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Original article

EFFECTS OF ADDITIONAL TRAINING WITH SINGLE LEG HAMSTRING BRIDGE ON THIGH MUSCLES STRENGTH, AND KNEE JOINT KINEMATICS DURING RUNNING IN ATHLETES AFTER ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION

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ABSTRACT

Anterior cruciate ligament reconstruction (ACLR) is essential for athletes recovering from ACL injuries, yet many face challenges in regaining pre-injury performance due to persistent muscle imbalances and altered knee biomechanics. **Objective**: To examine the effects of incorporating Single-Leg Hamstring Bridge (SLHB) exercises into standard ACLR rehabilitation protocols, focusing on hamstring strength and knee joint kinematics during running. **Methodology**: Eight male athletes (mean age 23.4 ± 3.1 years) who had undergone ACLR with hamstring tendon autografts were randomly assigned to a control group (standard rehabilitation only) or an intervention group (standard rehabilitation + SLHB) for six weeks. Hamstring strength was measured via isokinetic peak torque at 60°/sec, and knee kinematics, such as knee angle at foot strike, were recorded during treadmill running at 3.35 m/s. **Results**: The IG shows significant improvement in knee flexion peak torque of the uninvolved leg ($p = 0.016$) post-intervention, and knee angle at the foot strike of the uninvolved leg ($p = 0.037$) compared to the CG.

Conclusion: Adding SLHB to standard ACLR rehabilitation significantly enhanced hamstring strength in the uninvolved limb and improved knee positioning at foot strike, suggesting better dynamic knee stability and lower-limb function. However, because strength gains were confined to the uninvolved leg, conclusions about benefits for the operated limb remain tentative. SLHB may improve gait mechanics during ACLR rehabilitation; however, further studies with larger samples and longer follow-up are needed to confirm its effects on the surgical limb and long-term return-to-sport outcomes.

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KEYWORDS: ACL reconstruction/ Thigh muscle/ Training/ Knee kinematics

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นิพนธ์ต้นฉบับ

ผลของการฝึกเสริมด้วยซิงเกิ้ลเลคแฮมสตริงบริดจ์ ที่มีต่อความแข็งแรงของกล้ามเนื้อต้นขาและการเคลื่อนไหวของข้อเข่าขณะวิ่งในนักกีฬาหลังได้รับการผ่าตัดรักษาเอ็นไขว้หน้า

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บทคัดย่อ

การผ่าตัดฟื้นฟูเอ็นไขว้หน้า (Anterior Cruciate Ligament Reconstruction: ACLR) เป็นหนึ่งในวิธีการรักษาสำคัญสำหรับนักกีฬาที่ได้รับบาดเจ็บเอ็นไขว้หน้า อย่างไรก็ดี ผู้ป่วยจำนวนมากยังคงเผชิญความท้าทายในการฟื้นฟูสมรรถภาพสู่ระดับก่อนบาดเจ็บเนื่องจากความไม่สมดุลของกล้ามเนื้อที่คงอยู่และการเปลี่ยนแปลงทางชีวกลศาสตร์ของข้อเข่า **วัตถุประสงค์**: ศึกษาผลของการเพิ่มการฝึกซิงเกิ้ลเลคแฮมตริงบริดจ์ (Single-Leg Hamstring Bridge: SLHB) เข้าในโปรแกรมฟื้นฟูสมรรถภาพมาตรฐานหลังการทำการผ่าตัดฟื้นฟูเอ็นไขว้หน้า โดยมุ่งเน้นที่ความแข็งแรงของกล้ามเนื้อแฮมสตริงและชีวกลศาสตร์ของข้อเข่าในระหว่างการวิ่ง **วิธีการวิจัย**: นักกีฬาชาย 8 คน (อายุเฉลี่ย 23.4 ± 3.1 ปี) ที่ได้รับการผ่าตัดฟื้นฟูเอ็นไขว้หน้าโดยใช้เนื้อเยื่อเอ็นกล้ามเนื้อแฮมสตริงของตนเอง เข้าร่วมการทดลองระยะเวลา 6 สัปดาห์ โดยแบ่งผู้เข้าร่วมเป็นกลุ่มควบคุมที่ทำโปรแกรมฟื้นฟูมาตรฐาน และกลุ่มทดลองที่เพิ่มท่าการฝึกซิงเกิ้ลเลคแฮมสตริงบริดจ์พร้อมเพิ่มความต้านทานแบบก้าวหน้า **ผลการศึกษา**: กลุ่มทดลองมีการพัฒนาอย่างมีนัยสำคัญของค่าแรงบิดสูงสุดในการงอเข่าของขาข้างที่ไม่ได้รับบาดเจ็บ ($p = 0.016$) หลังการทดลอง และมุมข้อเข่าในจังหวะเท้าสัมผัสพื้นของขาที่ไม่ได้รับบาดเจ็บ ($p = 0.037$) เมื่อเทียบกับกลุ่มควบคุม

สรุปผลการวิจัย: การเพิ่มท่าออกกำลังกาย SLHB ในโปรแกรมฟื้นฟูหลัง ACLR มาตรฐาน ช่วยเพิ่มความแข็งแรงของกล้ามเนื้อแฮมสตริงในขาไม่ผ่าตัดและปรับปรุงมุมข้อเข่าในขณะเท้าสัมผัสพื้น แสดงให้เห็นถึงความมั่นคงของเข่าขณะเคลื่อนไหวและการทำงานรยางค์ล่างที่ดีขึ้น อย่างไรก็ตาม การเพิ่มขึ้นของความแข็งแรงพบเฉพาะในขาไม่ผ่าตัด จึงยังไม่สามารถสรุปประโยชน์ต่อขาที่ผ่าตัดได้อย่างชัดเจน SLHB อาจช่วยปรับปรุงกลไกการเดินขณะฟื้นฟูหลัง ACLR แต่จำเป็นต้องมีการศึกษาเพิ่มเติมที่มีขนาดกลุ่มตัวอย่างใหญ่ขึ้นและติดตามผลในระยะยาวเพื่อยืนยันประสิทธิผลต่อการฟื้นฟูขาข้างที่ผ่าตัดและการกลับไปเล่นกีฬาในระยะยาวต่อไป

(วารสารวิทยาศาสตร์และเทคโนโลยีการกีฬา 2567; 25(1):36-53)

Introduction

Anterior cruciate ligament (ACL) injuries are common, especially among athletes involved in multidirectional sports as well as sudden changes in direction, pivoting, and landing from jumps such as football, rugby, and basketball (1). In the United States, the number of ACL injuries is estimated to range from 80,000 to 250,000 cases per year (2). Over 70% of these injuries occur without direct contact to the knee or leg during sports activities (3). The ACL, located within the knee joint, connects the femur and tibia bones, playing a crucial role in preventing excessive forward movement of the tibia during sports. Consequently, rapid or abrupt movements such as sudden stops, high-speed running, and direction changes during intense training or competition can result in ACL tears (4, 5).

