Can Symmetry of Single-Leg Vertical Jump Height Represent Normal Lower Limb Biomechanics of Athletes After Anterior Cruciate Ligament Reconstruction?

Peng Chen, MSc,[†‡] Ling Wang, MSc,[†‡] Shiyu Dong, MMed,[§] Yue Ding, MSc,[†‡] Shaohui Jia, PhD,[†||] and Cheng Zheng, PhD, MD[¶*]

Background: After anterior cruciate ligament reconstruction (ACLR), single-leg horizontal hop distance limb symmetry index (LSI) >90% is recommended as a cutoff point for safe return to sport (RTS). However, athletes after ACLR have abnormal lower limb biomechanics despite an adequate single-leg hop distance LSI, implying that athletes are at high risk of reinjury. Symmetry of single-leg vertical jump height appears to be more difficult to achieve and can be a better representation of knee function than single-leg horizontal hop distance.

Hypothesis: Athletes after ACLR with single-leg jump height LSI >90% had similar biomechanical characteristics to healthy athletes.

Study Design: Controlled laboratory study.

Level of Evidence: Level 3.

Methods: A total of 46 athletes after ACLR were divided into low jump height (LJH, jump height LSI <90%, n = 23) and high jump height (HJH, jump height LSI >90%, n = 23) groups according to symmetry of single-leg vertical jump height, while 24 healthy athletes acted as a control (CONT) group. One-way analysis of variance was used to compare the kinematic and kinetic characteristics of the LJH, HJH, and CONT groups during single-leg vertical jump.

Results: Both the LJH and HJH groups demonstrated greater limb asymmetry (lower LSI) during landing compared with the CONT group in knee extension moment ($P < 0.05$), peak knee flexion angle ($P < 0.05$), and knee power ($P < 0.05$).

Conclusion: Symmetry in single-leg vertical jump height does not represent normal lower limb biomechanics in athletes after ACLR.

Clinical Relevance: Symmetrical jump height may not signify ideal biomechanical or RTS readiness, but single-leg vertical jump test can be used as a supplement to horizontal hop test or other functional tests to reduce the likelihood of false-negative results in the absence of detailed biomechanical evaluation.

Keywords: anterior cruciate ligament reconstruction; biomechanics; horizontal hop; limb symmetry index; return to sport; vertical jump

From [†]School of Sports Medicine, Wuhan Sports University, Wuhan, Hubei Province, China, [‡]Key Laboratory of Sports Engineering of General Administration of Sport of China, Wuhan Sports University, Wuhan, Hubei Province, China, [§]College of Basic Medicine of Fujian Medical University, Fuzhou, Fujian Province, China, [||]Hubei Provincial Key Laboratory of Sports Training and Monitoring, Wuhan Sports University, Wuhan, Hubei Province, China, and [¶]Department of Sports Medicine, Affiliated Hospital, Wuhan Sports University, Wuhan, Hubei Province, China

*Address correspondence to Cheng Zheng, MD, PhD, Department of Sports Medicine, Affiliated Hospital, Wuhan Sports University, 461 Luoyu Road, Hongshan District, Wuhan City, Hubei Province 430079, China (email: zchmily5460@126.com).

P.C. and L.W. contributed equally to this article and share first authorship.

The authors report no potential conflicts of interest in the development and publication of this article.

This work was supported by the Donghu Scholar Program of Wuhan Sports University and Research Fund for Young Teachers of Wuhan Sports University (No. 20Z01), and Young and Middle-Aged Scientific Research and Innovation Team Project of Wuhan Sports University (No. 21KT14).

DOI: 10.1177/19417381231190119

Rupture of the anterior cruciate ligament (ACL) is one of the most common knee injuries.[43] As the main static and dynamic stable structure of the knee joint, the ACL is essential to maintain normal movement and stability of this joint. ACL rupture can cause instability and decreased function of the knee joint, eventually developing into degenerative joint disease due to recurrent episodes of instability.[9] ACL reconstruction (ACLR) is considered the gold standard for regaining stability and improving knee function.[21,37] However, surgery is only 1 component of a successful treatment regimen. Up to 35% of patients do not return to their preinjury level of sport.[3] Furthermore, nearly a quarter of young athletes develop ACL reinjuries after return to sport (RTS).[56]

Many scholars have conducted studies on rehabilitation programs after ACLR, but the criteria for RTS have not been clearly defined.[15] Traditionally, muscle strength ratio of involved/uninvolved side and functional indicators have been used as criteria for RTS in patients after ACLR.[6,14] Potential causes of ACL reinjury are multifactorial, including deficits in muscle strength and/or functional performance considered in traditional RTS testing, and abnormal biomechanical characteristics of patients after ACLR.[28] The high incidence of ACL reinjury in athletes may be due to defects in the current RTS standards criteria.[28,53]

