Symmetry in Triple Hop Distance Hides Asymmetries in Knee Function After ACL Reconstruction in Athletes at Return to Sports

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Background: After anterior cruciate ligament reconstruction (ACLR), a battery of strength and hop tests is frequently used to determine the readiness of an athlete to successfully return to sports. However, the anterior cruciate ligament reinjury rate remains alarmingly high.

Purpose: To evaluate the lower limb function of athletes after ACLR at the time when they had been cleared to return to sports (RTS). We aimed to evaluate if passing discharge criteria ensures restoration of normal lower limb biomechanics in terms of kinematics, kinetics, work, and percentage work contribution during a triple hop for distance.

Study Design: Controlled laboratory study.

Methods: Integrated 3-dimensional motion analysis was performed in 24 male athletes after ACLR when cleared to RTS and 23 healthy male controls during the triple-hop test. The criteria for RTS were (1) clearance by the surgeon and the physical therapist, (2) completion of a sports-specific on-field rehabilitation program, and (3) limb symmetry index >90% after quadriceps strength and hop battery tests. Lower limb and trunk kinematics, as well as knee joint moments and work, were calculated. Between-limb differences (within athletes after ACLR) and between-group differences (between ACLR and control groups) were evaluated using mixed linear models.

Results: Although achieving 97% limb symmetry in distance hopped and displaying almost 80% symmetry for knee work absorption in the second rebound and third landing, the ACLR cohorts demonstrated only 51% and 66% limb symmetry for knee work generation in the first and second rebound phases, respectively. During both work generation phases of the triple hop, the relative contribution of the involved knee was significantly smaller, with a prominent compensation from the hip joint ($P < .001$, for all phases) as compared with the uninvolved limb and the controls. In addition, patients deployed a whole body compensatory strategy to account for the between-limb differences in knee function, mainly at the hip, pelvis, and trunk.

Conclusion: Symmetry in the triple hop for distance masked important deficits in the knee joint work. These differences were more prominent during work generation (concentric-propulsive) than work absorption (eccentric-landing).

Clinical Relevance: Symmetry in hop distance during the triple hop test masked significant asymmetries in knee function after ACLR and might not be the appropriate outcome to use as a discharge criterion. Differences between limbs in athletes after ACLR were more prominent during the power generation than the absorption phase.

Keywords: anterior cruciate ligament reconstruction; return to sport; injury prevention; biomechanics; hop test

Anterior cruciate ligament (ACL) injuries occur with a relatively low incidence but have a high injury burden in terms of days lost from sports participation.[4] Individuals who wish to return to sports (RTS) are often advised to undergo ACL reconstruction (ACLR) to restore stability and knee function.[6,26] However, more than a third of those who undergo surgery are unable to return to preinjury levels of activity.[3] In addition, the reinjury rate after ACLR is alarmingly high, with studies reporting up to 19% of young athletes rupturing the reconstructed ACL and up to 22% experiencing an ACL rupture in the contralateral (healthy) knee after RTS.[38]

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Traditionally, the time from surgery has been used as the main criterion to establish whether an athlete is ready to RTS.[8] More recently, there has been a shift toward a criteria-based progression and the use of a battery of tests for the decision to RTS.[2] Typically, symmetry between limbs is assessed using strength and hop test batteries.[16,23] The primary 4 hop tests used as part of an RTS test battery require horizontal propulsion; 3 of them include a rebound component (triple hop, crossover hop, and 6-m timed hop).[27] With these tests, a limb symmetry index (LSI) >90% is recommended as a cutoff for safe RTS.[35]

The single leg hop for distance is the most frequently used test[1] and the most explored in terms of biomechanics[21] in individuals after ACLR, as compared with other hop tasks. A recent in-depth assessment of biomechanical outcomes during a single-leg hop for distance revealed several kinematic and kinetic interlimb deficits and alterations after ACLR, despite adequate hop distance performance at RTS; that is, athletes after ACLR selectively unload the involved knee via hip and upper body kinematic adaptations.[22] In contrast, triple hop for distance in patients after ACLR has not been biomechanically evaluated, possibly because of the expensive equipment required to capture all 3 landings involved. During many sports, it is unusual for an athlete to be required to make a single movement, such as an isolated jump or hop. More commonly, one movement will transition into another. Therefore, the triple hop for distance—with 1 initial propulsive hop, followed by 2 rebounding hops and a final landing—can capture more information relevant to sporting activities where repeated movements are typically observed. Moreover, research has identified sex, knee-related confidence, and performance in the triple hop at the time of RTS as the primary predictors of a second ACL injury in adolescents.[31] It is plausible that the dynamic requirements of concentric (propulsive), eccentric (landing), and stretch-shortening (rebound) elements of the task better capture the spectrum of sporting requirements than do isolated single jumps or hops.

Accordingly, we aimed to investigate the biomechanical function of athletes during the triple hop for distance at RTS after ACLR. Specifically, we sought to evaluate the biomechanical performance (kinematics, kinetics, work done, and contribution of each joint to the total lower limb work done) during all landings of a triple hop for athletes at the time of RTS after ACLR as compared with healthy controls. Our hypothesis was that despite achieving the 90% LSI threshold in the triple hop for distance and being cleared for RTS, athletes would still display crucial biomechanical differences after ACLR. Additionally, these differences would be more pronounced in the triple hop when compared with differences in the literature for the single hop.

METHODS

Participants

This laboratory study involved a case-control comparative analysis of an ACLR cohort and a healthy cohort. All participants provided informed consent, and the study was approved by the institutional ethics committee (F2017000227; Anti-Doping Lab Qatar).

