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NEUROMUSCULAR SYMMETRY AND FUNCTIONAL RECOVERY FOLLOWING ACL RECONSTRUCTION IN A RECREATIONAL SKIER: A CASE STUDY

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Abstract. *Background.* Anterior cruciate ligament (ACL) injuries are among the most frequent and functionally limiting conditions in winter sports, particularly in amateur alpine skiing. Due to the high rotational forces and unpredictable terrain, even recreational athletes face significant risk. Additionally, ACL injuries can compromise long-term functionality and affect occupational activities that require prolonged standing or postural stability. Effective surgical intervention and a personalized rehabilitation plan are essential for regaining neuromuscular control and returning to both sport and professional activity.
Objectives. This case study aimed to evaluate the functional recovery and neuromuscular symmetry of a 26-year-old female recreational skier and dental practitioner who sustained a complete ACL rupture in the left knee. The study focused not only on achieving a safe return to sport but also on enabling her reintegration into daily professional activity, which involves long hours of standing and maintaining static posture. After ligament reconstruction with a hamstring autograft, the patient followed a structured, 9-month rehabilitation program with progressive goals, from anatomical healing to functional and occupational reintegration.
Methods. The protocol was divided into three phases and included mobility exercises, strength training, proprioceptive and neuromuscular control drills. Functional assessments were conducted using biomechanical equipment: Leg Press and Leg Extension (eccentric and isokinetic), execution speed, Drop Jump Test, Stiffness Test, and stabilometric postural evaluation. Data analysis included the Wilcoxon signed-rank test, symmetry index (SI), and coefficient of variation (CV%).
Results. The outcomes showed no significant limb differences ($p = 0.929$), with SI values below 10% in most tests. CV values were lower for strength and slightly higher for speed metrics. Quadriceps circumference increased (+8.9%), and all functional return-to-activity criteria were met.
Conclusion. The applied rehabilitation protocol effectively restored neuromuscular symmetry and functional capacity, supporting a confident return to both recreational skiing and physically demanding professional work. Additionally, improvements in joint mobility and dynamic knee stability were essential in facilitating safe reintegration into daily and sport-specific activities.

Keywords: ACL injury, rehabilitation protocol, neuromuscular symmetry, return to work, recreational skiing, functional recovery.

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Introduction

Anterior cruciate ligament (ACL) injuries are among the most frequent and functionally limiting injuries in winter sports, particularly in non-professional alpine skiing. Due to the high rotational forces and unpredictable terrain, recreational athletes face an increased risk of knee instability and ligament damage [1].

The ACL is essential for stabilizing the knee joint during both rotational and translational motions. Damage to this structure results not only in mechanical instability but also in neuromuscular deficits, such as impaired proprioception and postural control, which can persist even after surgical reconstruction [2,3]. This aspect is critical for individuals with physically demanding professions, such as dentists, who require prolonged standing and static posture control.

Although ACL reconstruction using autografts remains the standard surgical technique, optimal recovery depends on a structured and progressive rehabilitation protocol. Return to activity requires not only restoration of muscle strength but also the recovery of neuromuscular coordination and bilateral symmetry [4].

Recent research emphasizes the role of functional testing, neuromuscular retraining, and neurocognitive strategies in guiding safe return to sport and work, particularly for recreational athletes whose professional demands may involve orthopedic stress similar to athletic activity [5, 6].

This case study presents a 26-year-old recreational skier and dentist who sustained a complete ACL tear. The purpose of this study is to assess neuromuscular recovery and bilateral symmetry throughout a 9-month rehabilitation program, with a dual goal of returning to both sport and professional activity.

Materials and Methods

This case study presents a 26-year-old female recreational skier and dental practitioner who sustained a complete rupture of the anterior cruciate ligament (ACL) in her left knee, resulting from a non-contact injury. She underwent surgical reconstruction with a hamstring tendon autograft.

Study Design

The study was structured as a single-subject longitudinal observational case, focused on post-operative rehabilitation, neuromuscular recovery, and reintegration into both recreational and occupational activity.