Biomechanical analysis of the movement quality in patients after ACLR can provide valuable information for identifying abnormal loading strategies and determining the timing of RTS.[1] However, biomechanical tests are not universally available due to equipment requirements and financial burdens. It is important for rehabilitation professionals to identify simple and reliable tools for measuring functional outcomes after ACLR. A common method for assessing RTS readiness in ACLR patients in the clinic is to use a combination of subjective and objective measurements, including isokinetic strength testing, single-leg horizontal hop test, knee examination, patient-reported outcome measures, neuromuscular control assessments, and psychological tests.[5,15] The single-leg horizontal hop test is often used to assess lower limb muscle strength and the ability of the patient to perform challenging knee stability tasks.[42] The hop distance reflects the overall performance of hip, knee, and ankle function and coordination, and is representative of the demands of high-level exercise.[18] In addition, the single-leg horizontal hop test, which has no time or space limitations, can be implemented widely and the results are easy to interpret. Therefore, the single-leg horizontal hop test is now used widely in the evaluation of patient RTS after ACLR.

Most studies recommend a hop distance limb symmetry index (LSI) >90% as 1 of the criteria for RTS after ACLR.[1,10] However, after ACLR, patients have abnormal lower limb biomechanics despite an adequate single-leg hop distance LSI,[55,57] implying that patients are at high risk of reinjury. In single-leg horizontal hop, the contribution of hip, knee, and ankle joints to the hop distance is 44.3%, 12.9%, and 42.8%, respectively.[23] The single-leg horizontal hop distance seems to be determined mainly by the hip and ankle joints, and does not fully reflect knee joint function. Single-leg vertical jump places high demands on joint load and range of motion.[18,19,34] Kotsifaki et al[24] found that, after ACLR, athletes achieved 97% symmetry in single-leg horizontal hop distance, but only 83% symmetry in single-leg vertical jump height. Moreover, in single-leg vertical jump, the hip, knee, and ankle joints contribute roughly similarly to vertical jump height, and vertical jump height is determined by the hip, knee, and ankle joints together.[23] Vertical jump height symmetry appears to be more difficult to achieve than hop distance symmetry and can be a better representation of knee function. Whether jump height LSI >90% can represent good lower limb biomechanics has not been explored. Based on this, the present study evaluated the kinematic and kinetic characteristics of athletes after ACLR with jump height LSI >90% during single-leg vertical jump. We hypothesized that athletes after ACLR with jump height LSI >90% had biomechanical characteristics similar to those of healthy athletes.

METHODS

Study Design

This laboratory study involved a case-control comparative analysis of an ACLR cohort and a healthy cohort. All participants were informed about the test process and signed an informed consent form. This study was approved by the medical ethics committee of Wuhan Sports University (No. 2022023).

Participants and Eligibility Criteria

A total of 70 athletes participated in this study: 46 athletes after ACLR and 24 healthy athletes (Table 1). The ACLR cohort athletes were eligible for enrollment if they (1) suffered a complete unilateral ACL injury and were treated with an autologous ipsilateral bone-patellar tendon-bone or hamstring tendon graft (semitendinosus and/or gracilis tendon); (2) were cleared for return to all high-level athletic activities by their surgeon and treating rehabilitation specialist, and intended return to cutting and pivoting sports on a regular basis (≥50 hours per year)[44]; (3) had a hop distance LSI >90% in the single-leg horizontal hop test; (4) engaged in a certain sport and had a Tegner score ≥7 preinjury; (5) were informed and willing to cooperate; and (6) had no mental or psychological disorders and could follow medical advice. Athletes were excluded if they (1) had concomitant grade III knee ligament injury, full-thickness articular cartilage lesion, history of other lower limb surgery (in either limb), back pain, or lower limb injury in the previous 3 months; (2) could not complete the tasks; and (3) had missed motion-analysis data during jumping.

Athletes after ACLR were not enrolled consecutively. Athletes after ACLR were included retrospectively in the current investigation if they met the inclusion criteria and if biomechanical variables were collected at the time they were cleared to RTS. Athletes were assigned to the low jump height (LJH, jump height LSI <90%, n = 23) or high jump height (HJH, jump height LSI >90%, n = 23) group based on the LSI of single-leg vertical jump height, while 24 healthy athletes were recruited as the control (CONT) group.