A total of 47 male athletes participated in this study between November 2018 and March 2020 at Aspetar, Orthopaedic and Sports Medicine Hospital, Doha, Qatar (Table 1). Twenty-four consecutive eligible patients who underwent primary ACLR were enrolled after completion of a standardized rehabilitation protocol and after receiving clearance to RTS, having met prespecified clinical criteria (Figure 1). The criteria for RTS were (1) clearance by the surgeon and the physical therapist, (2) completion of a sports-specific on-field rehabilitation program, (3) quadriceps strength LSI >90%, and (4) hop battery tests LSI >90%.[23] The ACLR cohort included athletes (preinjury Tegner score ≥7) with a complete unilateral ACL injury treated with an autologous ipsilateral bone–patellar tendon–bone or hamstring tendon graft (semitendinosus and/or gracilis tendon), as decided by the treating surgeon and athlete. Patients with concomitant meniscal injuries that did not significantly impede the rehabilitation course, as decided by the treating clinician, were also included in the study. Potential participants were excluded if they had concomitant grade III knee ligament injury (other than ACL), full-thickness articular cartilage lesion, history of other lower extremity surgery (in either limb), back pain, or lower extremity injury (other than primary ACL) in the previous 3 months. As a convenience sample, 23 athletic male control participants (Tegner score ≥7) were recruited by contacting health care providers and sports club physicians. Inclusion criteria were as follows: age between 18 and 35 years, participation in level I or II sports ≥3 times per week, and no history of musculoskeletal injury of the lower limb 3 months before testing.

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TABLE 1
Patient Data[a]

	No. or Mean ± SD		
	ACL Reconstruction	Control	*P* Value
Participants	24	23	
Age, y	23.4 ± 3.4	28.3 ± 4.4	<.001
Body mass, kg	72.5 ± 11.8	76.1 ± 7.4	.21
Height, cm	175.5 ± 10.7	178.2 ± 6.9	.35
Body mass index	23.3 ± 2.3	23.9 ± 1.6	.34
Tegner score preinjury	8.9 ± 0.5	7.6 ± 1.2	<.001
IKDC, %	95.6 ± 6.2	100	<.001
ACL-RSI scale, %	93.6 ± 8.3		
LSI, %			
Quadriceps strength	95 ± 5		
SLHD	97 ± 4	100 ± 5	.02
TRHD	97 ± 5	100 ± 5	.13
Return to sports, mo	9.5 ± 2.7		
Hamstring/BTB autograft	8/16		
Isolated ACL injury	14		
Meniscal injury	8		
Meniscal injury and cartilage lesion	2		

[a]Independent-samples *t* tests were used for between-group comparison (significant difference, $P < .05$). Blank cells indicate *not applicable*. ACL, anterior cruciate ligament; ACL-RSI, Anterior Cruciate Ligament–Return to Sport After Injury; BTB, bone–patellar tendon–bone; IKDC, International Knee Documentation Committee subjective knee form; LSI, limb symmetry index; SLHD, single-leg hop for distance; TRHD, triple-hop for distance.

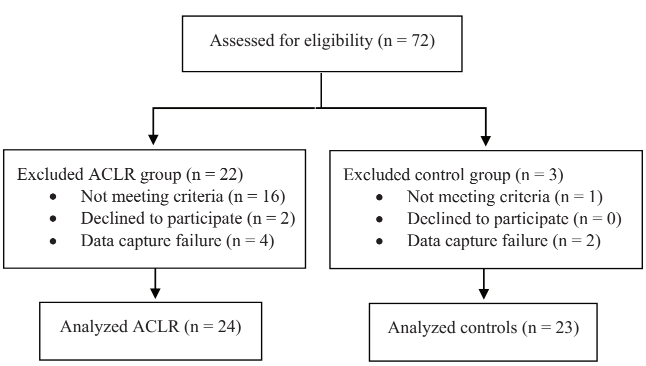

Figure 1. Study flow diagram. ACLR, anterior cruciate ligament reconstruction.

Subjective knee function was evaluated using the International Knee Documentation Committee subjective knee form (IKDC) questionnaire,[18] and psychological readiness to RTS was measured by using the Anterior Cruciate Ligament–Return to Sport After Injury (ACL-RSI) scale.[36]

Equipment, Participant Preparation, and Marker Set

Forty-two reflective markers were placed according to a full-body Plug-in-Gait marker set,[11] extended using additional anatomic markers on the sacrum, medial knee, and medial ankle. Three marker clusters replaced the single marker laterally on each thigh and shank since cluster-based models have less intersubject variance of frontal plane variables.[12] The markers' motion was captured using a 14-camera motion capture system (250 Hz; Vicon). During the dynamic trials, ground-reaction forces were collected synchronously via marker trajectories using 5 ground-embedded force plates (1000 Hz; Kistler), located in a row to capture the 3 landings of the triple hop.