Following ACL reconstruction (ACLR), athletes often face significant rehabilitation challenges, including muscle weakness and altered biomechanics. Specifically, quadriceps and hamstring muscle imbalances are common, with hamstring weakness being a significant risk factor for re-injury (6). Hamstring strength deficits can range from 9% to 27% in the injured limb, with some studies (7) indicating that these deficits may persist for years post-surgery (8). The implications of such weakness extend beyond mere muscle function; they can compromise knee stability and increase the risk of ACL re-injury, particularly in activities requiring deep knee bending and rapid changes of direction (9). Moreover, despite advancements in rehabilitation protocols, many athletes struggle to regain their pre-injury performance levels, with less than 50% returning to their previous level of competition after ACLR (10). The high incidence of re-injury, estimated at over 30% in some cases (11). A key factor contributing to this risk is muscle weakness, particularly in the hamstrings, which play a crucial role in absorbing force and preventing excessive forward movement of the tibia. In Vitro studies on ACL tears, it has been found that activation of the hamstring muscles reduces tibial movement and impact on the tibiofemoral joints upon landing during running and jumping (12). Additionally, hamstring activation increases knee stability and decreases shear force, which is a key factor in ACL tears (13). Targeted rehabilitation strategies that focus on strengthening the hamstrings are crucial for restoring muscle balance, enhancing neuromuscular control, and improving knee kinematics, ultimately reducing the risk of ACL re-injury (14). Traditional exercises like the Nordic hamstring curl effectively strengthen hamstrings at higher knee flexion angles (90°–70°), but ACLR athletes often struggle to perform them properly due to significant hamstring weakness (15). Moreover, hamstring activation during running peaks near 30° knee flexion (16), a range not targeted by Nordic curls. The Single-Leg Hamstring Bridge (SLHB), in contrast, involves closed kinetic chain, weight-bearing movements that engage the hamstrings at these lower, more functionally relevant angles while combining hip extension with knee stabilization (17, 18). Therefore, SLHB may offer a more practical and effective option for restoring running-specific knee stability in ACLR rehabilitation. The SLHB begins in a supine position with one heel on a 60-centimeter box and the knee bent at 30 degrees, involving pressing the heel down to lift the body and hips to full extension. The SLHB is widely recognized for its ability to replicate running mechanics, particularly the late swing phase, where the hamstrings pull the swinging leg forward for ground contact by generating concentric hip extension and isometric knee stabilization (17-19), and it improves peak torque and muscle activation, essential for dynamic knee stability, while correcting altered knee kinematics (20, 21). Despite the importance of hamstring strengthening in ACL rehabilitation, there is a notable lack of research examining the specific impact of hamstring exercises on running biomechanics after ACLR. Studies have shown that impaired hamstring function post-ACLR is associated with persistent biomechanical deficits during running, including altered knee joint loading and reduced shock absorption capabilities (20, 22). These deficits underscore the biomechanical justification for targeting hamstring strength to restore normal gait mechanics and reduce re-injury risk. Especially as running is a critical activity for athletes returning to sports, as it involves repetitive landing and deceleration maneuvers that can stress the knee joint. In addition to muscular strength, specific knee joint kinematic variables were analyzed to assess functional adaptations during running. These included knee joint angle at foot strike, which reflects limb positioning and impact preparedness at initial ground contact and is associated with lower limb loading mechanics (23). Maximum knee flexion during stride was also assessed, as it represents swing-phase range of motion and is influenced by hamstring flexibility and control (16). Moreover, maximum knee flexion and extension angles during the stance phase provide insight into dynamic stability, shock absorption capacity, and neuromuscular control under load (20, 21). Alterations in these metrics may reveal compensatory strategies or functional improvements that impact re-injury risk and overall movement efficiency in athletes post-ACLR (13).

A literature review reveals a lack of research utilizing the Single Leg Hamstring Bridge exercise to enhance hamstring strength, and knee joint kinematics during running, particularly in individuals undergoing surgery for ACL tears. In this pilot study of eight male athletes, we aim to determine whether adding the Single-Leg Hamstring Bridge (SLHB) exercise to a standard six-week ACLR rehabilitation protocol improves hamstring strength and knee joint kinematics during running. We hypothesized that training with additional SLHB exercise can enhance hamstring strength and knee joint movement patterns by reducing excessive anterior tibial translation during running in athletes following ACLR. The hamstrings act as dynamic stabilizers of the knee by opposing anterior shear forces, particularly during the late swing and stance phases of gait. By strengthening the hamstrings, SLHB exercises may enhance their capacity to limit anterior tibial movement relative to the femur, thereby improving joint stability. This biomechanical effect may reduce the risk of re-injury. Our study explored this relationship by examining changes in knee flexion angles and peak hamstring torque, key indicators of the hamstrings' ability to modulate anterior tibial translation during functional movement.

Method

Participants

A total of 8 male athletes (Age: 23.4 ± 3.07 years, Weight: 75.0 ± 11.1 kg, Height: 176 ± 3.93 cm, BMI 23.9 ± 5.06 kg/m²) in sports that primarily involved running, including football and basketball players, who had undergone ACLR using hamstring tendon autograft, were recruited. The sample size was based on a similar pilot study design used in middle-phase rehabilitation research, where 4 to 8 participants per group were deemed sufficient to detect large effect sizes in biomechanical or strength-related outcomes (Harput et al., 2015; Freckleton et al., 2014). Due to strict inclusion criteria and the logistical limitations of conducting instrumented biomechanical analyses, a smaller sample was chosen to maintain methodological control. While underpowered for detecting small effects, this sample size was considered adequate for preliminary evaluation of the intervention's feasibility and effect trends. The inclusion criteria were: (1) age between 18 and 30 years; (2) a pain level, measured using the Visual Analogue Scale (VAS), ranging from no pain to low-level pain (0-3); (3) having undergone ACLR using hamstring tendon autograft between 6 to 24 months prior; and (4) a knee showing no swelling and the ability to bear weight. The exclusion criteria were: (1) an unforeseen event, such as illness, injury from the research, or other reasons hindering continued participation; (2) unwillingness to continue participating; and (3) research participants attending less than 80% of the training sessions, missing more than 2 out of a total of 12 sessions. Participants were randomly allocated by the order in which they joined the research to either a control group (CG, n=4) or an intervention group (IG, n=4) while the assessors were blind.