Table 1. Participant characteristics

	LJH Group	HJH Group	CONT Group	*P* Value
Participants	23	23	24	
Sex, female/male	8/15	6/17	12/12	0.25
Age, y	21.9 ± 1.5	21.5 ± 1.3	22.5 ± 1.5	0.06
Height, cm	172.6 ± 10.5	174.9 ± 7.5	173.5 ± 6.7	0.64
Body mass, kg	64.7 ± 10.4	67.1 ± 9.0	63.1 ± 8.6	0.34
Body mass index	21.6 ± 1.7	21.9 ± 2.0	20.9 ± 1.6	0.15
Injured side left/right	13/10	16/7		0.54
Tegner score preinjury	8.2 ± 0.7	8.3 ± 0.6	8.2 ± 0.6	0.95
IKDC score	94.5 ± 2.5	95.7 ± 2.4	100	<0.01[a,b]
SLHHD LSI, %	94.8 ± 3.3	98.3 ± 3.0	99.8 ± 3.3	<0.01[a,c]
SLVJH LSI, %	78.8 ± 5.1	98.3 ± 5.1	101.0 ± 5.7	<0.01[a,c]
Time since surgery, mo	15.3 ± 4.5	16.4 ± 5.7		0.45
Hamstring tendon/BTB autograft	13/10	12/11		≥0.99
Isolated ACL injury	18	16		
Meniscal injury	5	7		

BTB, bone-tendon-bone; CONT, control; HJH, high jump height; IKDC, International Knee Documentation Committee; LJH, low jump height; LSI, limb symmetry index; SLHHD, single-leg horizontal hop distance; SLVJH, single-leg vertical jump height.
[a]Significantly different between LJH and CONT groups.
[b]Significantly different between HJH and CONT groups.
[c]Significantly different between LJH and HJH groups.

Procedures

Equipment, Participant Preparation, and Marker Set

Participants first performed a standardized warm-up, including bodyweight squats, lunges, high kicks, high knees, and repeated jumps in place, and then 38 reflective markers were applied (left and right anterior superior iliac spine, iliac crest, posterior superior iliac spine, greater trochanter of the femur, lateral femoral condyle, medial femoral condyle, lateral malleolus, medial malleolus, heel, first metatarsal head, fifth metatarsal head, and 4 markers on the side of each thigh and shank). Furthermore, participants were allowed to familiarize themselves with the test procedures by performing 2 or 3 practice repetitions before each test. A 9-camera infrared high-speed motion capture system was applied to collect kinematic parameters of the lower limb during single-leg vertical jumping (Vicon; 200 Hz). The kinetic parameters were collected synchronously with marker trajectories using 4 ground-embedded force plates (1000 Hz; Kistler).

Testing Protocol

For measurement of single-leg vertical jump performance, participants stood upright on a single leg on a force plate with their hands held across their chest for interference prevention, and followed a standardized procedure. Participants performed a downward motion until they reached their preferred self-selected depth, and then jumped vertically with maximum effort and landed on the same force plate (Figure 1).[24] Jumping was considered successful if landing occurred within the visual field of the motion analysis system and the subject was able to maintain balance for more than 2 seconds after landing. If the position of the tested leg moved after the subject landed, it was remeasured until 3 jumps were successful, and the average of the 3 jumps was selected for analysis. The order in which the limbs were tested was assigned randomly using a coin toss.

Data Processing

Data were processed using Visual 3D (Version 5.0 C-Motion). Marker position and ground-reaction force (GRF) were filtered using a Butterworth filter with a cutoff frequency at 12 Hz, which minimizes artifacts during inverse dynamic analysis in high-impact activities.[20,27,39] Initial contact and take-off were expressed as the point when vertical GRF (vGRF) became >50 and <50 N, respectively. The propulsion phase was defined as 400 milliseconds before toe-off until toe-off. The landing

