FACTORS INFLUENCING SINGLE LEG VERTICAL JUMP PERFORMANCE IN ACLR PATIENTS

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This study explores the differences in jump strategy and strength characteristics between athletes who do and do not achieve adequate symmetry in single-leg countermovement jump (SLCMJ) performance following Anterior Cruciate Ligament Reconstruction (ACLR). Including 372 male athletes recovering from primary ACL injuries, the study utilizes independent sample t-tests and regression models to analyze strength and key jump variables. Our findings reveal key differences in knee extensor strength and jump metrics for the involved limb despite no differences in uninvolved limb jump height. These results highlight the significance of SLCMJ testing in ACL rehabilitation, providing valuable insights into patient functional status. This approach can be instrumental in developing targeted rehabilitation strategies, thereby enhancing recovery outcomes post-ACLR.

KEYWORDS: ACL, vertical jump, return to performance.

INTRODUCTION: Functional tests, such as hop and jump tests, are commonly used to monitor the progress of rehabilitation after anterior cruciate ligament reconstruction (ACLR). An athlete's progress during rehabilitation can be charted using these tests against established normative data. Indeed, the long-term health of the knee may be improved and the risk of future injury to the operated knee may be reduced, if the athlete meets established discharge criteria (Kyritsis, Bahr, Landreau, Miladi, & Witvrouw, 2016) and achieves symmetry in strength between the operated and non-operated leg.
Recent research indicates that vertical hop testing provides a more accurate assessment of knee function in ACLR patients than traditional horizontal hop tests. This is due to the knee joint's greater work contribution -approximately 30%- to the propulsive phase of a vertical jump, compared to just 10% in horizontal hop, making vertical tests a preferred measure for evaluating rehabilitation progress(A. Kotsifaki, Van Rossom, Whiteley, Korakakis, Bahr, Sideris, & Jonkers, 2022; A. Kotsifaki, Van Rossom, Whiteley, Korakakis, Bahr, Sideris, Smith, et al., 2022). During the return-to-sport phase, even after meeting traditional discharge criteria, athletes often exhibit significant asymmetries in phase-specific kinetic variables such as eccentric and concentric impulse, in both bilateral and unilateral jumps. This is particularly evident in single-leg countermovement jumps, where patients show notable asymmetries in jump height and lower performance compared to matched controls (R. Kotsifaki, Sideris, King, Bahr, & Whiteley, 2023).
The aim of this study is to examine the differences in strength characteristics and key jump metrics between patients who excel versus those who fail in achieving adequate single-leg countermovement jump height symmetry post-ACLR and to understand how these factors contribute to the performance of a vertical jump with the involved limb. Despite undergoing similar rehabilitation programmes, substantial variation in patient outcomes exists. Understanding inter-individual differences in performance may provide information for targeted rehabilitation.

METHODS: A total of 372 male athletes with index ACL injury, including both recreational and professional athletes, were enrolled in this study (Table 1). The Inclusion criteria required patients to have no other knee ligament or cartilage surgeries in either leg. Each participant underwent an intensive, supervised rehabilitation program, ranging from three to five days a week, at the same sports medicine hospital, commencing immediately post-surgery.
Patients underwent periodic neuromuscular assessments every six weeks during rehabilitation. Vertical jump testing was typically initiated 4.5 months after surgery and continued periodically until discharge. These tests employed two ground-embedded force

plates (AMTI, Watertown, Massachusetts, USA) at a sampling rate of 1000 Hz. Data capture and analysis were conducted using ForceDecks software (Vald Performance, Newstead, Australia) version 2.0. Prior to testing, patients completed a standardized warm-up protocol. After calibrating the force plates and weighing the athletes, each test was demonstrated and then practiced by the patients. The test battery, performed in sequence, included double-leg countermovement jumps(CMJ), single-leg countermovement jumps (SLCMJ), double-leg drop jumps (DJ), and single-leg drop jumps (SLDJ). For this study, only the SLCMJ results were analyzed. During the SLCMJ, athletes stood upright on one foot on the force plate, with the free leg positioned behind at approximately 60° knee flexion and hands on hips, remaining motionless for a minimum of 3 seconds before initiating the jump. Athletes were instructed to perform a quick countermove followed by a maximal vertical jump. Jump events were identified by a 20 N change in ground reaction force. After completing the jump tests, patients' maximum knee extension and flexion strength were measured using an isokinetic dynamometer (Biodex Medical Systems). In a seated position with their hips flexed at 90°, participants performed five repetitions of concentric knee extension and flexion at a speed of 60°/s. The highest peak torque value from these repetitions was recorded.