Experimental Setup, Procedure, and Testing

All participants were evaluated in the same laboratory by the same investigator (A.K.) and wore athletic shorts and standard shoes. They performed a 7-minute warm-up including running, side running, deep squats, and double-leg jumps. A physical therapist (A.K.) provided verbal instructions and demonstrated the testing task. Subsequently, participants practiced the triple hop for distance while oral feedback was provided until they were comfortable proceeding with testing. For measurement of triple-hop performance, participants stood upright on a single leg on a force plate with their hands placed over their hips. They then dropped to a self-selected depth before jumping horizontally in 3 consecutive hops as far as possible and landing on the same leg. A successful trial required participants to land inside the borders of the force plates and to hold the final landing for at least 2 seconds. Data were collected for both limbs, and 4 successful trials were retained for analysis. Test limb order was randomized using a coin toss. For the first landing of the triple hop, data exist for 11 patients owing to laboratory configuration changes. Limb dominance was determined by asking the participants the limb with which they would prefer to kick a ball.[34]

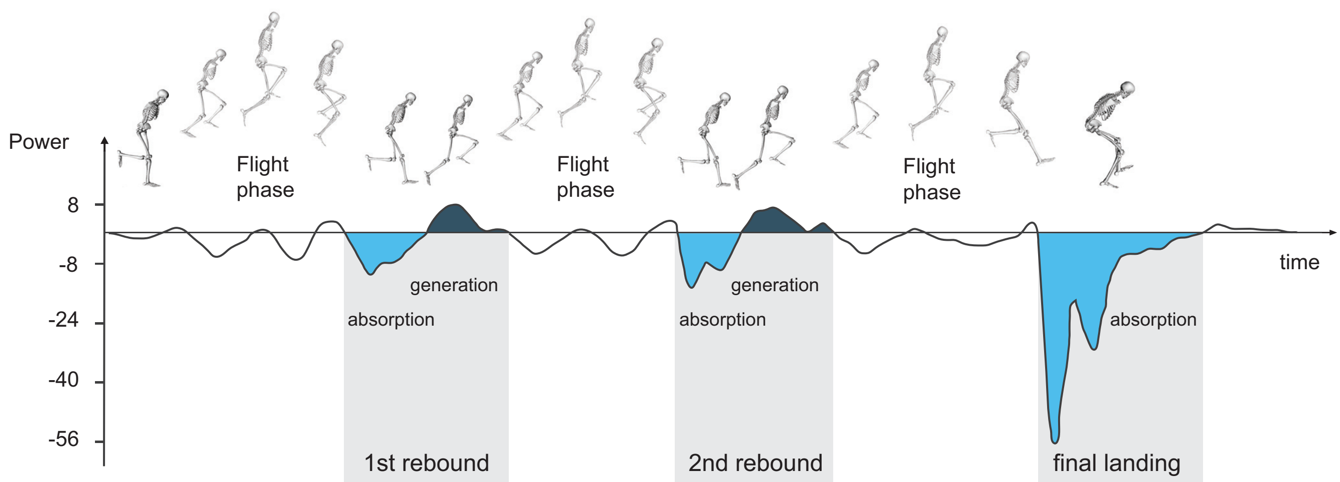

Figure 2. Representation of the 3 analyzed phases (shaded regions of the knee power curve) of the triple hop for distance. After the initial propulsion phase to begin the first hop, there are 2 rebounds—first a landing with negative work (absorption, shaded area below the solid line) followed by positive work (propulsive, shaded area above the solid line)—then a final landing phase. The final landing is defined from initial contact to peak knee flexion. Work was calculated as net joint power integrated over time.

Data Processing

Data were processed using Visual 3D (C-Motion, Inc). Marker trajectories and ground-reaction forces were low pass filtered using a zero-lag, fourth-order Butterworth filter with the same 15-Hz cutoff frequency. All data were extracted for the 3 landing phases, defined from initial contact to toe-off and from initial contact to peak knee flexion for the third landing. Toe-off and initial contact were expressed as the point when ground-reaction force became <50 and >50 N, respectively.

Joint angles were determined using a Visual 3D hybrid model with a Cardan X-Y-Z rotation sequence (mediolateral, anteroposterior, vertical).[10] Ankle, hip, and knee joint angles were defined as those between the distal and proximal segments. Pelvis was defined using the model.[7] Pelvis and trunk segment angles were determined with respect to the global coordinate system. Kinematic and kinetic variables were calculated for the hip, knee, and ankle joints for both limbs. The variables of interest were as follows: hop distance, peak joint angles, peak knee internal joint moments, joint work, and work contribution of each joint to the total work performed. We determined work generation as the net-positive joint power integrated over time and work absorption as the net-negative joint power integrated over time. Joint power was calculated by using all 3 components. The work contribution of each joint was determined as the percentage of the sum of the work of all 3 lower limb joints during each phase. Performing a triple hop involves an initial propulsion-only phase, followed by 2 rebounding phases (landing then propulsion) and a final landing phase (work absorption, eccentric) (Figure 2). All variables were extracted for each phase. Work and knee moments were normalized to body mass. Hop distance was calculated as the difference of the heel marker from the standing position to the final landing and normalized to leg length (anterior superior iliac spine to lateral malleolus). LSI was determined as the percentage of the involved limb divided by the uninvolved limb for the ACLR group and the nondominant limb divided by the dominant limb for the control group.[1,27] For the analysis, we used a randomly selected control limb from each control.

Statistical Analysis

Descriptive statistics were used to summarize the characteristics of the participants and measurements. Normality of data distribution was assessed using the Shapiro-Wilk test[32] and normal probability (Q-Q) plots.[13] Between-limb comparisons (involved, uninvolved, and control) were assessed using mixed effect models with participant-specific random effects. Post hoc comparisons (Tukey) were performed to adjust for multiple comparisons. The parameters estimates were adjusted for age, Tegner score, and body mass index. $P < .05$ was considered for statistical significance. Effect sizes were calculated using the pooled[9] (between limb) and pooled weighted[17] (between group) SD. Values of 0.2, 0.5, and 0.8 were identified as the lower thresholds for small, moderate, and large effects, respectively.[9] All statistical analysis was performed using JMP (Version 15; SAS Institute).