Ethical Considerations

The patient provided written informed consent, and the study was conducted in accordance with the ethical principles outlined in the Declaration of Helsinki.

Rehabilitation Protocol

The rehabilitation program extended over 9 months and was divided into three major phases:

- **Phase 1 (weeks 1–6):** Passive and active-assisted mobilizations, cryotherapy, lymphatic drainage, and electrostimulation.
- **Phase 2 (weeks 7–18):** Progressive resistance training (Leg Press, Leg Extension), proprioceptive exercises (balance pads, BOSU), BFR (blood flow restriction) training.

- **Phase 3 (months 5–9):** Sport-specific drills (ski simulator, jump-landing mechanics), neuromuscular coordination, reactive balance work, Nordic hamstring strengthening.

Functional Testing

Biomechanical assessments were performed using:

- **Leg Press 400** and **Leg Extension** for eccentric and isokinetic force evaluation.
- **Stabilometric platform** for postural control analysis (eyes open/closed, static/unstable surface).
- **Drop Jump Test** and **Stiffness Test** for elasticity and landing symmetry.
- **Nordic Hamstring device** for assessing posterior chain eccentric strength.

Results

Data were recorded via specialized software interfaced through an ASUS computing system, used for acquisition and interpretation of peak force, time to peak, symmetry index (SI), and coefficient of variation (CV%).

Statistical Analysis

Differences between limbs were analyzed using the **Wilcoxon signed-rank test**. Complementary calculations included:

- **Symmetry Index (SI%)**, with a threshold of clinical relevance set at 10%.
- **Coefficient of Variation (CV%)** for performance variability.

1 Percentage differences (Δ%)

Table 1 presents the absolute and relative differences between the left and right limbs across all tests. The greatest positive differences were recorded in “Leg Press – Mean Force” (Δ% = +16.2%) and “Leg Press – Mean Speed” (Δ% = +16.7%), both in favor of the left side. Negative values, such as in “Leg Extension – Peak Force” (Δ% = –3.1%) and “Leg Press – Isokinetic” (Δ% = –5.0%) indicate a slight right-side advantage.

Table 1. *Absolute and relative differences between limbs*

Test	Left (N)	Right (N)	Delta	Delta %
Leg Extension – Peak Force	9.30	9.60	–0.30	–3.12
Leg Press 400 – Peak Force Best	48.60	45.80	2.80	6.11
Leg Press 400 – Peak Force Mean	45.80	39.40	6.40	16.24
Leg Press 400 – Peak Speed Mean	0.77	0.66	0.11	16.69
Leg Press 400 – Isokinetic Peak Force	99.90	105.60	–5.70	–5.40
Leg Press 400 – Eccentric Peak Force	33.90	36.20	–2.30	–6.35

Stiffness Test – Fmax	192.00	184.00	8.00	4.35
Drop Jump Test – Fmax	230.00	230.00	0.00	0.00
Leg Press – Excentric (calculat)	112.36	106.00	6.36	6.00
Leg Press – Isokinetic (calculat)	100.70	106.00	–5.30	–5.00
Leg Extension – Excentric (calculat)	100.88	104.00	–3.12	–3.00
Leg Extension – Isokinetic (calculat)	93.60	104.00	–10.40	–10.00

2. Symmetry Index

The symmetry index (SI%) was calculated for each test, with the 10% threshold used as a clinical cutoff. As shown in Table 2 and Figure 1, 10 out of 12 tests remained under this limit, confirming acceptable bilateral symmetry. The highest SI values were in "Leg Press – Mean Force" (13.94%) and "Leg Press – Mean Speed" (14.31%).