Table 1 shows the mean and standard deviation (SD) of subject characteristics

Variable	Control Groups	Intervention Groups	p-Value
Age	24.25 ± 4.42	22.50 ± 0.57	0.463
Height	175.00 ± 1.82	177.75 ± 5.25	0.361
Weight	77.32 ± 11.66	72.75 ± 11.64	0.5
BMI	24.55 ± 5.54	23.22 ± 5.26	0.741
Injured side (right/left)	0/4	4/0	
Time from surgery, mouth	10.50 ± 3.87	9.50 ± 3.31	0.708

Research procedures

All participants attended 2 testing sessions 6 weeks (i.e., PRE and POST-test). At each testing session, participants performed a 5-minute warm-up using a stationary bike at a cadence of 70 - 80 revolutions per minute (RPM) and a constant work rate of 100 watts (W). Before the formal testing commenced, participants were presented with a detailed outline of the testing procedures and voluntarily agreed to participate in the research and signing of the consent form. After that, they were allowed to familiarize themselves with the testing apparatus. The testing procedures consisted of (1) measurement of thigh muscle circumference by using a measurement tape, measure 15 centimeters above the superior pole of the patella, and use this position to measure the circumference of the thigh in centimeters while lying in prone position, (2) use of an isokinetic dynamometer (Biodex System 4 Pro^{TM} Medical Systems Inc, Shirley, NY) at 60 degrees/sec to test the peak torque, and (3) conducting a running analysis using a treadmill with 10 optical electronic cameras (BTS, Bioengineering, Italy) set a frequency of 200 Hz, and 44 retro-reflective markers (16 mm diameter) were attached to the participant's body following the lower limb and trunk model as shown in Figure 1 (24, 25).

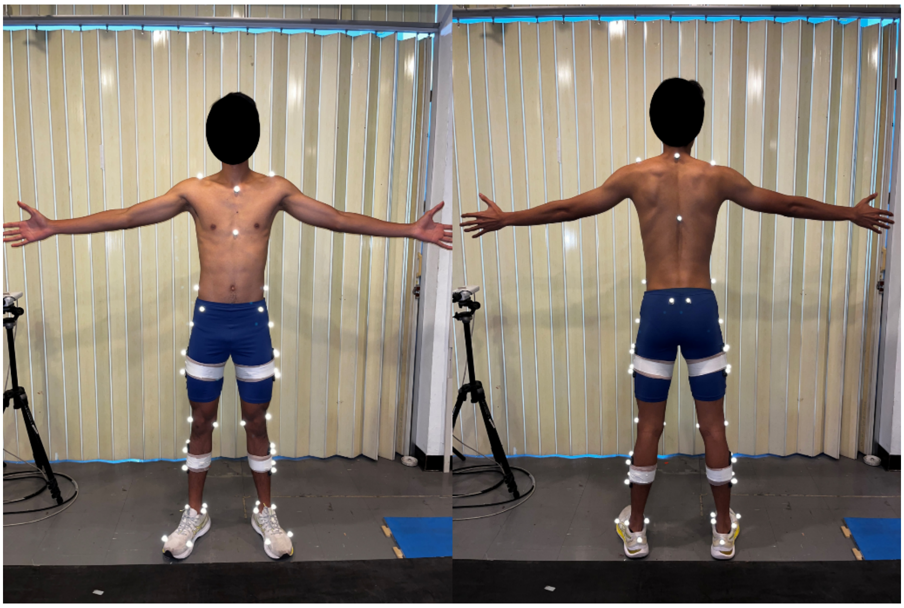

Figure 1 Marker placement

The testing speed on the treadmill was set at 3.35 meters/second (12 kilometers/hour) (20). Data was collected over a total of 15 steps after the participants were able to run at the specified speed for 30 seconds. After the PRE-test, subjects were trained using the ACLR training protocol, 2 sessions per week for 6 weeks, following the Bousquet protocol (26). The protocol included: (1) a warm-up using a stationary bike for 5 minutes (min); (2) 30 seconds (sec) of single-leg squat for 3 sets; (3) 8 repetitions (reps) of front squat at 60% 1RM for 3 sets; (4) 8 reps of reverse lunges for 3 sets; (5) 8 reps of Nordic hamstring curl for 3 sets; (6) 30 seconds of single-leg skater 3-way balance for 3 sets; and (7) 30 seconds of shuttle squat jump for 3 sets. For the IG, participants performed additional exercises of 3 reps for 10 seconds, holding each rep of the single-leg hamstring bridge for 3 sets with 2 minutes resting between sets. In the single-leg hamstring bridge training, the resistance was progressively increased every 2 weeks. In weeks 1-2, the load was at body weight; in weeks 2-4, the load was body weight plus 10 kilograms; and in weeks 4-6, the load was body weight plus 20 kilograms (15).

Data Processing

The 3D kinematic data were digitized using the Smart Tracker and Smart Analyzer software, and the 3D movement analysis was conducted using Visual3D software (Visual3D, Has-Motion, Kingston, Ontario, Canada). All marker trajectories were filtered at 6 Hz by a Butterworth low-pass filter from the location of the three-dimensional coordinates of the markers placed on the body. The knee joint angle was computed using inverse kinematic algorithms in the Visual 3D program. Spatiotemporal and knee kinematics variables were calculated consisting of (1) step length, (2) stride length, (3) stance time, (4) flight time, (5) knee joint angle at foot strike, (6) maximum knee flexion during stride, (7) maximum Knee flexion/extension during stance phase, and (8) maximum knee flexion/extension angle during stance phase. All Kinematics variables have been exported to ASCII for statistical analysis.

1. Warm up on the elliptical for 5 min

2. Single-Leg Squat for 30 seconds, 3 sets.

3. Front Squat – 8 reps for 3 sets.

4. Reverse Lunges – 8 reps per leg for 3 sets.

5. Nordic Hamstring Curl – 8 reps for 3 sets.

6. Single-Leg Skater (3-way) – 30 seconds for 3 sets.

7. Shuttle Squat Jump – 30 seconds for 3 sets.

8. Additional Single-Leg Hamstring Bridge – 3 reps with a 10-second hold each, for 3 sets.

Figure 2. ACLR Training Protocol: (1-7) Standard Rehabilitation and (8) Additional Intervention Exercise

Statistical Analysis

All statistical analyses were performed using Jamovi software (version 2.3.28). Descriptive statistics for all outcome variables are reported as mean ± standard deviation (SD). Prior to inferential testing, the Shapiro–Wilk test was conducted to assess the normality of data distributions. All variables met the assumption of normality ($p > 0.05$), supporting the use of parametric tests. To determine within-group changes (pre- vs. post-test) in each group (control and intervention), paired samples t-tests were applied. These analyses evaluated changes in thigh circumference, knee flexion/extension peak torque, and kinematic parameters over the 6-week intervention period. To assess between-group differences at both the pre-test and post-test phases, independent samples t-tests were conducted, comparing the control group (CG) and the intervention group (IG) across all primary outcomes. Statistical significance was defined as $p < 0.05$. In addition to p-values, Cohen's d was calculated to quantify effect sizes, interpreted as small (d = 0.2), medium (d = 0.5), and large (d ≥ 0.8).