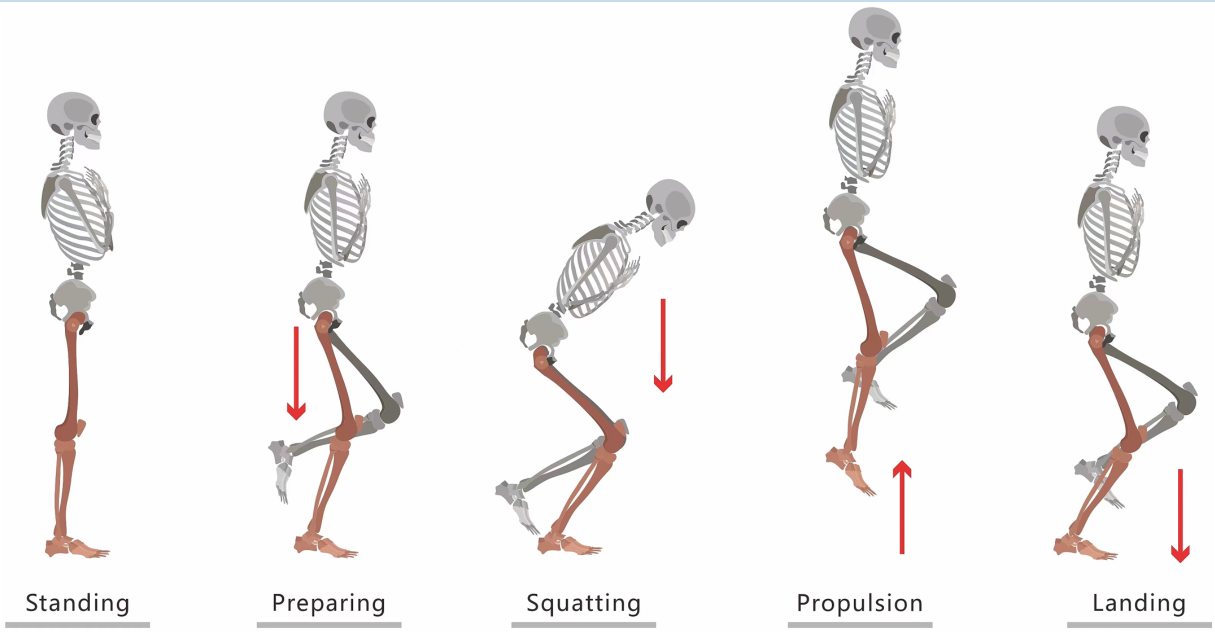

Figure 1. Visual representation of the tasks investigated. Single-leg vertical jump was analyzed during the propulsion and landing phase.

phase was defined as the time interval from postinitial contact to 250 milliseconds after landing, because this time interval captures the primary loading phase of the knee during landing.[29] This is also considered the most vulnerable stage for the ACL. The kinematic variables of interest were peak hip, knee, and ankle angles in the sagittal plane, and the kinetic variables of interest were average hip, knee, and ankle moment in the sagittal plane; average hip, knee, and ankle power in the sagittal plane; and average vGRF. All variables were extracted for the propulsion and landing phases separately. Standard inverse dynamics analysis was used to calculate kinetic variables at the ankle, knee, and hip. Joint angles of ankle up to hip segments were calculated in reference to the proximal segments. All kinematic variables were normalized by body weight. To assess symmetry between limbs, the kinematic and kinetic variables for the injured/nonpreferred limb were normalized to the uninjured/preferred limb using the LSI ([injured or nonpreferred limb/uninjured or preferred limb] × 100), with a value 100 reflecting perfect symmetry. The limb advantage of the healthy control group was determined by asking the participants which limb they would prefer to kick a ball with.[52] Jump height was calculated using the take-off vertical velocity derived from the vGRF signal using the impulse-momentum theorem.[22]

Statistical Analysis

An a priori power analysis (G*Power, Version 3.1.2) was performed to determine the appropriate sample size for the entirety of the study. After calculations, we determined the sample size of 22 participants per group was required to achieve a power of 0.80, with an alpha level of 0.05. IBM SPSS Version 25.0 was used for processing, and $P < 0.05$ was considered statistically significant. Descriptive analysis of demographic data included calculation of frequencies for categorical data, and means and standard deviations for continuous data. Participant demographics between different groups were compared using Fisher-Freeman-Halton for categorical variables and 1-way analysis of variance (ANOVA) for continuous variables. Kinematics and kinetics were compared between groups using 1-way ANOVA. If significant differences between groups were found, post hoc tests were performed using Bonferroni. Normality was confirmed with the Shapiro-Wilk test and equal variance was confirmed with the Levene test.

RESULTS

Groups did not differ in sex distribution, age, height, body mass, body mass index, or Tegner score preinjury ($P > 0.05$). The LJH group reported lower single-leg horizontal hop distance LSI and single-leg vertical jump height LSI than both the HJH and the CONT groups ($P < 0.05$). Both the LJH and the HJH groups reported worse IKDC scores than the CONT group ($P < 0.05$).

Propulsion Phase

For LSI of the variables of interest during propulsion, 1-way ANOVA revealed group differences in peak knee flexion angle ($P < 0.01$) (Figure 2b), peak ankle dorsiflexion angle ($P < 0.01$) (Figure 2c), knee extension moment ($P < 0.01$) (Figure 3b), knee power ($P < 0.01$) (Figure 4b), ankle power ($P = 0.01$)

