

Original Research

Is Deceleration the Key Element in Vertical Jump Performance to Return to Sport After Anterior Cruciate Ligament Reconstruction With Hamstring Graft? A Preliminary Study

Florian FORELLI^{1,2,3}, Ayrton MOIROUX--SAHRAOUI^{2,4} ^a, Branis NEKHOUEF², Ismail BOUZEKRAOUI ALAOUI^{5,6}, Amaury VANDEBROUCK², Pascal DUFFIET², Louis RATTE², Maciej BIALY^{7,8}, Andreas BJERREGAARD⁹, Jean MAZEAS^{2,4}, Maurice DOURYANG¹⁰, Alexandre RAMBAUD¹¹

¹ Haute-Ecole Arc Santé, HES-SO University of Applied Sciences and Arts Western Switzerland, Neuchâtel, Switzerland, ² Orthopaedic Surgery Department, Clinic of Domont, Ramsay Healthcare, @OrthoLab, Domont, France, ³ SFMKS Lab, Pierrefite sur seine, France, ⁴ Orthosport Rehab Center, Domont, France, ⁵ Mohammed VI Center for Research and Innovation, Rabat, Morocco, ⁶ Mohammed VI Faculty of Nursing and Allied Health Professions, Mohammed VI University of Sciences and Health, Casablanca, Morocco., ⁷ Institute of Physiotherapy and Health Sciences, The Jerzy Kukuczka Academy of Physical Education, Katowice, Poland., ⁸ Functional Diagnostics Laboratory, Sport-Klinika, Scanmed Sport, Żory, Poland, ⁹ Physiotherapy Department, University of Southern, Odense, Denmark, ¹⁰ Department of Physiotherapy and Physical Medicine, University of Dschang, Dschang, Cameroon., ¹¹ Physiotherapy School of Saint Etienne, St Michel Campus, Saint Etienne, France

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Background/Purpose

Anterior cruciate ligament reconstruction (ACLR) often leads to persistent neuromuscular deficits, complicating return-to-sport decisions. Reliable functional assessments are needed to guide RTS after ACLR. The main objective was to examine countermovement jump (CMJ) measures to identify which parameters can best distinguish between ACLR and control participants. The secondary objective was to determine whether performance alterations between operated and non-operated limb exist during CMJ after ACLR.

Design

Non-randomized, single blinded, cross-sectional study

Methods

Limb symmetry index (LSI) was calculated for vertical ground reaction force (vGRF), maximal power (MP), and eccentric rate of force development (RFDe) during countermovement jumps (CMJ) performed on force plates by an ACLR group (n=64) and a control group (n=47). First analysis compared LSI vGRF, LSI MP and LSI RFDe between groups. Secondary analysis compared vGRF, MP and RFDe between the operated/non-operated limb in the ACLR group and dominant/non-dominant limb in the control group. Between-group comparisons were made using Mann-Whitney tests due to non-normal data distribution. Effect sizes were calculated to assess the magnitude of differences.

Results

Participants included 64 ACLR patients (mean age 26.5 ± 5.0 years; 33 females) and 47 controls (mean age 23.6 ± 2.1 years; 24 females). CMJ measures in the ACLR group were significantly reduced for LSI vGRF ($p < 0.001$), LSI MP ($p < 0.001$) and LSI RFDe ($p < 0.001$). The ACLR group exhibited significant differences between both limbs in terms of

^a Corresponding author:

Ayrton MOIROUX--SAHRAOUI
Clinic of Domont, 85 route de Domont, 95330 Domont, France
ayrton.moirouxsahraoui@gmail.com,

vGRF ($p < 0.001$), MP ($p < 0.001$), and RFDe ($p < 0.01$). No significant limb differences were found in the control group.

Conclusion

Measures of deceleration from the CMJ are altered after ACLR and should be considered throughout rehabilitation.

Level of Evidence

3

INTRODUCTION

Anterior cruciate ligament (ACL) injuries are among the most prevalent and impactful knee injuries, especially in sports that involve pivoting, jumping, and cutting maneuvers.¹ ACL reconstruction (ACLR) is a common surgical intervention aimed at restoring knee stability and function, particularly for athletes seeking to return to high-demand activities.²⁻⁴ However, achieving a successful return to sport (RTS) after ACLR remains a complex challenge influenced by various factors, including graft type, rehabilitation protocols, and results of functional assessments.⁵⁻⁷