Results

All eight participants completed the study, four athletes assigned to the control group (CG) and four to the intervention group (IG). The results are reported in terms of changes within each group before and after the six-week intervention, as well as comparisons between groups at both pre-test and post-test phases.

Table 2: Within-group comparisons of thigh circumference, knee muscle strength, and knee joint kinematics before and after the intervention in the control and intervention groups. Data are presented as mean ± standard deviation.

Variable	Group	Pre-test	Post-test	p-value	Cohen's d
Circumference (cm)					
Involved	Control	49.82 ± 4.97	51.32 ± 6.44	0.173	-0.891
	Intervention	47.82 ± 7.37	50.95 ± 8.07	0.116	-1.094
Uninvolved	Control	53.07 ± 5.73	53.5 ± 6.67	0.441	-0.442
	Intervention	49.37 ± 6.37	52.8 ± 7.44	0.107	-1.138
Knee Flexion Peak Torque (Nm)					
Involved	Control	107.9 ± 23.42	102.45 ± 27.94	0.268	0.678
	Intervention	91.35 ± 10.85	101.52 ± 10.20	0.159	-0.932
Uninvolved	Control	122.37 ± 34.41	114.45 ± 32.75	0.224	0.763
	Intervention	106.27 ± 4.87	119.85 ± 6.33	0.016	-2.446
Knee Extension Peak Torque (Nm)					
Involved	Control	174.27 ± 48.27	197.92 ± 48.16	0.027	-2.027
	Intervention	162.27 ± 44.27	187.75 ± 35.46	0.264	-0.685
Uninvolved	Control	240.25 ± 65.53	231.22 ± 56.65	0.182	0.866
	Intervention	234.92 ± 49.42	252.5 ± 50.33	0.097	-1.194
Step Length (m)					
Involved	Control	0.57 ± 0.02	0.59 ± 0.01	0.199	-1.091
	Intervention	0.56 ± 0.03	0.56 ± 0.03	1.000	0.000
Uninvolved	Control	0.57 ± 0.02	0.59 ± 0.02	0.213	-0.789
	Intervention	0.58 ± 0.05	0.58 ± 0.04	1.000	0.000
Stride Length (m)					
	Control	1.14 ± 0.04	1.16 ± 0.07	0.408	-0.480
	Intervention	1.14 ± 0.09	1.14 ± 0.07	0.920	-0.550
Stance time (sec)					
Involved	Control	0.22 ± 0.01	0.22 ± 0.01	0.761	0.167
	Intervention	0.22 ± 0.01	0.23 ± 0.01	0.638	0.261
Uninvolved	Control	0.21 ± 0.01	0.21 ± 0.01	0.495	-0.387

	Intervention	0.22 ± 0.03	0.23 ± 0.01	0.824	-0.121
Flight time (sec)					
Involved	Control	0.48 ± 0.02	0.52 ± 0.06	0.397	-0.493
	Intervention	0.51 ± 0.03	0.50 ± 0.02	0.444	0.439
Uninvolved	Control	0.49 ± 0.03	0.50 ± 0.02	0.658	-0.245
	Intervention	0.50 ±0.03	0.49 ± 0.02	0.239	0.732
Knee angle at foot strike (deg)					
Involved	Control	18.13 ± 3.50	16.7 ± 3.29	0.492	0.390
	Intervention	18.51 ± 1.99	18.58 ± 1.17	0.958	-0.028
Uninvolved	Control	17.12 ± 3.1	16.64 ± 1.73	0.690	0.219
	Intervention	18.27 ± 4.48	19.45 ± 1.18	0.639	-0.260
Maximum knee flexion during stride (deg)					
Involved	Control	88.25 ± 5.69	88.05 ± 8.07	0.934	0.045
	Intervention	91.53 ± 3.39	90.55 ± 6.00	0.793	0.143
Uninvolved	Control	88.67 ± 3.85	86.46 ± 6.46	0.716	-0.200
	Intervention	91.18 ± 8.43	91.47 ± 10.02	0.936	-0.044
Maximum Knee Flexion/Extension during stance (deg)					
Involved	Control	40.7 ± 3.96	38.11 ± 5.37	0.047	1.637
	Intervention	39.23 ± 3.01	38.95 ± 0.99	0.861	0.095
Uninvolved	Control	41.38 ± 3.35	41.17 ± 2.26	0.877	0.084
	Intervention	43.13 ± 5.64	42.52 ± 2.05	0.819	0.125
Minimum Knee Flexion/Extension during stance (deg)					
Involved	Control	17.02 ± 4.05	17.56 ± 5.41	0.851	-0.103
	Intervention	16.76 ± 1.83	16.2 ± 4.94	0.780	0.153
Uninvolved	Control	17.31 ± 3.51	14.63 ± 2.69	0.010	2.879
	Intervention	17.49 ± 7.03	17.46 ± 9.05	0.987	0.009

For thigh circumference, both the CG and IG exhibited increases in both the involved and uninvolved limbs following the intervention, though none of these changes reached statistical significance. In the IG, the circumference of the involved limb increased from 47.82 ± 7.37 cm to 50.95 ± 8.07 cm ($p = 0.116$, $d = -1.094$), while the uninvolved limb increased from 49.37 ± 6.37 cm to 52.80 ± 7.44 cm ($p = 0.107$, $d = -1.138$). In the CG, the involved limb increased from 49.82 ± 4.97 cm to 51.32 ± 6.44 cm ($p = 0.173$, $d = -0.891$), and the uninvolved limb from 53.07 ± 5.73 cm to 53.50 ± 6.67 cm ($p = 0.441$, $d = -0.442$).

Regarding knee muscle strength, a statistically significant increase was observed only in the IG for knee flexion peak torque of the uninvolved leg, which improved from 106.27 ± 4.87 Nm to 119.85 ± 6.33 Nm ($p = 0.016$, $d = -2.446$). No other within-group strength changes have reached significance. In the CG, knee extension peak torque of the involved leg significantly increased from 174.27 ± 48.27 Nm to 197.92 ± 48.16 Nm ($p = 0.027$, $d = -2.027$), while other changes remained non-significant ($p > 0.05$).

For kinematic variables during treadmill running, the CG showed a significant decrease in maximum knee flexion/extension angle during stance phase of the involved leg, from 40.70 ± 3.96° to 38.11 ± 5.37° ($p = 0.047$, $d = 1.637$), and in minimum knee flexion/extension angle of the uninvolved leg, from 17.31 ± 3.51° to 14.63 ± 2.69° ($p = 0.010$, $d = 2.879$). No other within-group kinematic changes have reached statistical significance. Parameters such as step length, stride length, stance time, flight time, and knee angle at foot strike remained stable ($p > 0.05$) in both groups.