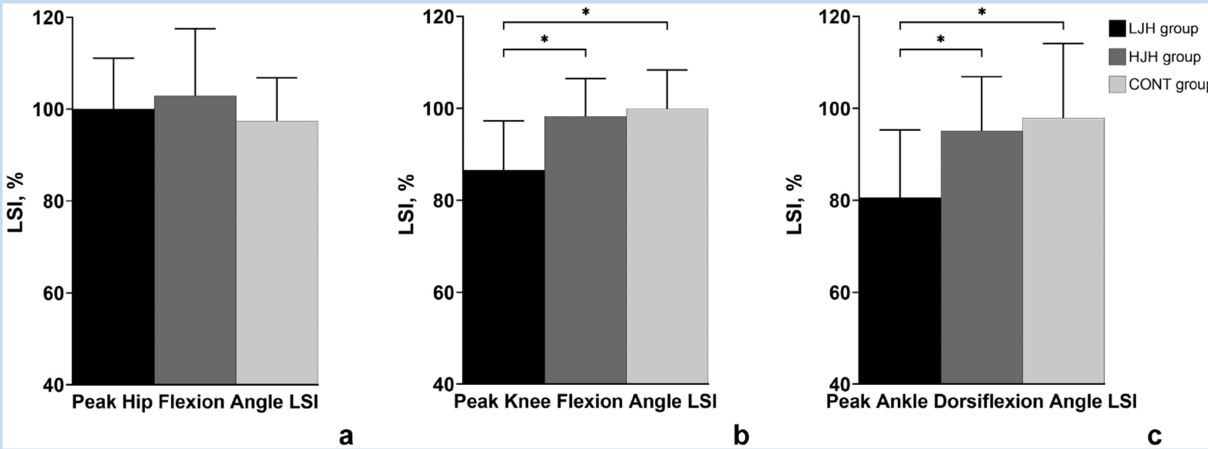

Figure 2. Group comparison of LSI during propulsion of the single-leg vertical jump for (a) peak hip flexion angle, (b) peak knee flexion angle, and (c) peak ankle dorsiflexion angle. *$P < 0.05$ for pairwise comparison. CONT, control; HJH, high jump height; LJH, low jump height; LSI, limb symmetry index.

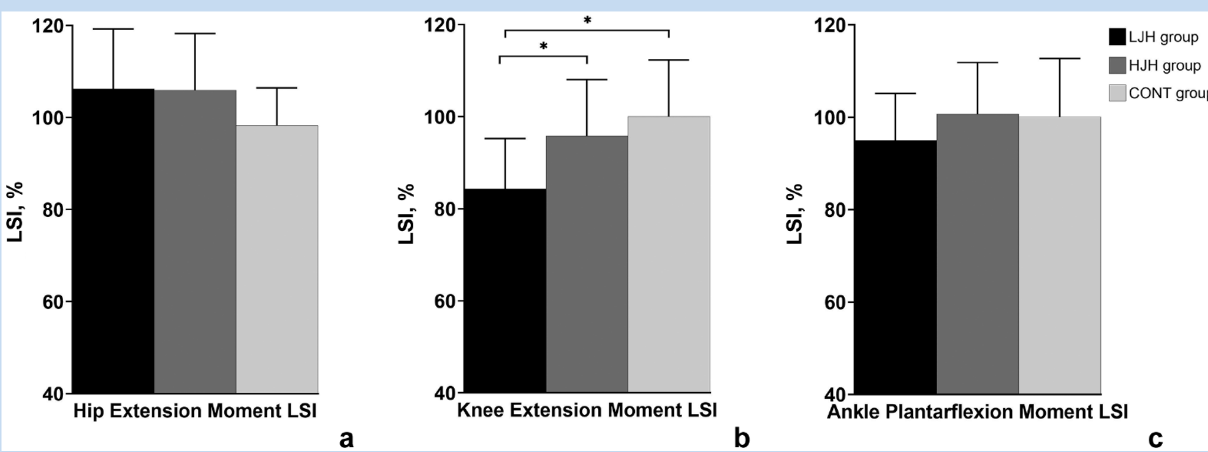

Figure 3. Group comparison of LSI during propulsion of the single-leg vertical jump for (a) hip extension moment, (b) knee extension moment, and (c) ankle plantarflexion moment. *$P < 0.05$ for pairwise comparison. CONT, control; HJH, high jump height; LJH, low jump height; LSI, limb symmetry index.

(Figure 4c), the total power of lower limb ($P < 0.01$) (Figure 5a), and vGRF ($P < 0.01$) (Figure 5b). Pairwise comparisons revealed that LJH groups demonstrated greater limb asymmetry (lower LSI) during landing compared with the HJH and CONT groups in peak knee flexion angle ($P < 0.01$ and $P < 0.01$, respectively), peak ankle dorsiflexion angle ($P < 0.01$ and $P < 0.01$, respectively), knee extension moment ($P < 0.01$ and $P < 0.01$, respectively), knee power ($P < 0.01$ and $P < 0.01$, respectively), the total power of lower limb ($P < 0.01$ and $P < 0.01$, respectively), and vGRF ($P < 0.01$ and $P < 0.01$, respectively). Compared with the HJH group, the LJH group demonstrated greater limb asymmetry (lower LSI) in peak ankle power ($P = 0.03$).