RESULTS

Time from surgery to RTS was 9.5 ± 2.7 months (mean ± SD). Groups did not differ in height, weight, or body mass index ($P > .05$). Control participants were older ($P < .001$) and had lower Tegner scores than the ACLR group ($P < .001$). The ACLR group achieved a 97.1% LSI during the triple hop. Normalized hop distance was 5.1 ± 0.4, 5.2 ±

TABLE 2
Kinematic and Kinetic Comparison Between Groups During the Triple Hop for Distance[a]

	Involved Limb		Uninvolved Limb		Controls		Involved vs Uninvolved		Involved vs Controls		Uninvolved vs Controls	
Variable	Mean ± SD	95% CI	Mean ± SD	95% CI	Mean ± SD	95% CI	P Value	Effect Size	P Value	Effect Size	P Value	Effect Size
First rebound												
Contact time, s	0.37 ± 0.06	0.34-0.41	0.34 ± 0.06	0.30-0.38	0.35 ± 0.05	0.32-0.37	.12		.42		.94	
Hip flexion, deg	76.0 ± 9.9	69.4-82.6	66.9 ± 8.8	61.0-72.9	64.5 ± 9.5	60.1-69.0	**.002**	0.97	**.012**	1.16	.78	
Knee flexion, deg	59.9 ± 4.8	56.7-63.1	64.2 ± 5.2	60.7-67.7	61.2 ± 5.7	58.5-63.8	**.032**	0.86	.80		.31	
Ankle dorsiflexion, deg	31.7 ± 3.3	29.5-33.9	33.6 ± 3.6	31.2-36.0	32.1 ± 3.8	30.4-33.9	.84		.56		.72	
Trunk flexion, deg	48.8 ± 7.8	43.5-54.0	37.4 ± 7.9	32.1-42.7	40.6 ± 9.5	36.2-45.0	**<.001**	1.45	.17		.27	
Anterior pelvic tilt, deg	43.7 ± 8.0	38.4-49.1	35.4 ± 5.8	31.6-39.3	34.4 ± 6.2	31.4-37.3	**<.001**	1.19	**.003**	1.27	.90	
Knee extension moment, N·m/kg	2.6 ± 0.5	2.22-2.89	3.1 ± 0.5	2.71-3.42	2.9 ± 0.5	2.62-3.12	**<.001**	1.00	.26		.60	
Second rebound												
Contact time, s	0.34 ± 0.06	0.31-0.37	0.31 ± 0.05	0.29-0.34	0.33 ± 0.05	0.31-0.35	**.008**	0.54	.86		.47	
Hip flexion, deg	71.9 ± 10.4	67.5-76.3	65.3 ± 8.7	61.7-69.0	62.7 ± 10.4	58.2-67.2	**.003**	0.69	**.008**	0.87	.63	
Knee flexion, deg	58.7 ± 5.0	56.5-60.8	62.7 ± 4.9	60.6-64.8	60.3 ± 5.0	58.2-62.5	**.002**	0.81	.49		.25	
Ankle dorsiflexion, deg	28.6 ± 4.3	26.8-30.4	30.2 ± 3.4	28.8-31.6	29.5 ± 2.8	28.3-30.7	.25		.78		.93	
Trunk flexion, deg	40.4 ± 8.4	36.9-43.9	30.4 ± 8.0	27.1-33.8	30.6 ± 11.3	25.7-35.5	**<.001**	1.22	**.003**	0.97	.99	
Anterior pelvic tilt, deg	37.6 ± 9.6	33.5-41.6	30.8 ± 7.4	27.7-33.9	29.9 ± 7.8	26.5-33.3	**<.001**	0.79	**.012**	0.86	.98	
Knee extension moment, N·m/kg	2.9 ± 0.6	2.63-3.11	3.5 ± 0.5	3.29-3.75	3.2 ± 0.7	2.91-3.48	**<.001**	1.09	**.049**	0.45	.63	
Final landing												
Hip flexion, deg	84.2 ± 14.2	78.2-90.2	80.2 ± 11.4	75.4-85.0	72.6 ± 12.3	67.3-77.9	.19		**.009**	0.86	.11	
Knee flexion, deg	66.6 ± 8.7	62.9-70.2	74.0 ± 6.5	71.2-76.7	70.4 ± 7.5	67.2-73.6	**<.001**	0.96	.14		.17	
Ankle dorsiflexion, deg	10.4 ± 5.9	7.9-12.9	12.5 ± 4.1	10.8-14.3	13.8 ± 5.3	11.5-16.0	**.025**	0.41	**.038**	0.60	.53	
Trunk flexion, deg	46.5 ± 12.7	41.1-51.8	37.3 ± 10.4	32.9-41.7	31.2 ± 11.9	26.0-36.3	**<.001**	0.79	**<.001**	1.22	.14	
Anterior pelvic tilt, deg	30.4 ± 11.4	25.6-35.2	22.9 ± 9.7	18.8-27.0	20.0 ± 10.2	15.6-24.4	**<.001**	0.71	**.004**	0.94	.62	
Knee extension moment, N·m/kg	4.0 ± 0.8	3.73-4.37	4.8 ± 0.6	4.49-5.03	4.5 ± 0.7	4.15-4.75	**<.001**	1.13	**.031**	0.65	.92	

[a]Effect sizes are shown only where $P < .05$. Bold indicates statistically significant difference.

