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Symmetry in triple hop distance hides asymmetries in knee function in ACL-reconstructed athletes at the time to return to sport

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Social media statement:

Triple hop for distance testing after #ACLR at #RTS

Symmetry in hop distance masks significant asymmetries in knee function after ACLR. Hop distance is not the best metric to use at the time to #RTS. Differences between limbs were more prominent during the power generation than the absorption phase.

@RoulaKotsifaki, @RodWhiteley, @KorakakisV, @RoaldBahr, @aspetar, @SamVanRossom, Ilse Jonkers @IJonkers, @PhilipGrahamSm2

ABSTRACT

Background: After ACL reconstruction (ACLR), a battery of strength and hop tests is frequently used to determine the readiness of an athlete to successfully return to sport. However, the ACL re-injury rate remains alarmingly high.

Purpose: To evaluate the lower limb function of athletes after ACL reconstruction (ACLR) at the time they had been cleared to return to sport (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 task.

Study Design: Cross-sectional controlled laboratory study

Methods: Integrated three-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 both their surgeon and physiotherapist, 2) completion of a sports-specific on-field rehabilitation program and 3) quadriceps strength and hop battery tests limb symmetry index (LSI) >90%. Lower limb and trunk kinematics were calculated, as well as knee joint moments and work. Between-limb (within ACLR subjects) and between-group differences (between ACLR subjects and controls) 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, ACLR subjects only demonstrated 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 lower, with a prominent compensation from the hip joint ($p<.001$, for all phases) compared to 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, the pelvis, and the trunk.

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

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

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

What is known about the subject: Our recent work on biomechanical outcomes during a single leg hop for distance revealed several kinematic and kinetic inter-limb deficits and alterations after ACLR, despite adequate hop distance performance at return to sport. In contrast, triple hop for distance in patients after ACLR has not been biomechanically evaluated, that includes all three landings. 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 can capture more information relevant to sporting activities where repeated movements are typically observed.

What this study adds to existing knowledge: We evaluated patients at the point they were cleared to RTS and after passing strict discharge criteria. We compared the involved limb not only with the control group but also with the uninvolved limb. Our findings suggest that three hops are no better than one; symmetry in triple hop distance hides asymmetries in knee function in ACL-reconstructed athletes and these asymmetries are more prominent during the generation than the absorption phases.

INTRODUCTION

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 sport (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 receive surgery are unable to return to preinjury levels of activity.[3] In addition, reinjury rate after ACLR is alarmingly high with studies reporting up to 19% of young athletes rupturing the reconstructed ACL, and up to 22% of young athletes suffering an ACL rupture in the contralateral (healthy) knee after RTS.[38]

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 towards a criteria-based progression and the use of a battery of tests for the decision to RTS.[2] Typically, symmetry between limbs is assessed with strength and hop test batteries.[16,23] The primary four hop tests used as part of a RTS test battery require horizontal propulsion; three of them include a rebound component (triple hop, cross-over hop, and 6m-timed hop) .[27] With these tests, a limb symmetry index (LSI) of >90% is recommended as a cut-off for safe RTS.[35]

The single leg hop for distance test is the most frequently used[1] and most explored in terms of biomechanics[21] in individuals after ACLR, compared to other hop tasks. A recent in-depth assessment of biomechanical outcomes during a single leg hop for distance revealed several kinematic and kinetic inter-limb deficits and alterations after ACLR, despite adequate hop distance performance at RTS; athletes after ACLR selectively unload the involved knee through hip and upper body kinematic adaptations.[22] In contrast, triple hop for distance in patients after ACLR has not been biomechanically evaluated, possibly due to the expensive equipment required to capture all three 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 one initial propulsive hop, followed by two 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] Plausibly the dynamic requirements of concentric (propulsive), eccentric (landing), and stretch-shortening (rebound) elements of the task better capture the spectrum of sporting requirements than isolated single jumps/hops.

Accordingly, we aimed to investigate the biomechanical function of ACLR-athletes during the triple hop for distance at RTS. 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 ACLR-athletes at the time of RTS as compared to healthy controls. Our hypothesis was that, despite achieving the 90% LSI threshold in the triple hop distance test and being cleared for RTS, athletes after ACLR would still display crucial biomechanical differences. Additionally, these differences would be more pronounced in the triple hop compared to the differences reported in the literature during the single hop for distance task.