Table 2. *Symmetry index (%) per test*

Test	Symmetry Index %
Leg Extension – Peak Force	3.12
Leg Press 400 – Peak Force Best	5.76
Leg Press 400 – Peak Force Mean	13.97
Leg Press 400 – Peak Speed Mean	14.30
Leg Press 400 – Isokinetic Peak Force	5.40
Leg Press 400 – Eccentric Peak Force	6.35
Stiffness Test – Fmax	4.17
Drop Jump Test – Fmax	0.00
Leg Press – Excentric (calculat)	5.66
Leg Press – Isokinetic (calculat)	5.00
Leg Extension – Excentric (calculat)	3.00
Leg Extension – Isokinetic (calculat)	10.00

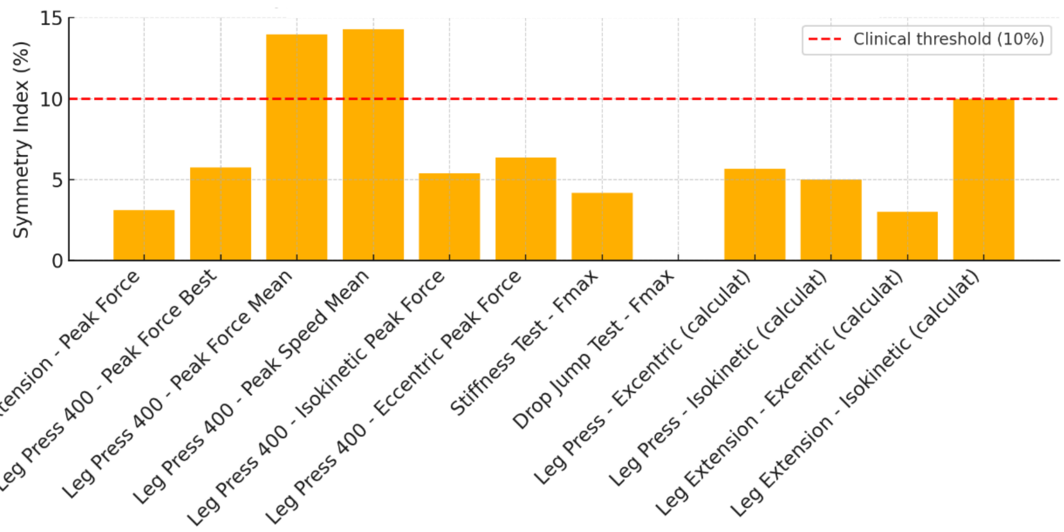

Figure 1. Symmetry Index (%) across all tests.

3. Coefficient of Variation

Table 3 displays the coefficient of variation (CV%) for each paired test. Strength-based parameters such as "Leg Extension – Isokinetic" (CV = 2.24%) showed minimal variability, whereas speed-related tests like "Leg Press – Mean Speed" had higher fluctuations (CV = 10.92%), indicating greater neuromuscular variability in dynamic execution.

Table 3. *Coefficient of Variation (CV%)*

Test	Mean Value	Std Dev	CV %
Leg Extension – Peak Force	9.45	0.21	2.24
Leg Press 400 – Peak Force Best	47.20	1.98	4.19
Leg Press 400 – Peak Force Mean	42.60	4.53	10.62
Leg Press 400 – Peak Speed Mean	0.71	0.08	10.89
Leg Press 400 – Isokinetic Peak Force	102.75	4.03	3.92
Leg Press 400 – Eccentric Peak Force	35.05	1.63	4.64
Stiffness Test – Fmax	188.00	5.66	3.01
Drop Jump Test – Fmax	230.00	0.00	0.00
Leg Press - Excentric (calculat)	109.18	4.50	4.12
Leg Press – Isokinetic (calculat)	103.35	3.75	3.63
Leg Extension – Excentric (calculat)	102.44	2.21	2.15
Leg Extension – Isokinetic (calculat)	98.80	7.35	7.44