0.4, and 5.2 ± 0.5 for the involved limb, uninvolved limb, and control group, respectively, with significant difference between limbs in the ACLR group ($P = .02$).

Kinematics and Kinetics

After ACLR, athletes landed on the involved limb with more hip flexion, trunk flexion, and anterior pelvic tilt compared with the uninvolved limb and the controls in all 3 phases. Peak knee flexion angle was less in the involved limb than the uninvolved limb during all 3 phases. Knee flexion moments were lower in the involved limb than the uninvolved limb in all 3 phases (Table 2).

Joint Work

Knee work absorption was less in the involved limb than the uninvolved limb during the second rebound and the final landing (Table 3, Figure 3). Knee work generation was significantly less in the involved limb than the uninvolved limb and controls during the first and second rebounds. In terms of LSI, athletes after ACLR displayed about 80% LSI for the knee work absorption during the second rebound and the final landing of triple hop but only 51% and 66% for the knee work generation during the first and second rebounds, respectively (Table 4).

Hip work absorption was higher in the involved limb than the controls during the first rebound. In the involved limb, ankle work generation was less during both rebounds, and ankle work absorption was less during the final landing when compared with the uninvolved limb and the control group. Participants after ACLR displayed less total work absorption in the involved limb than the uninvolved limb during the second rebound and the final landing. Also, the involved limb produced less total work (generation) than did the uninvolved limb and controls during both rebound phases (Table 3, Figure 4).

Work Contribution

During both work generation phases of the triple hop, there was a smaller percentage contribution of the involved knee as compared with the uninvolved knee and a larger contribution of the involved hip joint as compared with the uninvolved knee and the control group ($P < .001$, for almost all phases) (Figure 5; Appendix Table A1, available in the online version of this article). During the final landing (absorption), the involved limb displayed more hip work contribution than did the uninvolved limb ($P < .001$) and less ankle work contribution than did the control group ($P = .038$).

DISCUSSION

Our detailed biomechanical evaluation revealed that differences during the triple hop for distance persisted in athletes after ACLR between limbs and when compared with a healthy control group, despite passing clinical, functional, and performance testing criteria to RTS.

Normalized hop distance was statistically different between limbs in the ACLR group; however, since a passing

TABLE 3
Joint Work Comparison Between Groups During the Triple Hop for Distance[a]

	Involved Limb		Uninvolved Limb		Controls		Involved vs Uninvolved		Involved vs Controls		Uninvolved vs Controls	
Joint Work, J/kg	Mean ± SD	95% CI	Mean ± SD	95% CI	Mean ± SD	95% CI	*P* Value	Effect Size	*P* Value	Effect Size	*P* Value	Effect Size
First rebound												
ABSORPTION												
Hip	−0.93 ± 0.26	−1.10 to −0.76	−0.71 ± 0.16	−0.81 to −0.60	−0.67 ± 0.20	−0.76 to −0.57	**.025**	1.02	**.007**	1.10	.86	
Knee	−1.18 ± 0.41	−1.46 to −0.91	−1.32 ± 0.37	−1.57 to −1.07	−1.14 ± 0.42	−1.33 to −0.94	.47		.95		.46	
Ankle	−0.68 ± 0.24	−0.84 to −0.51	−0.71 ± 0.22	−0.86 to −0.57	−0.74 ± 0.22	−0.84 to −0.64	.89		.73		.93	
Total	−2.79 ± 0.55	−3.16 to −2.42	−2.74 ± 0.46	−3.05 to −2.43	−2.54 ± 0.47	−2.77 to −2.32	.95		.39		.54	
GENERATION												
Hip	1.76 ± 0.30	1.56 to 1.96	1.62 ± 0.24	1.46 to 1.78	1.72 ± 0.24	1.61 to 1.83	.22		.99		.16	
Knee	0.37 ± 0.17	0.26 to 0.49	0.72 ± 0.21	0.58 to 0.86	0.60 ± 0.15	0.53 to 0.67	**<.001**	1.83	**.004**	1.41	.15	
Ankle	1.32 ± 0.27	1.13 to 1.50	1.56 ± 0.35	1.33 to 1.79	1.66 ± 0.22	1.56 to 1.76	**.011**	0.77	**.005**	1.35	.54	
Total	3.45 ± 0.43	3.14 to 3.76	3.90 ± 0.54	3.54 to 4.26	3.99 ± 0.36	3.82 to 4.16	**.029**	0.92	**.001**	1.34	.19	
Second rebound												
ABSORPTION												
Hip	−1.04 ± 0.33	−1.18 to −0.90	−1.00 ± 0.34	−1.15 to −0.86	−0.98 ± 0.27	−1.10 to −0.87	.80		.80		.97	
Knee	−1.29 ± 0.41	−1.47 to −1.12	−1.62 ± 0.45	−1.81 to −1.42	−1.47 ± 0.41	−1.65 to −1.29	**.001**	0.77	.36		.46	
Ankle	−0.84 ± 0.23	−0.93 to −0.74	−0.87 ± 0.31	−1.00 to −0.74	−0.90 ± 0.22	−0.99 to −0.80	.86		.71		.94	
Total	−3.17 ± 0.47	−3.37 to −2.97	−3.49 ± 0.55	−3.72 to −3.26	−3.34 ± 0.58	−3.60 to −3.09	**.006**	0.63	.52		.63	
GENERATION												
Hip	1.76 ± 0.46	1.56 to 1.95	1.64 ± 0.32	1.51 to 1.78	1.69 ± 0.33	1.55 to 1.83	.34		.98		.63	
Knee	0.42 ± 0.15	0.36 to 0.48	0.64 ± 0.18	0.56 to 0.72	0.61 ± 0.22	0.52 to 0.71	**<.001**	1.33	**.006**	1.00	.83	
Ankle	1.27 ± 0.26	1.16 to 1.36	1.44 ± 0.30	1.31 to 1.56	1.63 ± 0.21	1.54 to 1.72	**.009**	0.61	**<.001**	1.49	**.035**	0.72
Total	3.45 ± 0.64	3.18 to 3.72	3.72 ± 0.48	3.52 to 3.92	3.93 ± 0.42	3.75 to 4.11	**.046**	0.48	**<.001**	0.87	.06	
Final landing												
ABSORPTION												
Hip	−1.37 ± 0.37	−1.52 to −1.21	−1.22 ± 0.49	−1.43 to −1.02	−1.30 ± 0.36	−1.45 to −1.14	.33		.82		.82	
Knee	−3.08 ± 0.78	−3.41 to −2.75	−3.92 ± 0.70	−4.22 to −3.63	−3.46 ± 0.78	−3.80 to −3.12	**<.001**	1.13	.21		.10	
Ankle	−0.54 ± 0.32	−0.67 to −0.40	−0.83 ± 0.33	−0.97 to −0.69	−0.86 ± 0.33	−1.01 to −0.72	**.031**	0.89	**.003**	0.97	.93	
Total	−4.98 ± 0.91	−5.36 to −4.60	−5.98 ± 0.75	−6.29 to −5.66	−5.62 ± 1.00	−6.05 to −5.18	**<.001**	1.20	.05		.37	