METHODS

Participants

This laboratory study involved a case-control comparative analysis of an ACLR 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, Orthopeadic 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 both their surgeon and physiotherapist, 2) completion of a sports-specific on-field rehabilitation program, 3) quadriceps strength LSI>90%, and 4) hop battery tests LSI>90%.[23] ACLR patients were athletes (pre-injury Tegner score ≥7) with a complete, unilateral ACL injury, either with an autologous ipsilateral bone-patellar-tendon-bone or a hamstring graft (semitendinosus and/or gracilis), 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 prior 3 months. A convenience sample of 23 athletic (Tegner score ≥7) male control participants was also recruited by contacting healthcare providers and sports club doctors. Inclusion criteria were: age range of 18 to 35 years, participation in level I or II sports three times a week or more, and no history of musculoskeletal injury of the lower limb 3 months prior to testing.

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

TABLE 1

Patient Data[α]

	Group, No. or Mean ± SD		
	ACLR	Controls	P Value
Participants	24	23	
Age (years)	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 (kg/m^2)	23.3 ± 2.3	23.9 ± 1.6	.34
Tegner score pre-injury	8.9 ± 0.5	7.6 ± 1.2	<.001
IKDC %	95.6 ± 6.2	100	<.001
ACL-RSI %	93.6 ± 8.3	NA	NA
Quadriceps strength LSI %	95 ± 5	NA	NA
SLHD LSI %	97 ± 4	100 ± 5	.02
TRHD LSI %	97 ± 5	100 ± 5	.13
Return to sport (months)	9.5 ± 2.7	NA	NA
Hamstrings/BTB autograft, n	8/16		
Isolated ACL injury, n	14		
Meniscal injury, n	8		
Meniscal injury and cartilage lesion, n	2		

[α] ACLR, anterior cruciate ligament reconstruction; IKDC, International Knee Documentation Subjective Knee questionnaire; ACL-RSI, Anterior Cruciate Ligament-Return to Sport after Injury scale, LSI, limb symmetry index; SLHD, single leg hop for distance; TRHD, triple hop for distance; BTB, bone-patellar-tendon-bone. Independent-sample t tests were used for between groups comparison, significant difference (P < .05).

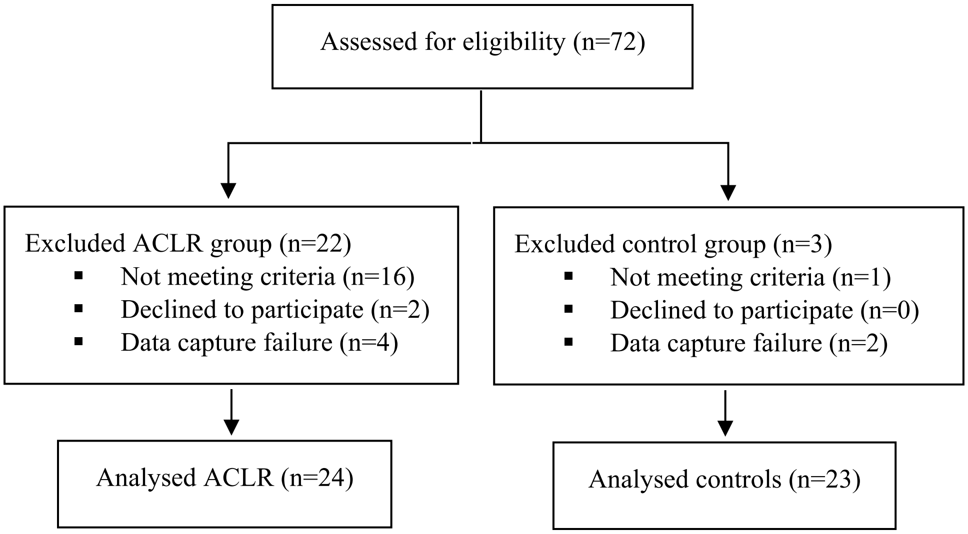

Figure 1. Study flow diagram. ACLR, anterior cruciate ligament reconstruction.