Table 3: Between-group comparisons of thigh circumference, knee muscle strength, and knee joint kinematics at pre-test and post-test between the control and intervention groups. Data are presented as mean ± standard deviation.

Variable	Pre-test				Post-test			
	Control	Intervention	p-value	Cohen's d	Control	Intervention	p-value	Cohen's d
Circumference (cm)								
- Involved	49.82 ± 4.97	47.82 ± 7.37	0.669	0.318	51.325 ± 6.44	50.95 ± 8.07	0.944	0.051
- Uninvolved	53.07 ± 5.73	49.37 ± 6.37	0.421	0.611	53.50 ± 6.67	52.80 ± 7.44	0.893	0.099
Knee Flexion Peak Torque (Nm)								
- Involved	107.90 ± 23.42	91.35 ± 10.85	0.247	0.907	102.45 ± 27.94	101.52 ± 10.20	0.952	0.044
- Uninvolved	122.37 ± 34.41	106.27 ± 4.87	0.390	0.655	114.45 ± 32.75	119.85 ± 6.33	0.757	-0.229
Knee Extension Peak Torque (Nm)								
- Involved	174.27 ± 48.27	162.27 ± 44.27	0.727	0.259	197.92 ± 48.16	187.75 ± 35.46	0.745	0.240
- Uninvolved	240.25 ± 65.53	234.92 ± 49.42	0.905	0.088	231.22 ± 56.65	252.5 ± 50.33	0.595	-0.396
Step Length (m)								
- Involved	0.57 ± 0.02	0.56 ± 0.03	0.802	0.186	0.59 ± 0.01	0.56 ± 0.03	0.121	1.425
- Uninvolved	0.57 ± 0.02	0.58 ± 0.05	0.812	-0.176	0.59 ± 0.02	0.58 ± 0.04	0.701	0.285
Stride Length (m)								
	1.14 ± 0.04	1.14 ± 0.09	1.000	0.000	1.16 ± 0.07	1.14 ± 0.07	0.734	0.251
Stance time (sec)								
- Involved	0.22 ± 0.01	0.21 ± 0.01	0.458	0.560	0.22 ± 0.01	0.21 ± 0.01	0.494	0.514
- Uninvolved	0.22 ± 0.01	0.22 ± 0.03	0.862	-0.128	0.23 ± 0.01	0.23 ± 0.01	1.000	0.000
Flight time (sec)								
- Involved	0.48 ± 0.02	0.51 ± 0.03	0.157	-1.143	0.52 ± 0.06	0.50 ± 0.02	0.533	0.468
- Uninvolved	0.49 ± 0.03	0.50 ±0.03	0.832	-0.157	0.50 ± 0.02	0.49 ± 0.02	0.337	0.738

Knee angle at foot strike (deg)								
- Involved	18.13 ± 3.50	18.51 ± 1.99	0.854	-0.135	16.7 ± 3.29	18.58 ± 1.17	0.322	-0.763
- Uninvolved	17.12 ± 3.10	18.27 ± 4.48	0.687	-0.299	16.64 ± 1.73	19.45 ± 1.18	0.037	-1.895
Maximum knee flexion during stride (deg)								
- Involved	88.25 ± 5.69	91.53 ± 3.39	0.359	-0.702	88.05 ± 8.07	90.55 ± 6.00	0.637	-0.351
- Uninvolved	88.67 ± 3.85	91.18 ± 8.43	0.280	-0.840	86.46 ± 6.46	91.47 ± 10.02	0.433	-0.594
Maximum Knee Flexion/Extension during stance (deg)								
- Involved	40.70 ± 3.96	39.23 ± 3.01	0.576	0.418	38.11 ± 5.37	38.95 ± 0.99	0.771	-0.216
- Uninvolved	41.38 ± 3.35	43.13 ± 5.64	0.612	-0.378	41.17 ± 2.26	42.52 ± 2.05	0.409	-0.627
Minimum Knee Flexion/Extension during stance (deg)								
- Involved	17.02 ± 4.05	16.76 ± 1.83	0.912	0.082	17.56 ± 5.41	16.20 ± 4.94	0.724	0.261
- Uninvolved	17.31 ± 3.51	17.49 ± 7.03	0.965	-0.032	14.63 ± 2.69	17.46 ± 9.05	0.571	-0.424

At the post-test phase, between-group comparison revealed a statistically significant difference in knee angle at foot strike of the uninvolved leg, with the IG exhibiting a greater angle (19.45 ± 1.18°) than the CG (16.64 ± 1.73°; p = 0.037, d = –1.895). No other between-group comparisons showed statistical significance. However, several variables showed large effect sizes despite non-significant p-values. For example, the step length of the involved leg in the post-test was higher in the CG (0.59 ± 0.01 m) compared to the IG (0.56 ± 0.03 m), with a large effect size (d = 1.425, p = 0.121). Additionally, the difference in maximum knee flexion/extension during stance in the uninvolved leg yielded a moderate effect size (d = –0.627, p = 0.409), though not statistically significant. The findings indicate selective improvements in knee muscle strength and kinematic function, particularly in the uninvolved limb of the intervention group, following the 6-week SLHB training program.

DISCUSSION

This study aimed to determine the adding Single Leg Hamstring Bridge (SLHB) exercises to a standard ACLR rehabilitation protocol would improve thigh muscle strength and knee joint kinematics during running. Our primary hypothesis, suggesting that SLHB exercises would enhance hamstring strength and improve knee joint movement patterns, was partially supported. While baseline subject characteristics (age, height, weight, BMI, and time after surgery) were similar between groups, the intervention yielded noteworthy biomechanical adaptations.