[a]Effect sizes are shown only where $P < .05$. Bold indicates statistically significant difference.

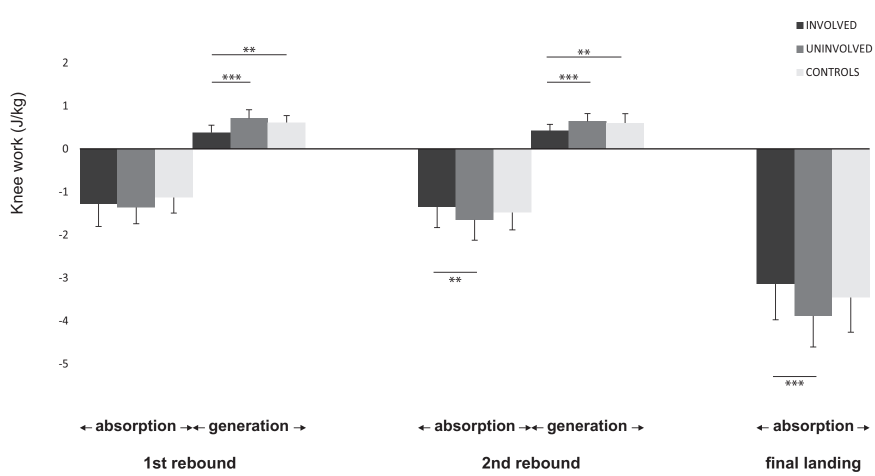

Figure 3. Knee work absorption (negative) and generation (positive) for the involved limb (black), the uninvolved limb (medium gray), and the controls (light gray) during the 3 phases of the triple hop for distance. Horizontal bars refer to the significant difference found for the knee work done between groups. Values are presented as mean ± SD. $^{**}P < .01$. $^{***}P < .001$.

threshold of 90% LSI is recommended in the literature,[16,23,35] this small difference was not deemed clinically important.

Whole Body Compensations

After ACLR, athletes landed on the involved limb by maintaining a more extended knee position accompanied by more hip flexion, anterior pelvic tilt, and trunk flexion. This positioning of the entire kinetic chain was adopted by athletes as a compensatory mechanism for the reduced knee work found in all phases of the triple-hop task.

Total lower limb work differences were evident during several phases of the triple hop. Especially during the final landing (absorption, eccentric phase), patients significantly unloaded the involved limb versus the uninvolved limb. ACL injury often occurs in the initial phase of the

TABLE 4
LSI of the Knee Work Generation and Absorption During the Phases of the Triple Hop for Distance[a]

	LSI, %	
Phase: Knee Work	ACLR	Control
First rebound		
Absorption	89	104
Generation	51	98
Second rebound		
Absorption	80	97
Generation	66	99
Final landing: absorption	79	102

[a]Absorption indicates eccentric phase. Generation indicates concentric phase. ACLR, anterior cruciate ligament reconstruction; LSI, limb symmetry index.

eccentric landing.[19] Our data revealed that after ACLR, athletes shift the demands away from the involved knee, plausibly for protection—a mechanism also seen in the landing after a single-leg hop for distance.[22,28,39] The adoption of a different upper body compensatory strategy might be a mechanism to reduce lower limb loading.

Work absorption and generation at the hip were not different between groups, except the first rebound absorption. However, the involved knee joint contributed less and the hip joint contributed more to the total work generation and absorption when compared with the uninvolved limb during all phases of the triple hop. This compensation can be interpreted as an attempt to unload the involved knee and thereby increase hip load, as previously observed in various tasks after ACLR,[29,33,39] likely because of the strong hip musculature that is able to withstand these loads.