Equipment, participant preparation and markers set

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

Experimental setup, procedure, and testing

All participants were evaluated in the same laboratory by the same investigator and wore athletic shorts and standard shoes. They performed a 7-minute warm up session including running, side running, deep squats and double leg jumps. A physiotherapist provided verbal instructions and demonstrated the testing task. Subsequently, participants practiced the triple hop for distance while verbal feedback was provided until they felt comfortable to proceed 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 three consecutive hops as far as possible and landed 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 s. Data were collected for both limbs, and four successful trials were retained for analysis. Test limb order was randomised using a coin toss. For the first landing of the triple hop, data exist for 11 patients due to lab configuration changes. Limb dominance was determined by asking the participants with which limb they would prefer to kick a ball.[34]

Data processing

Data were processed in Visual 3D (C-Motion, Inc., Germantown, MD). Marker trajectories and ground reaction forces were low-pass filtered using a zero-lag, fourth order, Butterworth filter with the same 15Hz cut-off frequency. All data were extracted for the three 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 less than 50 N and more than 50 N, respectively.

Joint angles were determined using a Visual 3D hybrid model with a Cardan X-Y-Z (mediolateral, anteroposterior, vertical) rotation sequence.[10] Ankle, hip and knee joint angles were defined as the angle between the distal and the proximal segment. 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: hop distance, peak joint angles, peak knee internal joint moments, joint work and work contribution of each joint to the total work performed. Work generation was determined 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 three components. The work contribution of each joint was determined as percentage of the sum of the work of all three lower limb joints during each phase. Performing a triple hop involves an initial propulsive only phase, followed by two rebounding (landing then propulsive) phases, and a final landing (work absorption, eccentric) phase **(Figure 2)**. All variables were extracted for each phase separately. Work and knee moments were normalized to body mass. Hop distance was calculated as the difference of the heel marker from standing position to final landing and normalized to leg length (ASIS to lateral malleolus). LSI was determined as the percentage of the involved divided by the uninvolved limb for the ACLR group and non-dominant divided by dominant limb for the control group.[1,27] For the analysis we used a randomly selected control limb from each control.