The result of the CG showed a significant increase in knee extensor peak torque of the involved leg (Fig 2.), a significant decrease in minimum and maximum knee flexion/extension during the stance phase of the involved leg (Fig 3.). These results show that the ACLR training protocol can enhance knee extensor strength and reduce Knee joint ROM during stance phase (27). Interestingly, despite CG and IG completing the same quadriceps strengthening protocol, only CG showed a significant improvement in knee extension peak torque. This discrepancy of the SLHB group may be explained by the activation of the hamstrings (agonists), which via spinal reflex circuits transiently inhibit the quadriceps (antagonists). This reciprocal inhibition (28) can alter inter-muscle coordination, reducing co-contraction around the knee and indirectly improving hamstring torque capacity. Alternatively, the control group may have directed greater neuromuscular resources toward quadriceps activation without the added posterior chain loading, resulting in more pronounced improvements. Moreover, the observation that the CG exhibited altered knee motion patterns during the stance phase, specifically a decrease in both minimum and maximum knee flexion/extension, suggests a stiffened gait pattern, commonly seen post-ACLR as a protective strategy to reduce graft strain (29, 30). This is consistent with previous research indicating that individuals with ACL injuries often develop altered movement patterns to minimize stress on the knee joint, which can reduce the risk of ACL loading and injury (31). However, while these compensatory mechanisms may initially be protective, they can also lead to altered loading patterns and an increased risk of secondary injuries due to muscle imbalances and inefficient movement strategies (32). Thus, these findings underscore the importance of targeted interventions to address these compensatory patterns and restore normal biomechanics (22). Conversely, adding SLHB exercise led to a significant increase in knee flexor peak torque of the uninvolved leg (Fig. 2) and greater knee flexion angle at foot strike (Fig. 3a). While the hamstrings are primarily responsible for controlling knee flexion during the swing phase, the quadriceps, especially the vasti muscles, are the main contributors to controlling knee flexion during the stance phase of running (33). During early stance, the quadriceps eccentrically contract to decelerate knee flexion and support weight-bearing. The observed increase in maximum knee flexion angle during stance may therefore reflect an indirect hamstring support for limb control and pre-activation patterns prior to foot strike, allowing for more efficient shock absorption and greater range of motion at the knee (34). This change in knee kinematics may thus represent a neuromuscular adaptation favoring smoother weight acceptance and potentially reducing aberrant loading patterns. Our findings align with existing evidence highlighting the critical role of SLHB exercises in optimizing knee biomechanics after ACL reconstruction (17, 18). The IG demonstrated a significant increase in knee flexion peak torque in the uninvolved leg following the 6-week intervention. This suggests that the addition of SLHB exercises improved the strength and power of the hamstrings in the uninvolved leg (35). This aligns with the well-established importance of hamstring strength for knee stability and function (32) and supports the incorporation of specific hamstring exercises into ACL rehabilitation programs (36). However, it is essential to acknowledge that the increase in peak torque was observed only in the uninvolved leg. This could be attributed to several factors, including a greater capacity for adaptation in the uninjured limb due to the absence of surgical trauma and associated pain or inhibition. Also, it is possible that a protective inhibition of muscle activation in the operated leg limits the extent of strength gains in that limb (37). This highlights the challenges of restoring muscle strength and function in the operated leg following ACLR and emphasizes the need for rehabilitation strategies that specifically address these limitations (38). These may be suggested that the involved leg may not have enough muscle strength for SLHB exercise, therefore the uninvolved leg assisted the action through motor control reinforcement across the leg (39), that causes the uninvolved leg to strengthen after training significantly. Moreover, these intervention subjects were ACLR for more than 6 months, therefore each subject may become habituated to using the uninvolved leg more than the involved leg. On the other hand, the contralateral improvements may reflect a systemic neuromuscular recalibration, where enhanced hamstring strength and activation patterns on the operated side facilitated improved motor control strategies bilaterally (40). This phenomenon supports the concept of cross-education effects in rehabilitation, where unilateral training can induce bilateral adaptations through central nervous system plasticity (41). The results underscore the hamstrings' dual role as both knee flexors and dynamic stabilizers of tibial translation, with their strengthened capacity likely reducing anterior shear forces during weight acceptance phases of gait (42).

The significant between-group difference in uninvolved limb knee angle during stance observed post-intervention suggests that SLHB may induce bilateral neuromuscular adaptations, potentially improving landing strategies even in the non-operative limb (32). As SLHB closely mirrors running mechanics, specifically at the late swing phase, where the hamstrings pull the swing forward leg for ground contact, involving an isometric contraction at the knee joint and a concentric force to extend the hip joint (18), which replicates running mechanics, particularly in generating concentric hip extension and isometric knee stabilization (17, 19). This aligns with evidence that persistent gait alterations post-ACLR often stem from hamstring function deficits, particularly in tibial stabilization during dynamic tasks (36). The intervention's focus on hamstring loading likely enhanced proprioceptive feedback and inter-limb coordination, creating more synchronized movement patterns across both lower extremities (32).

These biomechanical changes occurred without significant hypertrophy, suggesting the intervention primarily enhanced neural drive and inter-muscular coordination - a finding consistent with evidence that neuromuscular adaptations precede structural changes in ACL rehabilitation (43). The preserved spatiotemporal parameters across groups indicate that improved knee kinematics were achieved without compromising fundamental gait rhythm, a crucial consideration for maintaining functional movement patterns during rehabilitation (18, 23). Collectively, these findings reinforce the need for periodized hamstring strengthening protocols that progress from isometric stabilization to dynamic, multiplanar loading (44).

Incorporating exercises that challenge the hamstrings at varying muscle lengths and contraction velocities appears essential for restoring their capacity to modulate tibiofemoral forces during complex movements (45). This approach aligns with emerging rehabilitation strategies emphasizing the hamstrings' role as protector of the ACL through their ability to dynamically compensate for ligamentous insufficiency (32).

Practical implications

The findings of this study may have meaningful implications for ACLR rehabilitation. Incorporating SLHB exercises could help improve uninvolved limb knee angle at foot strike, potentially contributing to bilateral neuromuscular adaptations and more stable landing mechanics. This may be particularly relevant given prior evidence linking lower SLHB scores to increased hamstring injury risk (46). While SLHB is often considered during mid- to late-stage rehabilitation due to its biomechanical similarity to the late swing phase of running, its isometric and closed-chain characteristics may also allow for cautious application in the early stages, assuming the patient demonstrates adequate control. In this context, SLHB provides a lower-risk method to engage the posterior chain and reinforce hip-knee coordination. Clinicians should also be aware of potential compensatory patterns, such as those observed in the control group, and address them through individualized movement retraining (17). Furthermore, the observed increase in hamstring torque in the uninvolved leg suggests that contralateral training strategies, including SLHB, may be useful during phases when the involved limb cannot tolerate high loading (41). As the study’s biomechanical changes occurred without significant hypertrophy (47), rehabilitation strategies should emphasize neuromuscular efficiency and intermuscular coordination (23), gradually progressing from isometric control to dynamic, multiplanar tasks to support return-to-activity goals (17).

CONCLUSION

The findings of this study suggest that Single-Leg Hamstring Bridge (SLHB) training may have the potential to support neuromuscular adaptations, particularly in the uninvolved limb, as evidenced by improvements in knee flexion torque and increase in knee angle during foot strike. While knee angle during foot strike was the only kinematics variable to reach statistical significance, other kinematic changes, such as trends toward increased maximum knee flexion during stance and stride phases, suggest additional improvements in lower limb control. These changes, although not statistically significant, may reflect meaningful neuromuscular adaptations that support joint stability and running mechanics. However, given the absence of significant changes in the operated limb, these results should be interpreted with caution. It remains unclear whether SLHB alone can enhance rehabilitation outcomes for the injured leg. The observed effects may reflect bilateral motor control adjustments or compensatory limb use rather than direct improvements in the surgical limb. While SLHB may contribute to improved gait mechanics and dynamic knee stability, its role in optimizing long-term recovery remains to be determined, particularly considering the small sample size. Further studies with larger cohorts and longer follow-up periods are needed to confirm its clinical value.