Concentric vs Eccentric Phases

The eccentric landing phase of functional tasks has been the main focus in the literature.[14,24] However, the concentric phase might provide clinically meaningful information on how better performance is achieved. Assessment of all phases of the triple hop revealed that knee work differences between groups were more prominent during the concentric phases (generation) than during the eccentric phases (absorption) of the task. During all phases of work absorption, LSI was higher (around 80%) but did not pass the 90% symmetry threshold. Yet, during the first and second rebound phases, the LSIs for knee work generation were only 51% and 66%, respectively, for the ACLR group. These asymmetries in knee work during hops were not reflected in the hop distance, which was nearly identical; this highlights the inability of distance hopped to reflect knee function during triple hops. As a metric, the distance reflects the overall performance of a biomechanically multidimensional task, which involves function and coordination of 3 individual joints of the lower limb.[20,22]

Previous literature has questioned the use of LSI for functional tests, arguing that the decreased performance of the uninvolved limb will produce misleading LSIs and may overestimate the functional ability of the involved limb.[15,37] Indeed, after ACLR, the uninvolved limb often appears to exhibit decreased performance as compared with a healthy control.[15,30,40] Nevertheless, in our cohort, the uninvolved limb had no difference in performance when compared with the control, and still, significant biomechanical differences were observed between limbs, driving us to question, not the use of LSI, but the outcome: distance.

Comparison of the Triple- and Single-Hop Test

After ACLR, athletes compensated for less knee work with greater hip work contribution and by landing with more hip flexion, anterior pelvic tilt, and trunk flexion. Additionally, they adopted a different strategy between limbs to absorb and generate work, which was not reflected in the symmetry of the distance hopped. Similar results have been reported for the single-leg hop for distance.[22] When comparing the results from the single hop for distance, we found similar whole body compensatory adaptations and differences in work absorption between limbs. However, these differences were not more pronounced in the triple hop, as was our initial hypothesis. A strong correlation (r = .84) for the hop distance between these tests may explain these "compensatory" similarities.[5] The single-leg hop for distance reflects a single maximal effort, and the performance relies mainly on the propulsive phase.[20] Conversely, the triple-hop test provides additional information about the patient's ability in a more demanding task and possibly provides insight into the capacity of the musculotendinous system to absorb and release energy attributed to the consecutive plyometric loading. Repetitive hopping tasks such as the triple hop utilize the stretch-shortening cycle, which involves rapid eccentric loading at the absorption phase, followed by an amortization period that engages the musculotendinous tissue and, finally, concentric work generating muscle action.[25] In our cohort, the only differences were in contact time between limbs during the second rebound in the ACLR group; yet, this did not seem to affect the athletes' test performance (hop distance). Assessing horizontal rebound performance, which is part of a triple hop, did not provide additional information on the knee function status over a single hop. Details on the biomechanical performance of the task might inform rehabilitation strategies and decisions to enhance specific muscle task requirements, as well as the capacity of the tendon tissue, which is inarguably affected during the long-lasting recovery from surgery.

Clinical Implications

Symmetry in performance of a triple hop masked important lower limb deficits, especially in knee joint biomechanics in athletes after ACLR. Specifically, biomechanical analysis revealed altered knee function and compensatory adaptations from the adjacent joints and the upper body. Similar findings were observed during the single hop for

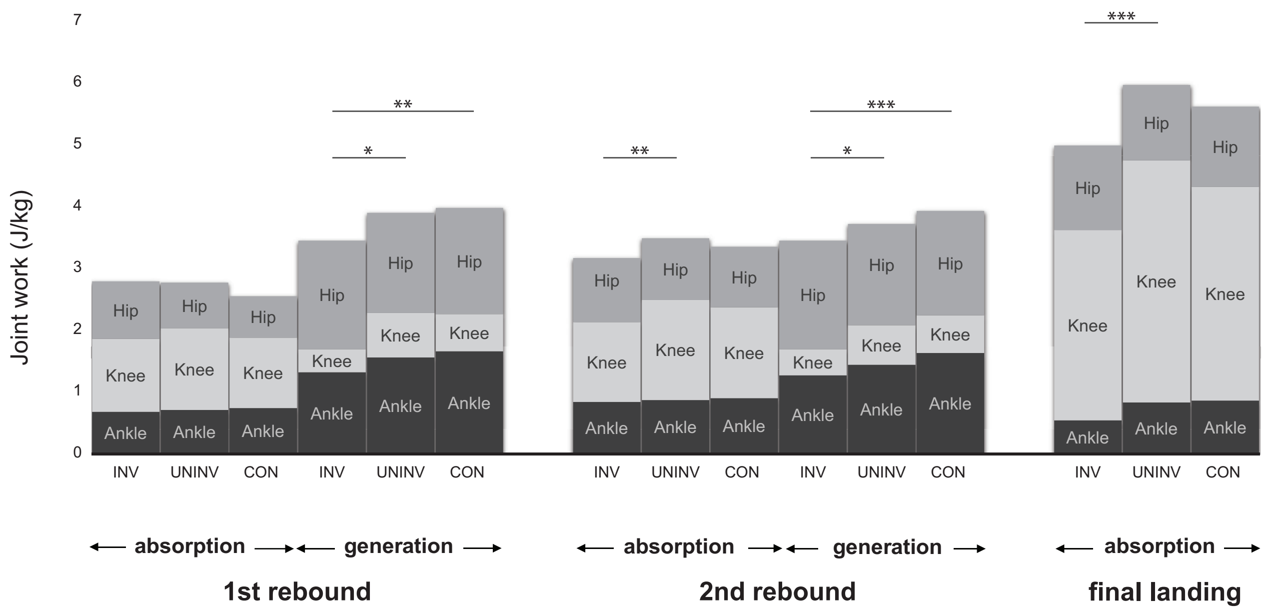

Figure 4. Visualization of work (absorption and generation) of the hip, knee, and ankle joints for the involved limb (INV), the uninvolved limb (UNINV), and the controls (CON) during the 3 phases of the triple hop for distance. Absorption work is negative, and generation work is positive. In the current figure, we report all values as positive for better visualization. Horizontal bars refer to the significant difference found for the total work done by the lower limb between groups. Values are presented as means. *$P < .05$. **$P < .01$. ***$P < .001$.