One of the critical components in the RTS process after ACLR is the assessment of lower limb function and performance.^{8,9} Harris et al. highlighted the inconsistency in RTS criteria, with 65% of reviewed studies omitting specific criteria for RTS, and only 10% reporting whether patients could return to their pre-injury sports level.¹⁰ Although extensive research exists on this topic, clear and conclusive guidelines for safe, unrestricted RTS are still lacking.^{9,11} This underscores the rationale for evaluating patients at the six-month postoperative period, a commonly referenced milestone, to identify additional functional parameters that may support informed RTS decisions.^{12,13}

Traditional clinical assessments, including evaluations of knee range of motion, strength, stability, and proprioception provide essential insights into knee recovery but may lack the sensitivity needed to detect subtle deficits in dynamic movement, particularly those pertinent to sports performance.^{9,14-16} Identifying these nuanced deficits is critical, as they can impact an athlete's full return to performance and may be indicative of reinjury risk.¹⁷ The rate of second ACL injury has been reported to be 17.8%, with 9.3% occurring in the ipsilateral knee and 8.5% occurring in the contralateral knee.¹⁸

In recent years, functional performance tests have gained prominence in evaluating RTS readiness after ACLR.^{9,19,20} Among these, the countermovement jump (CMJ) has emerged as a valuable tool for assessing neuromuscular function and asymmetries between the lower limbs. Studies have shown that ACLR patients frequently exhibit kinetic deficits during CMJ, even after meeting RTS criteria.^{14,21-23} The CMJ, characterized by a rapid downward motion followed by an explosive upward movement, closely replicates the biomechanical demands of various athletic actions, making it a relevant and dynamic tool for assessing lower limb performance.^{24,25}

The CMJ offers several advantages as an RTS assessment tool. First, it provides a dynamic measure of lower limb

power and force generation—a crucial factor in sports performance.²⁶⁻²⁸ Second, the CMJ enables clinicians to evaluate both bilateral and unilateral limb function, which is essential for detecting asymmetries between the ACL-reconstructed limb and the contralateral limb.²⁶⁻²⁸ Such asymmetries have been linked to an elevated risk of reinjury and may indicate lingering neuromuscular deficits that could compromise RTS outcomes.²⁸

Research supports the utility of CMJ parameters for predicting RTS outcomes and identifying residual functional impairments after ACLR.^{9,22} For instance, Myer et al. found that athletes meeting specific CMJ criteria before RTS had a lower risk of sustaining a second ACL injury.²⁹ Similarly, Di Stasi et al. observed that jump performance asymmetries were common even in athletes cleared for RTS, highlighting the need for comprehensive functional assessments beyond traditional clinical measures.²³

Moreover, advances in technology, such as force plates and motion capture systems, have enhanced the precision of CMJ assessments, allowing for detailed analysis of kinetic and kinematic variables during the jump. These tools enable clinicians to detect subtle movement patterns and compensatory strategies that might otherwise go unnoticed, offering insights into the neuromuscular deficits that may persist after ACLR.

In summary, the CMJ is a valuable tool for assessing RTS readiness after ACLR, as it provides critical insights into lower limb power, symmetry, and movement quality. Despite its benefits, there is still limited information on the specific CMJ parameters that are most informative for RTS decision-making. The main objective is to examine countermovement jump (CMJ) measures to identify which parameters can best distinguish between ACLR and control participants. The secondary objective was to determine whether performance alterations between operated and non-operated limb exist during CMJ after ACLR.

METHODS

STUDY DESIGN

This preliminary non-randomized, single blinded, cross-sectional study received approval by the COS-RGDS-ethics committee (IRB00010835). All patients were treated in agreement with the Declaration of Helsinki and provided written informed consent. The STROBE guidelines were followed in this study.

PARTICIPANTS

Data was retrieved for the records of the Clinic of Domont Physiotherapy department between January 2023 and March 2024.

Inclusion criteria were that participants had to be aged between 18 and 40 years old, have undergone an ACLR using a hamstring graft, have body mass index (BMI) lower than 30 kg.m^2 and above 18.5 kg.m^2 . Exclusion criteria were any history of knee injury prior to the ACL injury, pregnancy, missing information or data from the medical record and associated injuries other than meniscal injuries (treated either by meniscal suture or meniscectomy) such as osteochondral injury and/or other complex ligament injuries.

From the original 140 ACLR patients, 50 patients were excluded. 23 patients did not meet the inclusion criteria, two patients declined to participate, 24 had incomplete or missing data, and one patient was excluded because he had difficulty understanding English or French.