For our analysis, we selected the test that demonstrated each patient's highest SLCMJ height symmetry throughout their entire rehabilitation period. Symmetry was calculated by dividing the performance of the involved limb by that of the uninvolved limb, then multiplying by 100. Subsequently, patients were ranked by percentile, facilitating a comparative analysis of strength and kinetic characteristics. This analysis distinguished between the top performers (those above the 75th percentile) and the poor performers (those below the 25th percentile) in terms of SLCMJ height symmetry.

Informed consent was obtained from all patients, and the study was approved by the local institutional review board (IRB numbers: F2017000227 and E202009010).

To evaluate the differences in strength and key kinetic variables between the top and poor performers, an independent sample t-test was employed. Outlier detection involved boxplot inspections for each variable, and the Shapiro-Wilk test was used to confirm the normality of distribution. Additionally, Levene’s test for equality of variances was conducted to ensure homogeneity of variances.

Following the initial comparative analysis, a linear regression model was developed to predict involved leg jump height. Due to the nature of the kinetic data, addressing multicollinearity was a critical concern. The Variance Inflation Factor (VIF) was utilized to detect and mitigate multicollinearity. Features with exceptionally high VIF values were sequentially removed to optimize the balance between the model's complexity and predictive accuracy. The model's efficacy was evaluated using the Mean Squared Error (MSE) and the coefficient of determination (R^2).

Table 1: Participant information

	Total	**Poor Performers**	**Top Performers**
Patients(n)	372	84	99
Age (years)	24.4 ± 6.4	26.1 ± 6.4	22.7 ± 6.4
Body mass (kg)	75.5 ± 12.8	75.6 ± 15.8	74.8 ± 12.6
Height (cm)	175.7 ± 8.1	175.4 ± 8.9	176.1 ± 7.9
Tegner score	8.5 ± 1.1	8.2 ± 1.1	8.6 ± 1.0
Time after surgery(months)	8.0 ± 2.1	7.8 ± 2.3	8.1 ± 2.0
Jump Height LSI	86.2 ± 5.0	67.0 ± 6.5	103.3 ± 7.5
ACL graft type, n (%)			
Hamstring	218(58.6)	55(63.4)	62(63.4)
Bone-patellar-tendon-bone	138(37.1)	28(34.4)	30(30.4)
Quadriceps	16(4.3)	1(2.2)	7(6.2)

RESULTS: Statistical analysis highlighted significant differences between the top and poor performers in several key variables, as detailed in Table 2. Notably, jump height on the uninvolved side did not exhibit statistically significant differences. Additionally, other variables such as contraction time, eccentric duration, and concentric duration, showed no statistically significant differences between the groups.

Table 2: Key strength and jump variables

	Poor Performers	Top Performers	Δ	Effect Size
Involved Jump Height (cm)	10.48 ± 3.09*	15.98 ± 4.17	5.49	1.48
Uninvolved Jump Height (cm)	15.58 ± 0.44	15.51 ± 0.41	0.06	0.15
Knee Extensors Strength (Nm/kg)	2.38 ± 4.50*	2.98 ± 4.9	0.59	1.27
Knee Flexors Strength (Nm/kg)	151.97 ± 32.03*	166.32 ± 34.31	14.35	0.43
Peak Eccentric Force (N/kg)	15.63 ± 1.72*	17.03 ± 2.02	1.40	0.74
Eccentric Impulse (Ns/kg)	2.01 ± 0.61*	2.56 ± 0.71	0.55	0.83
Peak Concentric Force (N/kg)	17.57 ± 1.68*	18.48 ± 1.64	0.91	0.55
Mean Concentric Force (N/kg)	14.05 ± 1.06*	14.96 ± 1.11	0.91	0.84
Concentric Impulse (Ns/kg)	1.38 ± 0.21*	1.67 ± 0.25	0.30	1.28
Countermovement Depth (cm)	18.96 ± 4.89*	22.05 ± 5.12	3.09	0.61
Eccentric Peak Velocity(m/s)	0.65 ± 0.18*	0.82 ± 0.21	0.17	0.85
RSImodified (AU)	12.44±4.7*	19.39±5.99	6.95	1.28

Values are presented as mean ± standard deviation; * significant differences between poor and top performers; unless otherwise specified, all values pertain to the involved side

The linear regression model underwent several iterations to reduce multicollinearity. Initially, the model incorporated a comprehensive set of variables but exhibited significant multicollinearity, as evidenced by infinite VIF values for several features. Subsequent iterations involved excluding features with the highest VIF values such as concentric impulse and RSImodified.

