or exercise-induced muscle damage,^{15,33,49} this study helps to identify areas where clinicians can potentially intervene to promote more optimal rehabilitation programs. Specific interventions targeting these neuromuscular and mechanical properties of the quadriceps and hamstrings constitute an important area for future research, as they may be beneficial for rehabilitation after ACL injury and the prevention of ACL reinjury after ACLR.

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