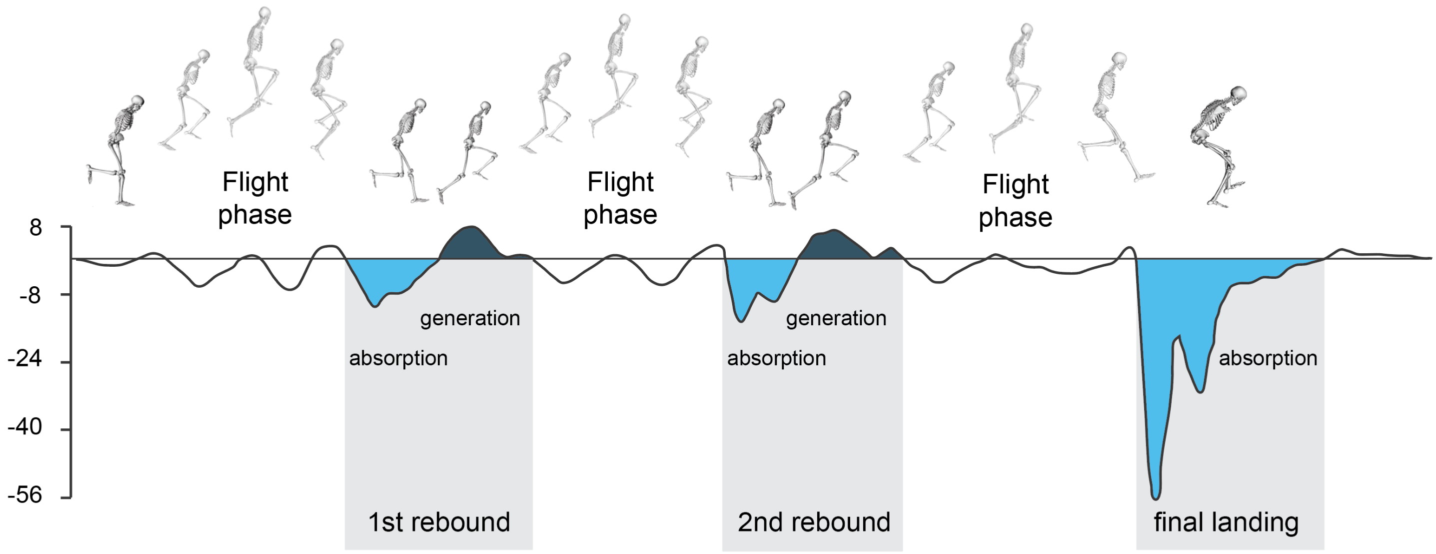

Figure 2. Representation of the three analysed phases (shaded regions of the knee power curve) of the triple hop for distance. After the initial propulsion phase to begin the first hop, there are two rebounds comprising first a landing with negative work (absorption, light blue shaded area) followed by positive work (propulsive, dark blue shaded area) components, 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.

Statistical analysis

Descriptive statistics were used to summarize the characteristics of the participants and measurements. Normality of distribution of data was assessed with the Shapiro-Wilk test[32] and by normal probability ("Q-Q") plots.[13] Between-limbs (involved, uninvolved and control) comparisons were assessed using mixed-effect models with subject-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 (BMI). P-value <0.05 was considered for statistical significance. Effect sizes (ES) were calculated using the pooled[9] (between-limb) and the pooled weighted[17] (between-group) standard deviation. 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. Groups did not differ in height, weight, or BMI (p>.05). Control participants were older (p<.001) and had lower Tegner score than the ACLR group (p<.001). ACLR group achieved 97.1% LSI during the triple hop. Normalized hop distance was 5.1 ± 0.4, 5.2 ± 0.4 and 5.2 ± 0.5 for the involved limb, uninvolved limb, and control group, respectively, with significant difference between limb in the ACLR group (p=.02).

Kinematics and kinetics

Athletes after ACLR landed on the involved limb with more hip flexion, trunk flexion, and anterior pelvic tilt than the uninvolved limb and the control subjects, in all three phases. Peak knee flexion angle was less in the involved limb than the uninvolved during all three phases. Knee flexion moments in the involved limb were lower than the uninvolved in all three phases. (**Table 2**).

Joint work

Knee work absorption in the involved was less than the uninvolved limb during the second rebound and the final landing **(Table 3 and Figure 3)**. Knee work generation was significantly less in the involved than the uninvolved limb and than controls during the first and second rebound. 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 rebound, respectively.

TABLE 2

Kinematic and Kinetic Comparison Between Groups During the Triple Hop for Distance$^{\alpha}$

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

$^{\alpha}$s, second; N, Newton; effect sizes are only shown where p<.05. **Bold** indicates statistically significant differences and their respective effect sizes.

TABLE 3

Joint Work Comparison Between Groups During the Triple Hop for Distance$^{\alpha}$

Variable		**Involved Limb**		**Uninvolved Limb**		**Controls**		**Involved – Uninvolved**		**Involved – Controls**		**Uninvolved – 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													
ABS	Hip joint work	-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 joint work	-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 joint work	-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 work	-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	
GEN	Hip joint work	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 joint work	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 joint work	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 work	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													
ABS	Hip joint work	-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 joint work	-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 joint work	-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 work	-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	
GEN	Hip joint work	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 joint work	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 joint work	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 work	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													
ABS	Hip joint work	-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 joint work	-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 joint work	-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 work	-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	

$^{\alpha}$J, Joules; ABS, absorption; GEN, generation; Effect sizes are only shown where p<.05. **Bold** indicates statistically significant differences and their respective effect sizes.