Landing Phase

For LSI of the variables of interest during landing, 1-way ANOVA revealed group differences in peak knee flexion angle ($P < 0.01$), peak ankle dorsiflexion angle ($P < 0.01$), hip extension moment ($P = 0.02$), knee extension moment ($P < 0.01$), hip power ($P = 0.01$), knee power ($P < 0.01$), ankle power ($P < 0.01$), and total power of the lower limb ($P < 0.01$) (Table 2). Pairwise comparisons revealed that both the LJH and HJH groups demonstrated greater limb asymmetry (lower LSI) during landing compared with the CONT group in peak hip flexion angle ($P < 0.01$ and $P = 0.02$, respectively), knee extension moment ($P < 0.01$ and $P < 0.01$, respectively), and knee power

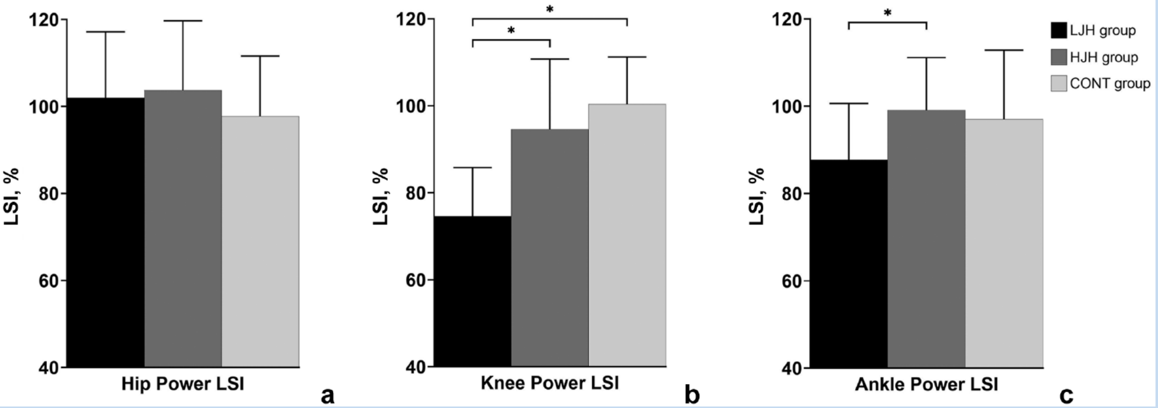

Figure 4. Group comparison of LSI during propulsion of the single-leg vertical jump for (a) hip power, (b) knee power, and (c) ankle power. *$P < 0.05$ for pairwise comparison. CONT, control; HJH, high jump height; LJH, low jump height; LSI, limb symmetry index.

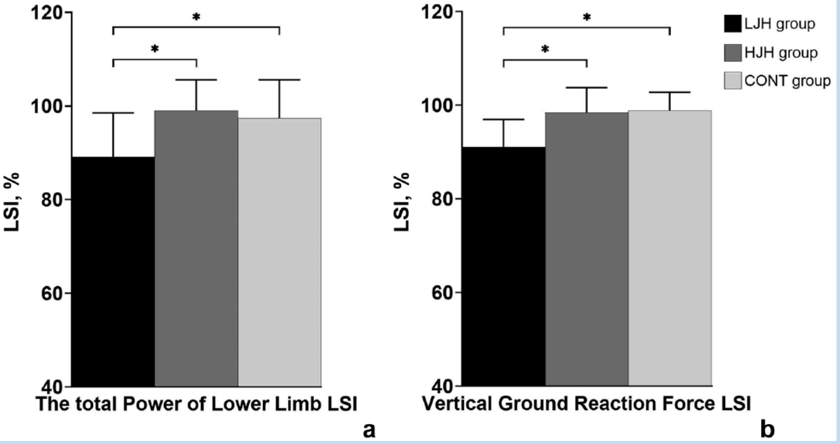

Figure 5. Group comparison of LSI during propulsion of the single-leg vertical jump for (a) the total power of lower limb, (b) vertical ground-reaction force. *$P < 0.05$ for pairwise comparison. CONT, control; HJH, high jump height; LJH, low jump height; LSI, limb symmetry index.

($P < 0.01$ and $P = 0.03$, respectively). Compared with the CONT group, the LJH group demonstrated greater limb asymmetry (lower LSI) in peak ankle dorsiflexion angle ($P = 0.03$), ankle power ($P = 0.01$), and total power ($P < 0.01$). Compared with the CONT group, the HJH group demonstrated greater limb asymmetry (higher LSI) in hip extension moment ($P = 0.02$). Compared with the CONT and LJH groups, the HJH group demonstrated greater limb asymmetry (higher LSI) in hip power ($P = 0.02$ and $P = 0.04$, respectively). Compared with the HJH group, the LJH group demonstrated greater limb asymmetry (lower LSI) in peak ankle dorsiflexion angle ($P = 0.03$), knee power ($P = 0.03$), and total power of the lower limb ($P = 0.02$).

DISCUSSION

The objective of this study was to explore whether the symmetry of jump height could reflect the normal lower limb biomechanical characteristics of athletes after ACLR. The results revealed that athletes after ACLR with jump height LSI >90% exhibited more symmetrical lower limb biomechanics compared with athletes after ACLR with a single-leg vertical jump height LSI <90%. However, athletes after ACLR with jump height LSI >90% still have abnormal lower limb biomechanics compared with healthy athletes.