A total of 64 recreational athletes (33 female and 31 male) were recruited six months after an ACLR surgery. The ACLR was performed by one of three orthopedic surgeons following the same surgical procedure using a hamstring graft. Participants were recruited from the three rehabilitation centers that followed the same ACLR rehabilitation programs. The ACLR rehabilitation programs follows the Aspetar guidelines by using OKC and CKC to recover muscle strength as well as isokinetic training.³⁰

A total of 47 recreational athletes (24 female and 23 male) with no lower limb injury or surgery history were recruited as the control group. Inclusion criteria were participants had to be between 18 and 40 years old, and BMI had to be lower than 30 kg.m^2 . Exclusion criteria were any history of lower limb injury, pregnancy, missing information or data from the medical record. Two groups were formed, an ACLR group ($n=64$) and a control group ($n=47$).

SAMPLE SIZE CALCULATION

The sample size calculation was performed using G*Power version 3.1.9.7, conducting a power analysis for an independent two-group comparison. Considering a large effect size ($d = 0.8$), a significance level of 5% ($\alpha = 0.05$), and a statistical power of 80% ($1 - \beta = 0.80$), the analysis estimated that a minimum of 26 participants per group (52 in total) would be required to detect a significant difference between the groups

ASSESSMENT PROTOCOL

The participant's height (cm), mass (kg), age and sport activity level (using a Tegner Activity scale) and operated limb or dominant leg (self-reported) were recorded before the start of the tests. Before the jump tests, participants performed a standardized warm-up that consisted of five minutes on a bicycle, five two-legged squats and two submaximal CMJ's. Participants were instructed to stand on two legs on the force plates (Delta Force Plate; Kinvent; V2; 2000 Hz; Montpellier; FRANCE). The data were collected

with Kinvent Physio App (v2.7.1). With their hands on their hips, they were asked to perform a CMJ, jumping as high and fast as possible without upper limb movement. Participants were instructed to remain motionless for at least three seconds before initiating the jump to ensure a stable baseline force measurement at body weight. Subsequently, players executed a downward movement (descent phase) until reaching their self-selected depth, followed by a rapid reversal involving triple extension at the hip, knee, and ankle joints. The objective was to maximize vertical acceleration and the displacement of the center of mass. Participants kept their hands on their hips throughout the jump, and no knee flexion was allowed while airborne. Each participant performed three trials, with a 30-second rest interval between jumps. The mean values of the three jumps were recorded for further analysis.³¹

The CMJ was evaluated using two synchronized force plates to independently capture ground reaction forces from each limb. This setup enabled precise calculation of the Limb Symmetry Index (LSI) for vertical ground reaction force (vGRF), maximal power (MP), and rate of force development during the deceleration phase (Decel RFD). For each parameter, the LSI was calculated as: $LSI = \frac{\text{Operated Limb}}{\text{Non-Operated Limb}} \times 100$. In the ACLR group, and similarly using dominant/non-dominant limbs in the control group. The maximal value from each limb across the three trials was used for analysis.³¹ First analysis compared LSI vGRF, LSI MP and LSI Decel RFD between both groups during CMJ. Secondary analysis compared vGRF, MP and Decel RFD between operated/non-operated limb in the ACLR group and dominant/non-dominant limb in the control group.

STATISTICAL ANALYSIS

All statistical tests were performed using a significance level of $\alpha = 0.05$, with corresponding 95% confidence intervals (CI) reported where applicable. Statistical analysis was conducted using the JASP® software.

Descriptive statistics were calculated for both groups for each of the variables in the population: age, height, weight, sex, BMI, Tegner score, Marx score, and the operated side or dominant leg.

The verification of the normality of data distribution was carried out using a Kolmogorov-Smirnov test, for each of the variables of the two groups.

To examine for differences in demographic characteristics between the ACLR and control groups, independent samples t-tests were used for normally distributed quantitative variables, and Mann-Whitney U tests were used for non-normally distributed variables. A Pearson's Chi-square (Chi-2) test was conducted for qualitative variables (sex, operated side).