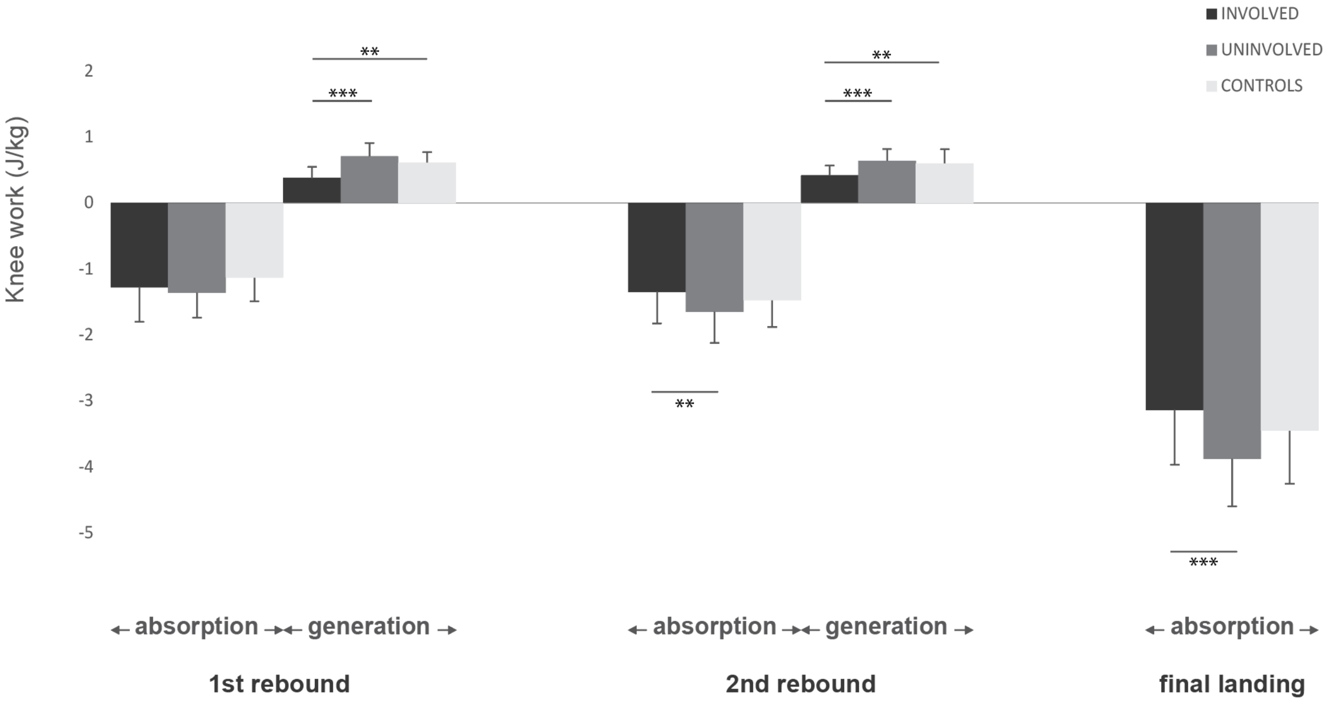

Figure 3. Knee work absorption (negative) and generation (positive) for the involved limb (black), the uninvolved (grey), and the controls (white) during the three phases of the triple hop for distance. Horizontal bars refer to the significant difference found for the knee work done between groups. **P<.01. ***P<.001.

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 to the uninvolved limb and the control group. Participants after ACLR displayed less total work absorption in the involved than the uninvolved limb during the second rebound and the final landing. Also, the involved limb produced less total work (generation) than the uninvolved and controls during both rebound phases **(Table 3 and Figure 4).**