Propulsion Phase

Patients after ACLR tend to compensate for lower knee power with higher hip and ankle power during the propulsion phase in single-leg horizontal hop.[36] In contrast, we did not find this compensatory pattern in single-leg vertical jump. The LJH group showed a decrease in knee power during the propulsion phase, and neither the LJH group nor the HJH group showed an increase in hip power or ankle power. The hop distance is easily perceived in horizontal hop, and the attention of the patient may

Table 2. Comparison between groups during landing of the single-leg vertical jump

Variable	LJH Group (n = 23)		HJH Group (n = 23)		CONT Group (n = 24)		*P* Value
	Mean ± SD	95% CI	Mean ± SD	95% CI	Mean ± SD	95% CI	
Peak joint motion LSI, %							
Hip flexion	96.71 ± 18.49	88.72-104.70	103.00 ± 22.60	93.23-112.78	99.23 ± 14.03	93.31-105.15	0.52
Knee flexion	85.43 ± 8.60	81.71-89.14	92.22 ± 12.16	86.96-97.48	100.77 ± 10.81	96.20-105.33	<0.01[a,b]
Ankle dorsiflexion	73.37 ± 16.39	66.28-80.45	89.29 ± 24.07	78.88-99.70	99.62 ± 19.92	91.20-108.03	<0.01[a,c]
Joint moment LSI, %							
Hip extension	99.68 ± 16.31	92.63-106.73	108.45 ± 16.56	101.29-115.61	97.29 ± 6.76	94.44-100.15	0.02[b]
Knee extension	85.99 ± 12.59	80.55-91.44	89.84 ± 10.70	85.22-94.47	100.39 ± 8.84	96.66-104.12	<0.01[a,b]
Ankle plantarflexion	99.53 ± 10.63	94.94-104.13	98.67 ± 8.67	94.92-102.42	99.89 ± 10.42	95.49-104.29	0.91
Joint power LSI, %							
Hip	99.66 ± 14.77	93.27-106.04	112.00 ± 19.98	103.36-120.64	98.86 ± 13.45	93.18-104.55	0.01[b,c]
Knee	81.82 ± 11.57	76.82-86.82	91.17 ± 13.95	85.14-97.20	100.37 ± 9.73	96.27-104.48	<0.01[a,b,c]
Ankle	84.25 ± 6.93	81.25-87.24	91.16 ± 14.82	84.76-97.57	98.26 ± 14.10	92.30-104.21	0.01[a]
Total	86.49 ± 5.17	84.25-88.73	92.82 ± 11.18	87.98-97.65	98.39 ± 8.64	94.74-102.04	<0.01[a,c]
vGRF LSI, %	94.37 ± 10.63	89.77-98.96	99.51 ± 8.41	95.88-103.15	98.81 ± 7.36	95.71-101.92	0.11

CONT, control; HJH, high jump height; LJH, low jump height; LSI, limb symmetry index; vGRF, vertical ground-reaction force.
[a]Significantly different between LJH and CONT groups.
[b]Significantly different between HJH and CONT groups.
[c]Significantly different between LJH and HJH groups.

be focused on the hop distance on the uninvolved side or a specific distance. The involved side of the patient tries its best to reach this distance by compensating for the hip and ankle joints, whereas the jump height is difficult to perceive in vertical jump, and the patient has no fixed focus of attention. This may cause the compensation pattern in single-leg horizontal hop to not exist in the single-leg vertical jump. Previous studies suggest that the focus of attention may affect the motor performance and biomechanical characteristics of participants.[2,13]

Unlike the landing phase, the propulsion phase contains information about how performance results are achieved. The knee joint contributes approximately one-eighth of the hop distance in a single-leg horizontal hop.[23] Symmetry of horizontal hop distance may not be sufficient to identify knee function deficits. The knee joint contributes about one-third of the jump height in a single-leg vertical jump.[23] Vertical jump height symmetry seems to be more sensitive to identifying knee functional deficits. This could explain why the LJH group achieved hop distance symmetry but not jump height symmetry. The reason for the functional deficit of the knee joint in the LJH group is perhaps due to the low quadriceps rate of torque development. Pua et al[40] noted that single-leg horizontal hop distance depends on quadriceps strength, while single-leg vertical jump height depends more on quadriceps rate of torque development.