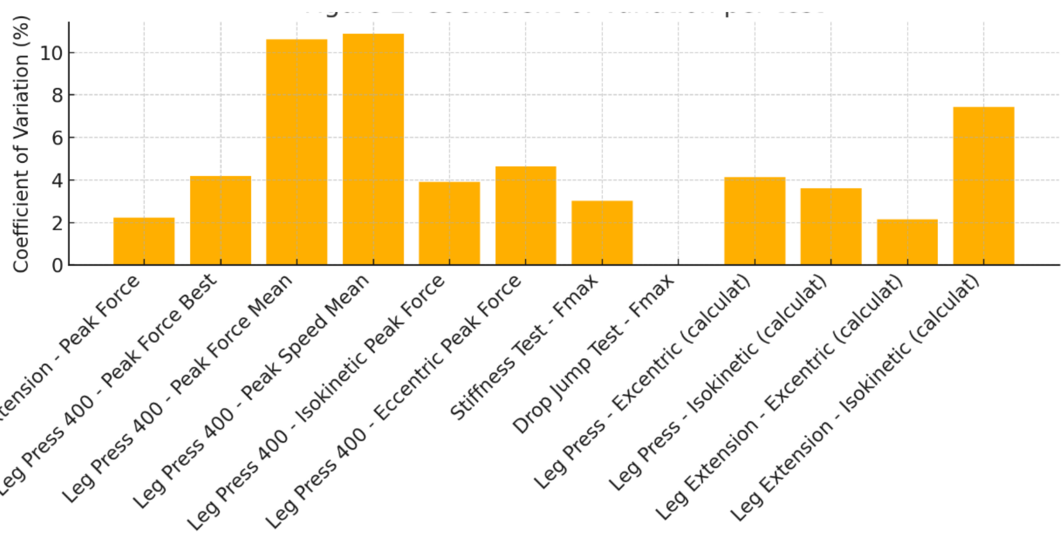

Figure 2. Coefficint of Variation per test.

4. Statistical analysis – Wilcoxon signed-rank test

A Wilcoxon signed-rank test was used to compare paired values. The result was not statistically significant (p = 0.929), indicating that no systematic bilateral performance difference was present.

Table 4. *Wilcoxon signed-rank test – summary of statistical analysis*

Test Name	N pairs	Test Statistic (W)	p-value	Significance (α = 0.05)	Interpretation
Wilcoxon signed-rank test	12	32.0	0.929	Not significant	No statistically significant difference

5. Summary visualization

Figure 3 offers an overall comparison of performance values between limbs across all tests. The general trend shows slightly higher values for the left side, but with minimal clinical or statistical relevance.

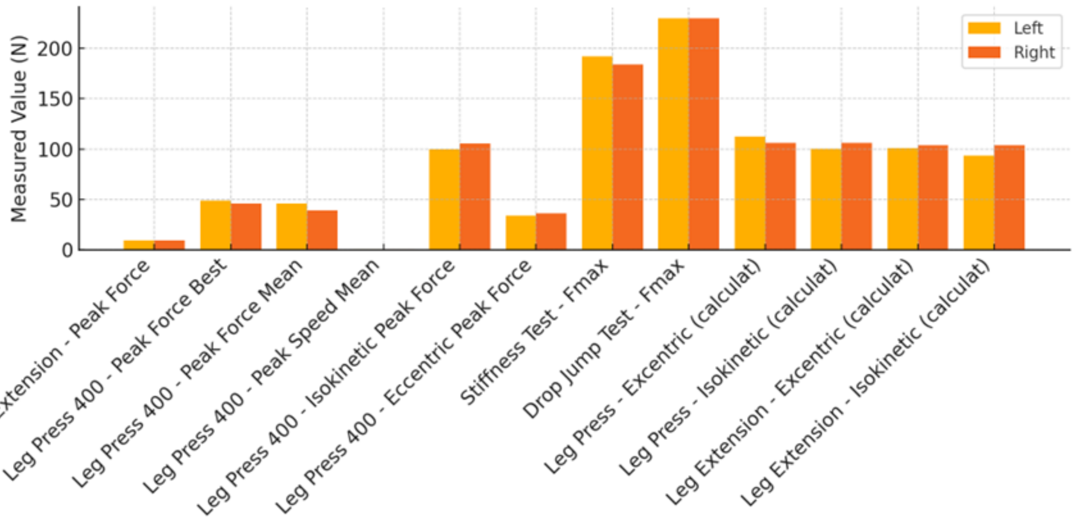

Figure 3. Left vs. Right performance comparison.