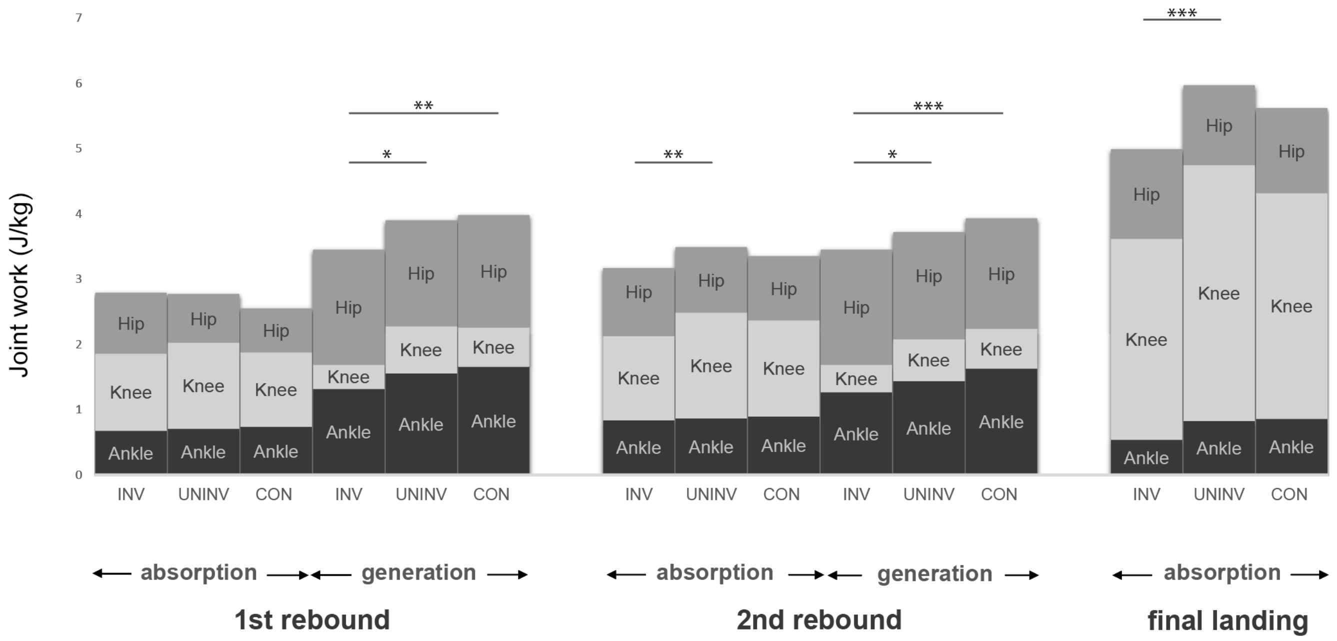

Figure 4. Visualization of work (absorption and generation) of the hip, knee, and ankle joints for the involved limb (INV), the uninvolved limb (UNINV), and the controls (CON), during the three phases of the triple hop for distance. During absorption work is negative and during generation work is positive.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

TABLE 4

LSI of the Knee Work Generation and Absorption During the Different Phases of the Triple Hop for Distance$^{\alpha}$

Limb Symmetry Index	Group	
	ACLR	Control
1st rebound absorption	89%	104%
1st rebound generation	51%	98%
2nd rebound absorption	80%	97%
2nd rebound generation	66%	99%
final landing absorption	79%	102%

$^{\alpha}$LSI, Limb Symmetry Index; absorption (eccentric phase); generation (concentric phase).

Work contribution

During both work generation phases of the triple hop, there was a lower percentage contribution of the involved knee compared to the uninvolved and a higher contribution of the involved hip joint compared to the uninvolved 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 the uninvolved limb (p<.001) and less ankle work contribution than controls (p=.038).