The final model iteration, which utilized a reduced set of predictors, achieved an R^2 value of 0.76 suggesting approximately 76% of the variance in the involved leg's jump height was accounted for by the model.

The regression equation was as follows:

Jump Height(cm) = -26.627 + 0.301Countermovment Depth(cm) + 2.006Mean Concentric Force(N/kg) + 1.799 Peak Knee Extensors Moment (Nm/kg)

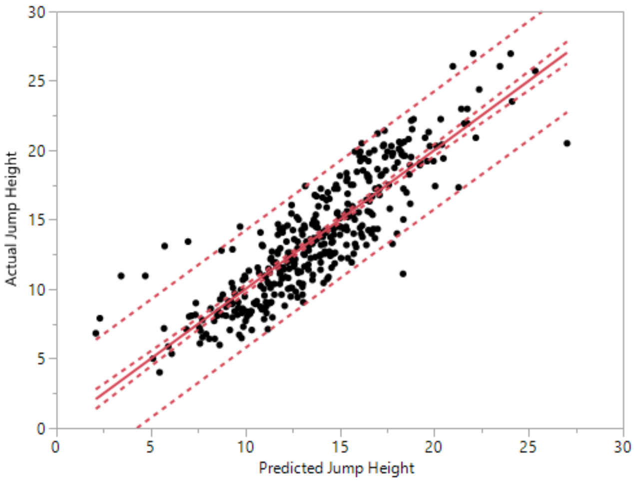

Figure 1: Scatter plot of the regression equation for predicted and actual jump height with 95% CI, R^2 = 0.76, p<0.01.

DISCUSSION: Our comparative analysis revealed that poor performers displayed significantly lower involved side SLCMJ height and reduced knee extensor strength. This was observed alongside notable differences in key jump variables when compared to top performers. These differences occurred despite there being no significant disparities in the jump height of the uninvolved limb. This observation suggests that the asymmetry observed in our study is primarily attributable to the performance of the involved side. Notably, prior research has shown that patients often achieve symmetry in hop-for-distance tests by reducing the hop distance of the uninvolved side, thereby masking true functional deficits (Wren et al., 2018).

The regression equation from our analysis indicates that the primary determinants of jump performance in the involved side of ACLR patients are countermovement depth, mean concentric force and knee extensor strength. These factors highlight crucial performance and strategy variables that can be targeted to address asymmetries in single-leg jump performance.

Regarding vertical jump testing, jump height is indicative of the athlete's capacity to generate vertical impulse, with the hip, knee, and ankle joints each contributing approximately 30% to the total work performed (A. Kotsifaki, Korakakis, Graham-Smith, Sideris, & Whiteley, 2021). It has also been reported that knee extensor strength accounts for about 30% of SLDJ performance in ACLR patients (Crotty, Daniels, McFadden, Cafferkey, & King, 2022), suggesting that optimal vertical jump performance may not be attainable unless knee extensor strength is fully restored. Our data reveal a significant difference in knee extensors strength between the two groups, underscoring the importance of strength enhancement for improved functional outcomes.

Beyond strength-related differences, our analysis identified significant disparities in jump strategy between the groups. Poor performers exhibited lower peak eccentric velocity, shallower countermovement depth and reduced RSImodified. This study contributes to the understanding of functional deficits following ACLR and holds numerous practical implications for training prescription and testing administration.

A key limitation of our study is its focus solely on male athletes, limiting the extrapolation of results to other populations. Additionally, we didn't examine the strength and contribution of other joints in jump performance. Future research should address these aspects to enhance rehabilitation strategies post-ACLR.

CONCLUSION:

Our study highlights the importance of evaluating SLCMJ performance in assessing lower limb function post-ACLR. Key findings include no significant jump height differences in the uninvolved limb and notable strength and strategy disparities between top and poor performers. These insights emphasize the need for targeted strength training in ACLR rehabilitation and suggest a potential for refining recovery strategies based on jump performance metrics.

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