Landing Phase

All athletes after ACLR displayed lower peak knee flexion angle LSI during landing, regardless of symmetry. In addition, patients with jump height LSI <90% showed lower peak ankle dorsiflexion angle LSI. A recent study showed a compensatory pattern of decreased knee flexion angle and increased hip flexion angle in athletes after ACLR despite a triple hop distance LSI >90%.[25] This could be a potential compensatory strategy to avoid a “stiff” landing by compensating for a smaller knee flexion angle with a larger hip flexion angle.[45] However, the smaller the knee flexion angle during landing, the greater the knee loading.[30,41] Athletes with limited motion in the sagittal plane tend to use a strategy of passive restraint in the anterior plane to control deceleration of the body’s center of gravity and exhibit greater knee abduction during landing.[12,31,38,47] Moreover, the reduction of knee flexion angle and ankle dorsiflexion angle also leads to a decrease in the potential to absorb the GRF.[11,32,51] All these factors may increase the risk of ACL injury. The reason for the reduced knee flexion angle during landing is not yet clear. Some scholars have suggested that altered quadriceps activation or reduced quadriceps strength results in a decreased ability to flex the knee during demanding tasks such as single-leg hop,[26,50,54,59] whereas others suggested that hamstring strength might influence knee flexion angle during landing.[4,17,51] This study did not test the electromyographic signal characteristics of patients in jump, and there was insufficient evidence to draw strong conclusions about the muscle activity pattern in ACLR patients. Overall, these studies highlight the importance of correcting abnormal landing patterns and improving muscle strength after ACLR.

All athletes after ACLR demonstrated lower knee power LSI during landing, regardless of symmetry. In addition, patients with jump height LSI >90% showed higher hip power LSI, while patients with jump height LSI <90% showed lower ankle power LSI. Our results showed a redistribution of power in the HJH group, whereas power in the LJH group decreased. Decreased knee power LSI during landing can be interpreted as an attempt by patients after ACLR to unload the knee and transfer the load to the hip. Paradoxically, this compensatory strategy may inhibit the stimulation of normal cartilage production and increase the long-term risk of osteoarthritis in the surgical knee.[35] It is worth mentioning that the hip power LSI of the LJH group was not significantly different from that of the CONT group, and the ankle power LSI was significantly lower than that of the CONT group, which is inconsistent with the compensatory pattern in previous studies. We believe that the reduction in jump height on the involved side of the LJH group may have led to an overall reduction in power. In addition, the LJH group may tend to unload moment and energy from the knee joint to the hip joint rather than the ankle joint. Wren et al[57] showed that athletes after ACLR with hop distance LSI <90% tended to unload energy from the knee to the ankle during landing, and athletes with hop distance LSI >90% tended to unload to the hip. This hypothesis seems plausible, considering that the ACLR cohort had a hop distance LSI >90%. On the other hand, the reduction in ankle power could occur as a result of the straighter, stiffer landing strategy adopted by patients after ACLR. This strategy may provide the same center of mass modulation with less muscular effort, but at the expense of greater axial knee joint loading.[46]

Clinical Implications

Single-leg horizontal hop distance LSI >90% is considered the cutoff point for RTS in patients after ACLR. However, the patient still has abnormal biomechanical characteristics even if the symmetry of the hop distance meets the RTS criteria, meaning that the patient is still at high risk of injury. Vertical jump height symmetry is considered to be a better indicator for evaluating knee function than hop distance symmetry. Results showed that athletes after ACLR with vertical jump height LSI >90% exhibited more symmetrical biomechanics during jumping compared with athletes with single-leg vertical jump height LSI <90%. However, there were still abnormal kinematic and kinetic characteristics compared with healthy athletes, suggesting that symmetrical jump height may not signify ideal biomechanical or RTS readiness. Given that there is only a weak-to-moderate relationship between LSI of single-leg vertical jump and horizontal hop tests,[49] single-leg vertical jump can be used as a supplement to horizontal hop and other functional tests to reduce the likelihood of false-negative results in the absence of detailed biomechanical evaluation.

Limitations

Several limitations were present in this study. First, the types of grafts were not uniform; current evidence suggests that there are no significant differences in biomechanical outcomes between bone-patellar tendon-bone and hamstring tendon grafts.[7,48] Second, quadriceps strength was not taken into account when grouping subjects. Despite the moderate positive correlation between quadriceps strength and hop distance,[33,58] we cannot assume that quadriceps strength was symmetric (LSI >90%). In addition, there is no differentiation of included athletes based on their sports. LSI is often used to represent functional outcomes[55]; however, decreased performance of the uninvolved limb will produce a misleading LSI and may overestimate the functional capacity of the affected limb.[8] Another limitation is that men and women were not analyzed separately due to the relatively small sample size, despite some evidence of biomechanical differences between genders.[16]

CONCLUSION

Athletes after ACLR with single-leg jump height LSI >90% still showed lower limb abnormal biomechanical characteristics compared with healthy athletes. Symmetry in single-leg vertical jump height does not represent normal lower limb biomechanics in athletes after ACLR.

ACKNOWLEDGMENT

The authors would like to thank the Key Laboratory of Sports Engineering of the General Administration of Sport of China, Wuhan Sports University for providing the experimental site and instrumentation. They also acknowledge the support of the Donghu Scholar Program of Wuhan Sports University and Research Fund for Young Teachers of Wuhan Sports University (No. 20Z01), and Young and Middle-Aged Scientific Research Team Project of Wuhan Sports University (No. 21KT14).

ORCID ID

Cheng Zheng https://orcid.org/0000-0003-1726-0258

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