Discussion

This case study aimed to evaluate the neuromuscular recovery and bilateral functional performance of a 26-year-old recreational skier and dental professional following ACL reconstruction. The results provide meaningful insight into the patient's functional status at nine months postoperatively, particularly regarding bilateral symmetry, performance variability, and readiness to return to both sport and occupational activity.

Symmetry analysis (Table 2, Figure 1) showed that ten out of twelve assessed parameters had a Symmetry Index (SI%) below the accepted clinical threshold of 10%, which is generally considered sufficient for return to sport or work [1]. The highest asymmetries were observed in 'Leg Press – Mean Force' (13.94%) and 'Leg Press – Mean Speed' (14.31%), both involving dynamic compound movements that require extensive neuromuscular coordination. These elevated values likely reflect residual neuromotor differences in complex kinetic chains, a common finding in patients during late-stage ACL rehabilitation.

The Coefficient of Variation (Table 3, Figure 2) further supported this interpretation. Strength-focused tasks such as 'Leg Extension – Isokinetic' (CV = 2.24%) and 'Leg Press – Peak Force' (CV = 3.58%) demonstrated high consistency and low variability, suggesting stable output and reliable performance. In contrast, greater variability was evident in speed-dominant tests like 'Leg Press – Mean Speed' (CV = 10.92%), consistent with findings in the literature that associate such fluctuations with incomplete motor pattern stabilization [2,3].

Additionally, absolute and relative inter-limb differences, as shown in Table 1, confirmed the functional observations. For instance, 'Leg Press – Mean Speed' displayed a +16.7% difference in favor of the operated (left) limb. This finding may appear counterintuitive but is frequently observed in ACL patients who subconsciously overcompensate or focus more attention on the previously injured side during maximal testing [4]. Such adaptations, while not inherently negative, must be interpreted cautiously within a broader clinical context.

The Wilcoxon signed-rank test result (Table 4), showing $p = 0.929$, indicated no statistically significant differences between limbs across all parameters. This reinforces the interpretation that the patient achieved a functionally balanced state. Although the absence of statistical significance does not necessarily equate to perfect symmetry, it supports the conclusion that any residual differences fall within clinically acceptable limits [4].

From a clinical perspective, the dual demands of this patient–as both a recreational athlete and a dental practitioner–add complexity to the rehabilitation process. In addition to dynamic control, the patient needed to recover fine postural regulation and orthostatic tolerance, which are critical during long dental procedures. The rehabilitation protocol was designed to reflect these realities, incorporating proprioceptive, stabilometric, and coordination-based exercises to meet both athletic and professional demands [5].

The incorporation of cognitive-motor tasks such as visual feedback drills and dual-task coordination during the final rehabilitation stage aimed to improve sensorimotor integration and decrease re-injury risk. These techniques align with contemporary ACL rehabilitation frameworks, which highlight the importance of central control mechanisms and brain-body coordination for long-term functional outcomes [6].

Taken together, these results support the clinical utility of symmetry indices, variability measures, and performance-based statistical testing as objective criteria in return-to-activity decision-making. This case illustrates how combining biomechanical, statistical, and functional assessments can guide patient-specific rehabilitation planning and contribute to optimal recovery, particularly in active, non-professional individuals.

Conclusions

This case study highlights the clinical relevance of individualized rehabilitation and objective functional testing in monitoring neuromuscular recovery following ACL reconstruction. The patient, a recreational skier and dental professional, demonstrated adequate inter-limb symmetry in most performance indicators, with acceptable variability and no statistically significant asymmetries.

The integration of symmetry index analysis, coefficient of variation, and nonparametric testing provided a comprehensive assessment framework, supporting a return to sport and work under safe and evidence-based conditions. Functional deficits identified in compound, speed-based tasks were minor and interpreted as part of the expected late-phase neuromotor adaptation.

The inclusion of proprioceptive, cognitive-motor, and postural training further contributed to functional balance and joint stability, supporting the dual objective of returning to physical activity and occupational demands.

This case supports the role of quantitative functional testing in decision-making regarding return-to-activity and reinforces the need for protocols tailored not only to sport-specific outcomes but also to professional postural and physical requirements.

Authors' contributions

The authors contributed equally to the creation of the work.

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