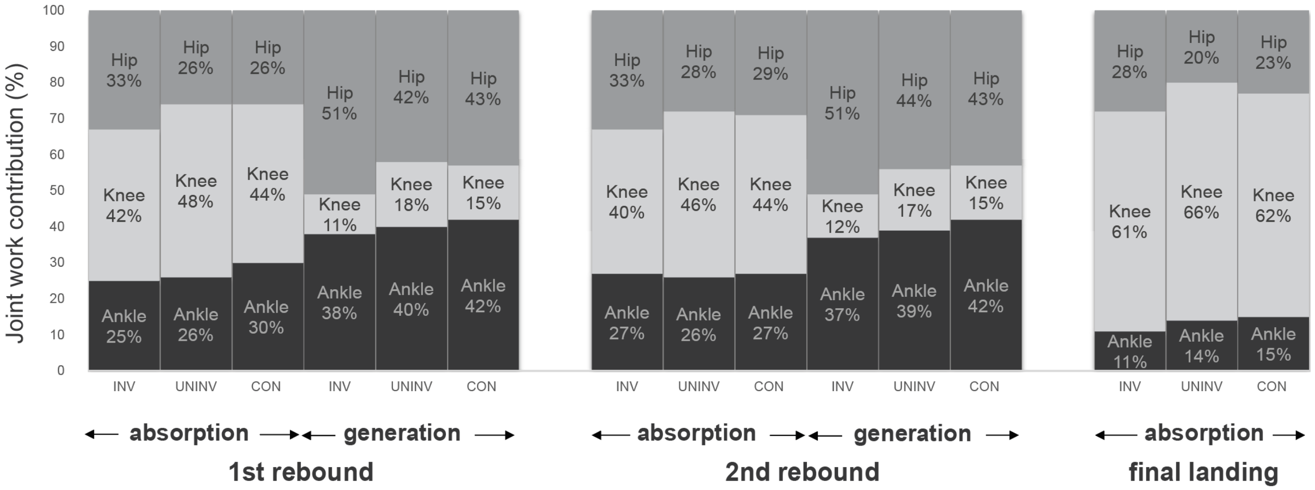

Figure 5. Average percentage work contributions from the hip, knee, and ankle joints for the involved limb (INV), the uninvolved limb (UNINV), and the controls (CON), during the three phases of the triple hop for distance. The rebound phases are presented as absorption/eccentric and generation/concentric.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

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 threshold of 90% LSI is recommended in the literature,[16,23,35] this small difference was not deemed to be 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 compared to the uninvolved limb. ACL injury often occurs in the initial phase of the eccentric landing.[19] After ACLR, our data revealed that athletes shift the demands away from the involved knee, plausibly for protection–a mechanism also seen in the single leg hop for distance landing.[22,28,39] The adoption of a different upper body compensatory strategy might be a possible mechanism to reduce lower limb loading.

Work absorption and generation at the hip were not different between groups. However, the involved knee joint contributed less and the hip joint more to the total work generation and absorption compared to the uninvolved limb during all phases of the triple hop. This compensation can be interpreted as an attempt to unload the involved knee thereby increasing hip load as was 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. Assessing all phases of the triple hop, 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%) although not passing the 90% symmetry threshold. On the other hand, during the first and second rebound phase the LSI for knee work generation was only 54% and 66%, respectively, for the ACLR group. These asymmetries in knee work during hops are 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 only reflects the overall performance of a biomechanically multidimensional task, which involves function and coordination of three lower limb individual joints.[20,22]

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

Comparison of the triple hop to a single hop test

ACLR-athletes compensated for lower 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 LSI of the distance hopped. Similar results have been reported for the single leg hop for distance.[22] Compared to the single hop for distance task, we found similar whole body compensatory adaptations and differences in work absorption between limbs. However, these differences where not more pronounced in the triple hop as was our initial hypothesis. A strong correlation (r=.84) for the hop distance between these two 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, as well as possibly providing insight of the capacity of the musculotendinous system to absorb and release energy due 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 there only were differences in contact time between limbs during the second rebound in the ACLR group; however, this did not seem to affect their 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-specific requirements, as well as the capacity of the tendon tissue, which inarguably has been affected during the long-lasting recovery from surgery.

Clinical implications

Symmetry in performance of a triple hop masks 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 distance[22], indicating that both 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 is minimal **(Figure 5)**. From a clinical perspective, we suggest that, given the low contribution of the knee joint to the task, measuring hop distance largely tests the hip and ankle function rather than the knee. Even when knee concentric ability to generate energy is lower in the involved limb than the uninvolved, as in our cohort, ACLR-athletes compensate from other lower limb joints and the upper body to achieve similar distance.

The landing phase of the hop for distance tests 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, due to the high cost and the expertise needed, a detailed biomechanical assessment is not routinely applicable in the clinical setting, especially evaluating all phases of a triple hop. In the absence of this technology, measuring hop distance alone is not recommended due to the clear possibility of false negative findings. Other tests and metrics may be more sensitive to capture the progression and the 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 for subsequent injury. Future work with large prospective studies is needed to evaluate the longitudinal changes in the asymmetries observed at the time to return to sport 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 due to changes in lab configuration as two of the five force plates were no longer available. We chose to capture the second and the third landing instead of the first and the 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 males, 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 the marker-based studies. However, we assume that all groups were affected similarly, thus not affecting our conclusions.