Limitations of the study

While this study provides valuable insights, several limitations should be acknowledged. First, the inherent trade-off between highly specific inclusion criteria and the resulting small sample size. While the narrow inclusion criteria focusing on male athletes aged 18–30 years who had undergone ACLR using hamstring tendon autografts were necessary to ensure a homogenous study population and minimize confounding variables, it directly contributed to the small sample size of only eight participants (4 in the IG and 4 in the CG). This limited sample size restricts the statistical power of the study and, consequently, the generalizability of the findings to a broader population, including female athletes or individuals with ACLR from different sports or graft types. Second, the short duration of the intervention (6 weeks) may not have been sufficient to elicit the full potential benefits of SLHB training on hamstring strength, knee kinematics, or running mechanics, potentially underestimating the long-term impact of the Single Leg Hamstring Bridge exercise and injury rates. Future studies should employ a substantially larger sample size to enhance statistical power and allow for more definitive conclusions. Also, the study should adopt a longitudinal design with extended follow-up periods (e.g., 6 months, 1 year, 2 years). This would allow for the examination of the sustained impact of the intervention on hamstring strength, knee joint kinematics during functional activities (such as running, jumping, and cutting), and, critically, re-injury rates. Assessing return-to-sport outcomes and long-term functional performance is essential for determining the true clinical value of the intervention. It is also important to note that the current sample includes only male athletes, which limits the generalizability of our findings to female populations. Given that females often exhibit different neuromuscular control patterns, hormonal influences, and injury mechanisms following ACL reconstruction (ACLR), caution should be exercised when applying these results to female athletes. Future research should specifically investigate SLHB effects in female cohorts to better understand sex-specific rehabilitation outcomes. Lastly, this study did not include electromyography (EMG) analysis, which limits our ability to directly confirm changes in hamstring activation patterns in response to the SLHB intervention. While torque improvements and kinematic changes were observed, the underlying neuromuscular strategies remain speculative. Additionally, the kinematic assessment was limited to linear running. Given that many ACL injuries occur during cutting or deceleration movements, which involve higher multiplanar stress on the knee joint, future research should examine whether the observed adaptations persist or differ under more demanding, sport-specific conditions.

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REFERENCES

1. Prodromos CC, Han Y, Rogowski J, Joyce B, Shi K. A meta-analysis of the incidence of anterior cruciate ligament tears as a function of gender, sport, and a knee injury-reduction regimen. Arthroscopy. 2007;23(12):1320-5.e6.

2. Griffin LY, Albohm MJ, Arendt EA, Bahr R, Beynnon BD, Demaio M, et al. Understanding and preventing noncontact anterior cruciate ligament injuries: a review of the Hunt Valley II meeting, January 2005. Am J Sports Med. 2006;34(9):1512-32.

3. Boden BP, Dean GS, Feagin JA, Jr., Garrett WE, Jr. Mechanisms of anterior cruciate ligament injury. Orthopedics. 2000;23(6):573-8.

4. Colby S, Francisco A, Yu B, Kirkendall D, Finch M, Garrett W, Jr. Electromyographic and kinematic analysis of cutting maneuvers. Implications for anterior cruciate ligament injury. Am J Sports Med. 2000;28(2):234-40.

5. Kopf S, Musahl V, Tashman S, Szczodry M, Shen W, Fu FH. A systematic review of the femoral origin and tibial insertion morphology of the ACL. Knee Surg Sports Traumatol Arthrosc. 2009;17(3):213-9.

6. Gupta R, Singhal A, Malhotra A, Soni A, Masih GD, Raghav M. Predictors for Anterior Cruciate Ligament (ACL) Re-injury after Successful Primary ACL Reconstruction (ACLR). Malays Orthop J. 2020;14(3):50-6.

7. Tsepis E, Vagenas G, Giakas G, Georgoulis A. Hamstring weakness as an indicator of poor knee function in ACL-deficient patients. Knee Surg Sports Traumatol Arthrosc. 2004;12(1):22-9.

8. Thomas AC, Villwock M, Wojtys EM, Palmieri-Smith RM. Lower extremity muscle strength after anterior cruciate ligament injury and reconstruction. J Athl Train. 2013;48(5):610-20.

9. Ko MS, Yang SJ, Ha JK, Choi JY, Kim JG. Correlation between Hamstring Flexor Power Restoration and Functional Performance Test: 2-Year Follow-Up after ACL Reconstruction Using Hamstring Autograft. Knee Surg Relat Res. 2012;24(2):113-9.

10. Paterno MV, Rauh MJ, Schmitt LC, Ford KR, Hewett TE. Incidence of Second ACL Injuries 2 Years After Primary ACL Reconstruction and Return to Sport. Am J Sports Med. 2014;42(7):1567-73.

11. Saki F, Shafiee H, Tahayori B, Ramezani F. The effects of core stabilization exercises on the neuromuscular function of athletes with ACL reconstruction. Sci Rep. 2023;13(1):2202.

12. Liu W, Maitland ME. The effect of hamstring muscle compensation for anterior laxity in the ACL-deficient knee during gait. J Biomech. 2000;33(7):871-9.

13. Wild CY, Steele JR, Munro BJ. Insufficient hamstring strength compromises landing technique in adolescent girls. Med Sci Sports Exerc. 2013;45(3):497-505.

14. Dedinsky R, Baker L, Imbus S, Bowman M, Murray L. Exercises that facilitate optimal hamstring and quadriceps co-activation to help decrease acl injury risk in healthy females: a systematic review of the literature. Int J Sports Phys Ther. 2017;12(1):3-15.

15. Macdonald B, O'Neill J, Pollock N, Van Hooren B. Single-Leg Roman Chair Hold Is More Effective Than the Nordic Hamstring Curl in Improving Hamstring Strength-Endurance in Gaelic Footballers With Previous Hamstring Injury. J. Strength Cond. Res. 2019;33(12):3302-8.

16. Delahunt E, McGroarty M, De Vito G, Ditroilo M. Nordic hamstring exercise training alters knee joint kinematics and hamstring activation patterns in young men. Eur J Appl Physiol. 2016;116(4):663-72.

17. Freckleton G, Cook J, Pizzari T. The predictive validity of a single leg bridge test for hamstring injuries in Australian Rules Football Players. Br J Sports Med. 2014;48(8):713-7.

18. Van Hooren B, Bosch F. Is there really an eccentric action of the hamstrings during the swing phase of high-speed running? part I: A critical review of the literature. J Sports Sci. 2017;35(23):2313-21.

19. Pori P, Kovčan B, Vodičar J, Dervišević E, Karpljuk D, Hadžić V, Šimenko J. Predictive Validity of the Single Leg Hamstring Bridge Test in Military Settings. Appl Sci. 2021;11(4):1822.