After verifying the normality of the distribution and the homogeneity, the Mann-Whitney test was used on the variables corresponding to the results of the jump test due to lack of normal distribution. This was to compare the two limbs for each group for any significant difference, operated versus non-operated for the ACLR group and dominant versus non-dominant for the control group. The Mann-Whit-

Table 1. Anthropometric data

Variable	ACLR Group (n=64) Mean $\pm$ SD	Control Group (n=47) Mean $\pm$ SD	p-value
Age (years)	26.50 $\pm$ 5.00	23.60 $\pm$ 2.10	<0.001
Height (m)	1.72 $\pm$ 0.09	1.75 $\pm$ 1.12	0.83
Weight (kg)	71.40 $\pm$ 10.00	70.30 $\pm$ 8.00	0.26
BMI (kg/m ²)	24.50 $\pm$ 2.40	21.60 $\pm$ 2.00	0.13
Tegner Activity Scale	6.50 $\pm$ 2.00	7.00 $\pm$ 1.50	0.67
Marx Score	11.90 $\pm$ 3.10	10.20 $\pm$ 3.30	0.46
Sex (M/F)	33/31	23/24	0.61
Operated side / Dominant side (R/L)	32/35	28/19	0.21

SD – standard deviation; cm – centimeter; kg – kilogram; kg/m² – kilogram per square meter; BMI – Body Mass Index; M/F – Male/Female; R/L – right/left.

ney test was also used to compare the quantitative values from the CMJ of the non-dominant limb of control group with the operated limb of group ACLR. In accordance with previous literature, the non-dominant limb is often used as a comparator for the operated limb in ACL research, as it is presumed to be less influenced by compensatory adaptations following surgery.³² This comparison helps to better assess residual deficits and neuromuscular asymmetries that may persist post-rehabilitation, providing a more accurate representation of functional recovery and injury risk. A Mann-Whitney test was used to compare the LSI values from the CMJ between groups, to determine whether differences in LSI were present in ACLR patients compared to the control group.³³

In addition to statistical significance testing, effect sizes were calculated to assess the magnitude of differences between groups. Cohen's d was used for normally distributed variables, while non-parametric effect size estimates ($r = Z / \sqrt{N}$) were used for data that did not meet normality assumptions. Effect size quantifies the strength of an observed difference by standardizing it relative to the variability in the data. According to conventional thresholds, an effect size of 0.2 is considered small, 0.5 moderate, and 0.8 large.³⁴ This approach enhances the understanding of the intervention's effectiveness beyond statistical significance alone, offering insights into the practical relevance of the observed changes.

RESULTS

PARTICIPANTS CHARACTERISTICS

A complete summary of the anthropometric data with details for each group is presented in [Table 1](#). No statistically significant differences were observed between the groups except for age, ($p < 0.001$) with the control group being younger.

Statistically significant differences were observed for the LSI vGRF and the LSI MP. For the LSI vGRF ([Table 2](#)), there is a difference of 9% ($94.90\% \pm 5.28$ vs $85.90\% \pm 9.57$; $p < 0.001$; ES= -0.64). For the LSI MP, there is a difference of 10.7% ($95.60\% \pm 4.15$ vs $84.90\% \pm 8.39$; $p < 0.001$; ES= -0.78). For the LSI Decel RFD, there is a difference of 8.7% ($76.70\% \pm 17.2$ vs $68.00\% \pm 23.14$; $p = 0.081$; ES= -0.19). For

jump height, a significant difference of 7.6 cm is observed (28.7 ± 10.03 cm vs 21.1 ± 7.44 cm; $p < 0.001$; ES = -0.42)

For vGRF, there is a difference of 1.60 N.kg^{-1} ($9.20 \text{ N.kg}^{-1} \pm 1.19$ vs $10.60 \text{ N.kg}^{-1} \pm 1.36$; $p < 0.001$; ES= 1.1). For MP, there is a difference of 2.70 W.kg^{-1} ($17.60 \text{ W.kg}^{-1} \pm 4.03$ vs $20.30 \text{ W.kg}^{-1} \pm 4.16$; $p < 0.001$; ES= 0.70). For Decel RFD, there is a difference of 383 N.s^{-1} ($842.00 \text{ N.s}^{-1} \pm 621$ vs $1225.00 \text{ N.s}^{-1} \pm 878$; $p = 0.004$; ES= 0.50). The detailed results are summarized in [Table 3](#).

No statistically significant differences were observed between the dominant and non-dominant limbs for any of the variables in the control group. These results are summarized in [Table 4](#).

DISCUSSION

The primary aim of this study was to determine which CMJ parameters could most effectively differentiate ACLR patients from a control group and identify asymmetries between operated and non-operated limbs during bilateral tasks. Six months post-surgery, ACLR participants displayed notable deficits in LSI for vGRF and MP compared to healthy controls. Additionally, significant discrepancies were observed between the operated and non-operated limbs within the ACLR group, highlighting ongoing kinetic asymmetries despite clearance to RTS.