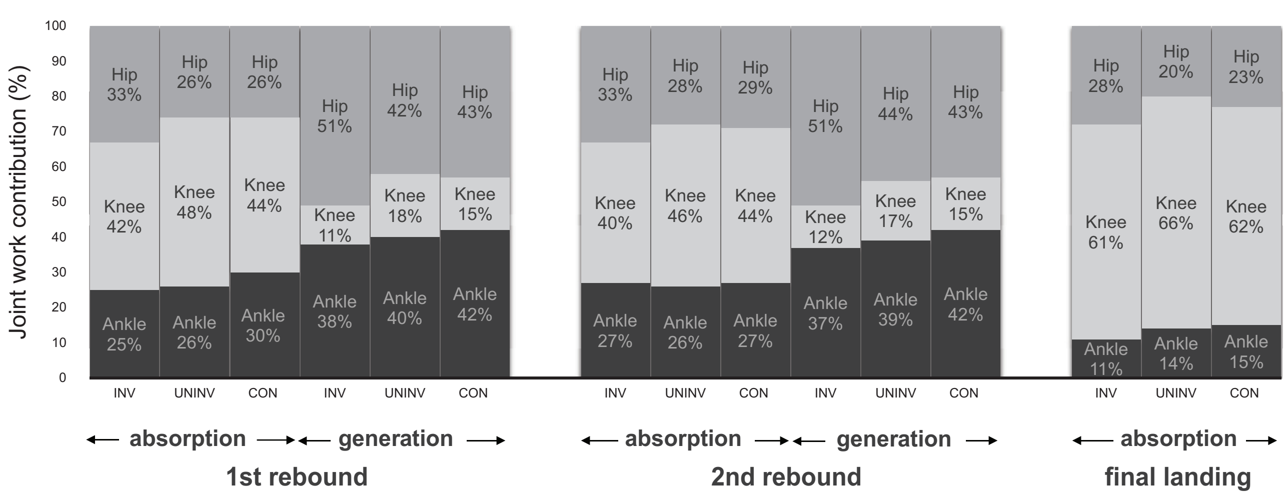

Figure 5. Average percentage work contributions from the hip, knee, and ankle joints for the involved limb (INV), the uninvolved limb (UNINV), and the controls (CON) during the 3 phases of the triple hop for distance. The rebound phases are presented as absorption/eccentric and generation/concentric. The involved knee had less contribution in all phases with compensatory increases at the hip joint. Detailed statistics are reported in Appendix Table A1 (available online).

distance,[22] indicating that the tests likely measure the same construct. Performance of the horizontal task (distance) is by default connected with the concentric phases; however, the contribution from the knee to the total work was minimal (Figure 5). From a clinical perspective, we suggest that, given the small contribution of the knee joint to the task, measuring hop distance largely tests hip and ankle function rather than knee function. Even when knee concentric ability to generate energy is lower in the involved limb than the uninvolved one, as in our cohort, athletes compensate with other lower limb joints and the upper body to achieve similar distance after ACLR.

The landing phase of the hop for distance evaluates dynamic stabilization and the ability of the knee to work eccentrically and absorb high impact forces. This stresses the importance of the biomechanical assessment and evaluation of patients' landing performance with the aim to guide rehabilitation and set objectives and progression criteria. However, given the high cost and expertise needed, a detailed biomechanical assessment is not routinely applicable in the clinical setting, especially in evaluating all phases of a triple hop. In the absence of this technology, measuring hop distance alone is not recommended owing to the clear possibility of false-negative findings. Other tests and metrics may be more sensitive to capture the progression and readiness of an athlete to RTS. Future research should focus on exploring more feasible options to help clinicians formulate an objective decision on the status of an athlete at RTS. It is also unknown if and how long the observed asymmetries at the time of discharge persist and if they predispose athletes to subsequent injury. Future work with large prospective studies is needed to evaluate the longitudinal changes in the asymmetries observed at the time of RTS and their associations with future injuries.

Limitations

For the first phase of the triple hop, data from 11 athletes after ACLR and 20 controls were available owing to changes in laboratory configuration, as 2 of the 5 force plates were no longer available. We chose to capture the second and third landings instead of the first and second. Consequently, findings of the first phase should be interpreted with caution. We also acknowledge the limitation in the generalizability of our results. The recruitment of only male athletes from a single site suggests interpretation of these results with caution in females, patients not participating in level I sports activities, and other populations with lower limb injuries. We acknowledge the skin motion artifacts relative to the underlying bone as a limitation of marker-based studies. However, we assume that all groups were affected similarly, thus not affecting our conclusions.

CONCLUSION

Symmetry in the triple hop for distance masked important deficits in knee joint work and other biomechanical parameters of interest after ACLR during the decision to progress to unrestricted RTS. These differences were more prominent during work generation (concentric phase) than work absorption (eccentric) in the triple hop for distance.

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