20. Knurr KA, Kliethermes SA, Stiffler-Joachim MR, Cobian DG, Baer GS, Heiderscheit BC. Running Biomechanics Before Injury and 1 Year After Anterior Cruciate Ligament Reconstruction in Division I Collegiate Athletes. Am J Sports Med. 2021;49(10):2607-14.

21. Koichi Kamiike TM, Shinichi Yoshiya, Kotaro Kawaguchi, Shigeo Fukunishi. Effectiveness of single leg standing up exercise for recovery of knee muscle strength and lower extremity motion function following anterior cruciate ligament reconstruction. J Joint Surg Res. 2023;Volume 1(Issue 1):Pages 179-85.

22. Abourezk MN, Ithurburn MP, McNally MP, Thoma LM, Briggs MS, Hewett TE, et al. Hamstring Strength Asymmetry at 3 Years After Anterior Cruciate Ligament Reconstruction Alters Knee Mechanics During Gait and Jogging. Am J Sports Med. 2017;45(1):97-105.

23. Dicharry J. Kinematics and kinetics of gait: from lab to clinic. Clin Sports Med. 2010;29(3):347-64.

24. Jamkrajang P, Suwanmana S, Limroongreungrat W, Verheul J. Spatiotemporal and kinematic adjustments in master runners may be associated with the relative physiological effort during running. Front Sports Act Living. 2023;5.

25. Vanrenterghem J, Gormley D, Robinson M, Lees A. Solutions for representing the whole-body centre of mass in side cutting manoeuvres based on data that is typically available for lower limb kinematics. Gait Posture. 2010;31(4):517-21.

26. Bousquet BA, O'Brien L, Singleton S, Beggs M. Post-operative criterion based rehabilitation of acl repairs: a clinical commentary. Int J Sports Phys Ther. 2018;13(2):293-305.

27. Kaya D, Guney-Deniz H, Sayaca C, Calik M, Doral MN. Effects on Lower Extremity Neuromuscular Control Exercises on Knee Proprioception, Muscle Strength, and Functional Level in Patients with ACL Reconstruction. Biomed Res Int. 2019;2019(1):1694695.

28. Andrushko JW, Lanovaz JL, Björkman KM, Kontulainen SA, Farthing JP. Unilateral strength training leads to muscle-specific sparing effects during opposite homologous limb immobilization. J Appl Physiol (1985). 2018;124(4):866-76.

29. Langford JL, Webster KE, Feller JA. A prospective longitudinal study to assess psychological changes following anterior cruciate ligament reconstruction surgery. Br J Sports Med. 2009;43(5):377-81.

30. Knoll Z, Kiss RM, Kocsis L. Gait adaptation in ACL deficient patients before and after anterior cruciate ligament reconstruction surgery. J Electromyogr Kinesiol. 2004;14(3):287-94.

31. Blackburn JT, Norcross MF, Cannon LN, Zinder SM. Hamstrings Stiffness and Landing Biomechanics Linked to Anterior Cruciate Ligament Loading. J Athl Train. 2013;48(6):764-72.

32. Buckthorpe M, Danelon F, La Rosa G, Nanni G, Stride M, Della Villa F. Recommendations for Hamstring Function Recovery After ACL Reconstruction. Sports Med. 2021;51(4):607-24.

33. Zhao K, Shan C, Luximon Y. Contributions of individual muscle forces to hip, knee, and ankle contact forces during the stance phase of running: a model-based study. Health Inf Sci Syst. 2022;10(1):11.

34. Chen B, Wu J, Jiang J, Wang G. Neuromuscular and Biomechanical Adaptations of the Lower Limbs During the Pre-Landing and Landing Phase of Running Under Fatigue Conditions. Appl Sci. 2025;15(5):2449.

35. Harput G, Kilinc HE, Ozer H, Baltaci G, Mattacola CG. Quadriceps and Hamstring Strength Recovery During Early Neuromuscular Rehabilitation After ACL Hamstring-Tendon Autograft Reconstruction. J Sport Rehabil 2015;24(4):398-404.

36. Myer GD, Ford KR, Barber Foss KD, Liu C, Nick TG, Hewett TE. The relationship of hamstrings and quadriceps strength to anterior cruciate ligament injury in female athletes. Clin J Sport Med. 2009;19(1):3-8.

37. Edouard P, Reurink G, Mackey AL, Lieber RL, Pizzari T, Järvinen TAH, et al. Traumatic muscle injury. Nat Rev Dis Primers. 2023;9(1):56.

38. Gharpinde MR, Pundkar A, Dhanwani Y, Chandanwale R, Jaiswal AM. Navigating Post-operative Challenges: A Comprehensive Review of Complications Following Anterior Cruciate Ligament (ACL) Tear Surgery. Cureus. 2024;16(8):e67768.

39. Chaput M, Criss CR, Onate JA, Simon JE, Grooms DR. Neural Activity for Uninvolved Knee Motor Control After ACL Reconstruction Differs from Healthy Controls. Brain Sci. 2025;15(2).

40. Stańczak M, Swinnen B, Kacprzak B, Pacek A, Surmacz J. Neurophysiology of ACL Injury. Orthop Rev (Pavia). 2025;17:129173.

41. Hendy AM, Lamon S. The Cross-Education Phenomenon: Brain and Beyond. Frontiers in Physiology. 2017;8.

42. Behrens M, Mau-Moeller A, Wassermann F, Bruhn S. Effect of fatigue on hamstring reflex responses and posterior-anterior tibial translation in men and women. PLoS One. 2013;8(2):e56988.

43. Eva Ageberg. Consequences of a ligament injury on neuromuscular function and relevance to rehabilitation — using the anterior cruciate ligament-injured knee as model,. J Electromyogr Kinesiol. 2002;Volume 12(Issue 3,):Pages 205-12,.

44. Widodo AF, Tien C-W, Chen C-W, Lai S-C. Isotonic and Isometric Exercise Interventions Improve the Hamstring Muscles' Strength and Flexibility: A Narrative Review. Healthcare. 2022;10(5):811.

45. Morrissey MC, Brewster CE. Hamstring weakness after surgery for anterior cruciate injury. J Orthop Sports Phys Ther. 1986;7(6):310-3.

46. Behan FP, van Dyk N, Rane L, Thorne E, Banaghan A, Gilsenan K, Whyte EF. Implementing hamstring injury prevention programmes remotely: a randomised proof of concept trial. BMJ Open Sport Exerc Med. 2024;10(1):e001728.

47. Larson D, Vu V, Ness BM, Wellsandt E, Morrison S. A Multi-Systems Approach to Human Movement after ACL Reconstruction: The Musculoskeletal System. Int J Sports Phys Ther. 2022;17(1):27-46.