These findings align with the growing body of evidence indicating that kinetic asymmetries often persist after ACLR, even when patients achieve standard clinical benchmarks, such as full range of motion, absence of pain, and clearance for return to sport based on strength and functional assessments (e.g., limb symmetry index $>90\%$).^{9,35} Myer et al. demonstrated that asymmetrical performance in tests like the CMJ could be predictive of reinjury risk, underscoring the clinical relevance of assessing inter-limb discrepancies in the rehabilitation context.²⁹ Specifically, athletes who did not meet established kinetic criteria had an increased risk of reinjury compared to those with symmetrical performance, suggesting that asymmetries might serve as critical indicators of neuromuscular deficiencies that increase the likelihood of reinjury upon RTS.^{9,12,17,36, 37}

Table 2. Comparison of CMJ values between ACLR group and control group

Variable	ACLR Group (n=64) Mean $\pm$ SD	Control Group (n=47) Mean $\pm$ SD	p-value	Effect Size (ES)
Jump Height (cm)	21.1 $\pm$ 7.44	28.7 $\pm$ 10.03	< 0.001	-0.42
vGRF LSI (%)	85.90 $\pm$ 9.57	94.90 $\pm$ 5.28	< 0.001	-0.64
MP LSI (%)	84.90 $\pm$ 8.39	95.60 $\pm$ 4.15	< 0.001	-0.78
Decel RFD LSI (%)	68.00 $\pm$ 23.14	76.70 $\pm$ 17.21	0.081	-0.19

LSI - Limb Symmetry Index; SD – standard deviation; vGRF - vertical Ground Reaction Force; MP – Maximal Power ; Decel RFD - Rate of Force Development. Negative effect sizes indicate that the ACLR group had lower values than the control group for the respective variable.

Table 3. Comparison between operated and non-operated limbs during the CMJ for ACLR group.

Variable	Operated Limb (OP) Mean $\pm$ SD	Non-Operated Limb (NOP) Mean $\pm$ SD	p-value	Effect Size (ES)
vGRF (N.kg ⁻¹)	9.20 $\pm$ 1.19	10.60 $\pm$ 1.36	< 0.001	-0.91
MP (W.kg ⁻¹)	17.60 $\pm$ 4.03	20.30 $\pm$ 4.16	< 0.001	-0.66
Decel RFD (N.s ⁻¹)	842 $\pm$ 621	1225 $\pm$ 878	0.004	-0.50

OP - operated limb; NOP - non-operated limb; vGRF - vertical Ground Reaction Force; MP - Maximum Power; Decel RFD - Rate of Force Development; N - Newton; kg - kilogram; W - Watt; s - second. Negative effect sizes indicate that the ACLR group had lower values than the control group for the respective variable.

Table 4. Comparison between dominant and non-dominant limbs during the CMJ for control group

Variable	Non-Dominant Limb (NDL) Mean $\pm$ SD	Dominant Limb (DL) Mean $\pm$ SD	p-value	Effect Size (ES)
vGRF (N.kg ⁻¹)	10.80 $\pm$ 1.45	11.00 $\pm$ 1.49	0.42	-0.14
MP (W.kg ⁻¹)	23.30 $\pm$ 6.34	23.60 $\pm$ 6.14	0.76	-0.05
Decel RFD (N.s ⁻¹)	1464.00 $\pm$ 898	1772.00 $\pm$ 1049	0.13	-0.32

NDL - non-dominant limb; DL - dominant limb; vGRF - vertical Ground Reaction Force; MP -Maximum Power; Decel RFD - Rate of Force Development; N - Newton; kg - kilogram; W - Watt; s - second. Negative effect sizes indicate that the ACLR group had lower values than the control group for the respective variable.

The observed deficits in LSI vGRF in the current study are consistent with findings from Read et al., who noted decreased symmetry in vGRF among ACLR patients, particularly within the six to nine month postoperative window.³⁸ These authors also reported that vGRF asymmetries are particularly prevalent in the early stages of rehabilitation, with symmetry often only marginally improving as rehabilitation progresses. However, unlike the current findings, Read et al. observed higher symmetry in their control group, with their ACLR patients displaying more pronounced asymmetries.³⁸ This discrepancy could stem from methodological differences, such as variations in CMJ protocol and differences in sample demographics. Such differences emphasize the need for standardized, consistent testing protocols in clinical research to facilitate comparability across studies.