CONCLUSION

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

Supplementary file

TABLE S1

Joint Work Percentage Contribution Comparison Between Groups During the Triple Hop for Distance[α]

Joint Work Contribution (%)		Involved Limb		Uninvolved Limb		Controls		Involved – Uninvolved		Involved – Controls		Uninvolved – Controls	
		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													
ABS	Hip joint	33.2 ± 6.8	28.6 to 37.7	26.1 ± 5.7	22.3 to 29.9	26.1 ± 5.7	23.4 to 28.8	**0.006**	**1.13**	**0.002**	**1.11**	0.67	
	Knee joint	41.6 ± 7.8	36.3 to 46.8	47.6 ± 6.6	43.2 to 52.0	43.8 ± 11.6	38.4 to 49.3	**0.018**	**-0.83**	0.82		0.59	
	Ankle joint	25.3 ± 11.6	17.5 to 33.1	26.3 ± 8.5	20.6 to 32.0	30.1 ± 10.7	25.1 to 35.1	0.94		0.46		0.61	
GEN	Hip joint	51.1 ± 6.4	46.8 to 55.4	41.9 ± 6.1	37.8 to 46.0	43.2 ± 4.3	41.1 to 45.2	**<0.001**	**1.47**	**0.006**	**1.42**	0.28	
	Knee joint	10.9 ± 5.0	7.5 to 14.3	18.4 ± 4.1	15.7 to 21.2	15.1 ± 3.4	13.5 to 16.7	**<0.001**	**-1.64**	0.09		**0.036**	**0.86**
	Ankle joint	38.0 ± 4.6	34.9 to 41.1	39.7 ± 5.1	36.3 to 43.2	41.7 ± 4.2	39.8 to 43.7	0.38		0.09		0.47	
SECOND REBOUND													
ABS	Hip joint	32.8 ± 9.4	28.8 to 36.8	28.5 ± 7.0	25.5 to 31.4	29.3 ± 6.5	26.5 to 32.1	**0.019**	**0.52**	0.27		0.92	
	Knee joint	40.2 ± 8.2	36.8 to 43.7	45.9 ± 9.1	42.1 to 49.8	43.5 ± 8.4	39.9 to 47.2	**0.020**	**-0.66**	0.39		0.61	
	Ankle joint	26.9 ± 8.2	23.5 to 30.4	25.6 ± 10.4	21.2 to 30.0	27.1 ± 6.9	24.1 to 30.1	0.60		0.98		0.58	
GEN	Hip joint	50.5 ± 7.2	47.5 to 53.6	44.2 ± 6.5	41.4 to 46.9	42.9 ± 6.1	40.2 to 45.5	**<0.001**	**0.92**	**<0.001**	**1.12**	0.78	
	Knee joint	12.3 ± 4.4	10.5 to 14.2	17.2 ± 4.3	15.4 to 19.1	15.5 ± 5.3	13.2 to 17.8	**<0.001**	**-1.13**	**0.013**	**-0.65**	0.83	
	Ankle joint	37.1 ± 5.3	34.9 to 39.3	38.6 ± 5.3	36.3 to 40.8	41.6 ± 4.1	39.8 to 43.4	0.44		**0.009**	**-0.93**	0.10	
FINAL LANDING													
ABS	Hip joint	27.6 ± 6.1	25.0 to 30.2	20.4 ± 7.6	17.2 to 23.6	23.3 ± 6.5	20.5 to 26.2	**<0.001**	**1.04**	0.11		0.19	
	Knee joint	61.4 ± 8.6	57.8 to 65.0	65.6 ± 8.1	62.1 to 68.9	61.5 ± 6.9	58.4 to 64.4	**0.038**	**-0.49**	0.95		0.10	
	Ankle joint	11.0 ± 6.5	8.2 to 13.7	14.1 ± 5.9	11.6 to 16.6	15.3 ± 5.4	12.9 to 17.6	0.13		**0.008**	**-0.71**	0.52	

[α] ABS, absorption; GEN, generation; Effect sizes are only shown where p<.05. **Bold** indicates statistically significant differences and their respective effect sizes.

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