Lastly, the current findings are corroborated by Baumgart et al., who showed that vGRF asymmetries strongly correlate with poorer subjective function, as measured by the International Knee Documentation Committee score, in ACLR patients — a measure that was not included in the current study.³⁹ This correlation between subjective func-

tion and kinetic asymmetry supports the notion that kinetic measures—specifically, bilateral assessments like CMJ—can serve as objective markers of functional recovery. Baumgart's findings align with the current results, indicating that even six months after ACLR, kinetic discrepancies remain significant, suggesting that kinetic asymmetries should be a critical consideration in the RTS decision-making process.^{8, 9,40}

Similarly, the present study's findings on LSI MP echo results from King et al., who found that MP asymmetries in ACLR patients were strongly associated with incomplete functional recovery.⁴¹ However, King et al. reported a smaller MP deficit than observed in the current study, which could be attributed to the unipedal CMJ protocol used in their research.⁴¹ A unilateral testing approach may yield lower MP deficits by isolating performance in each limb, while the current study approach using a bipedal protocol potentially heightens asymmetries due to the interplay of both limbs during the jump task. This contrast underscores the need for future studies to explore whether unilateral CMJ assessments might provide a different and potentially more accurate picture of limb-specific deficits

than bilateral assessments, potentially offering a more sensitive measure of neuromuscular function.

Another notable finding in the current study is the deficit observed in Decel RFD within the ACLR group compared to controls. Decel RFD represents a crucial parameter, capturing an individual's capacity to modulate force absorption during landing—a fundamental aspect of jump mechanics relevant to injury prevention and RTS.^{42,43} While Decel RFD has not yet been widely adopted as a clinical measure, a recent study by Kotsifaki et al. support its potential utility in RTS assessments.²² Their research highlights that deficiencies in force absorption can persist even in athletes who meet clinical strength criteria, suggesting that Decel RFD may capture residual neuromuscular deficits overlooked by conventional strength and functional performance metrics.^{22,44}

The current study results further suggest that reliance on LSI as a singular measure for RTS clearance may oversimplify the complex interplay between limbs. Wellsandt et al. cautioned against the sole use of LSI in RTS decisions, emphasizing that LSI assumes the non-operated limb functions as a reliable benchmark, which may not always be accurate. Instead, they advocate for a multifaceted approach that considers the unique compensatory strategies developed during rehabilitation, as well as potential deficits in both limbs.⁴⁵ Incorporating independent measures of both limbs' functional status may therefore provide a more nuanced view of an athlete's readiness for unrestricted sports participation.⁴⁶

The findings from this study reinforce the clinical importance of comprehensive functional assessments, such as bilateral CMJ, in determining RTS readiness post-ACLR. The results suggest that continued kinetic asymmetries in load absorption, power generation, and force modulation may signify incomplete neuromuscular recovery, underscoring the need for protocols that assess these parameters longitudinally. While LSI remains a valuable measure, its limitations call for supplementary metrics like Decel RFD and independent limb assessments to capture more accurate functional recovery profiles. Future research should focus on standardizing CMJ protocols and exploring Decel RFD's predictive value for reinjury risk to establish evidence-based guidelines for RTS following ACLR.

LIMITATIONS

This study has several notable limitations that should be considered when interpreting the results. One significant limitation is the age discrepancy between the ACLR and

control groups, as our control group included younger participants, leading to a lack of homogeneity. Age-related differences in neuromuscular performance could have influenced the findings, and a more age-matched control group would provide more comparable data. Additionally, the time each ACLR participant had been allowed to engage in jump-related activities was not accounted for. Participants who recently resumed jumping may display lower performance metrics than those who had more time to retrain and adapt. Although the rehabilitation protocols across centers were similar, individual variations in specific rehabilitation phases may have introduced variability in performance outcomes.

Another potential source of bias is the absence of psychological assessment before the CMJ test. Psychological factors, such as apprehension or fear of reinjury, could affect jump performance, particularly in ACLR patients, and the inclusion of a psychological assessment measure could provide valuable context for interpreting CMJ outcomes. Future studies should also consider using additional functional assessments alongside CMJ to create a more comprehensive view of neuromuscular recovery and RTS readiness.

CONCLUSION

The current findings indicate more pronounced asymmetries in load absorption, force generation, and power in patients with ACLR than in controls. The findings align with previous literature using similar protocols, emphasizing significant compensatory strategies that may be used for load absorption, force production, and power among ACLR patients during bipedal vertical jumps compared to healthy controls. Load absorption, force generation, and power appear to be valuable markers in assessing readiness to RTS. Future research should explore whether targeted rehabilitation strategies can effectively address deficits in these areas and influence return-to-sport outcomes.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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