



Changes in the sensorimotor system and semitendinosus muscle morphometry after arthroscopic anterior cruciate ligament reconstruction: a prospective cohort study with 1-year follow-up

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Abstract

Purpose To evaluate the time course of sensorimotor integration processes involved in balance capability during 1-year follow-up after arthroscopic anterior cruciate ligament (ACL) reconstruction. To evaluate whether an association exists between balance performance and semitendinosus muscle morphometry features.

Methods Twenty-seven patients (mean age 29.6 ± 10.8 years) were prospectively followed with stabilometry and ultrasound at 3 months (T0), 6 months (T1), and 1 year (T2) after arthroscopic ACL reconstruction. Body sway and sensorimotor integration processes were evaluated by calculating the percentage difference of sway (PDS) on two surface conditions.

Results A significant difference in PDS was observed over time ($p < 0.001$). The interaction “Time \times Condition” showed significant differences ($p = 0.02$), with worse performance on the compliant than the firm surface. There was a significant difference in CSA ($p < 0.001$), MT ($p < 0.001$), and %HRD ($p < 0.001$) over time. The interaction “Time*side” was significant for CSA ($p = 0.02$) and %HRD ($p = 0.01$). A negative correlation between PDS on compliant surface and CSA was measured at 3- ($r = -0.71$, $n = 27$, $p < 0.001$) and 6-month post-surgery ($r = -0.47$, $n = 27$, $p = 0.013$).

Conclusions Balance was regained within the first 6 months after surgery, while morphometry of the semitendinosus muscle improved mostly between 6 and 12 months in patients who returned to sports activities. Balance capabilities paralleled semitendinosus muscle morphometry improvements. The instrumental assessment of sensorimotor integration processes is relevant in clinical practice as screening tests for primary and secondary prevention of ACL injury.

Level of evidence Prospective studies, Level II.

Keywords Sonoelastography · Ultrasonography · Gait · Postural balance · Proprioception

Introduction

Rupture of the anterior cruciate ligament (ACL) is one of the most common knee injuries worldwide [16]. ACL reconstruction is recommended as it significantly improves knee stability and the likelihood of return to pre-injury activity [18]. Recently, a low rate of patients that meet the return to sports criteria 6 months after surgery has been reported [23]. This could reflect the complex multifactorial nature of rehabilitation after ACL reconstruction and the need for the development of a comprehensive assessment protocol [9].

ACL rupture affects both knee mobility and stability; it results in abnormal knee kinematics, pain, and functional instability [21]. While objective measurements can help the attending physician and physical therapist in deciding whether to return their patients to sports, the

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clinical difficulty remains of determining the time at which patients can be safely returned to sports and at what level [8, 21]. Finally, clear criteria on progression in rehabilitation are lacking, leaving the current practice of ACL rehabilitation inconsistent [8, 21].

A variety of test batteries have been developed to identify the domains (e.g., muscle function and the range of motion), but more detailed criteria on the time course of the balance recovery are needed. Based on an extensive literature review by Gokeler et al., proprioception testing to date has a low-to-moderate correlation with balance after ACL injury [7]. The methodological quality of the included studies was generally low, however, indicating that newer and more accurate methodologies might be warranted.

It seems plausible that the central nervous system may play a more important role after ACL injury than previously thought [7]. The information consolidated from the vestibular, vision, and proprioception systems is necessary for achieving and maintaining balance [5, 10]. Efficient central somatosensory processes are critical for the development of an effective strategy to stabilize the affected knee and to maintain high athletic activity [7]. The role of sensorimotor integration processes in recovery after ACL injury [7] and the role of muscle morphometry features on balance recovery have been little studied to date.

The aim of the present study was to evaluate the time course of sensorimotor integration processes involved in balance recovery during 1-year follow-up after arthroscopy and to understand whether an association exists between balance performance and semitendinosus muscle morphometry features. It has been hypothesized that over time specific patterns of balance recovery would emerge with progressive optimization of sensorimotor integration processes and improvements in semitendinosus muscle morphometry. To this end, clinical and instrumental assessments were performed by a multidisciplinary team.

Materials and methods

Patient participation was voluntary for this prospective, observational cohort study with 1-year follow-up. Patients underwent arthroscopic ACL reconstruction at the Orthopedic and Traumatology Unit, Borgo Trento Hospital (AOUI of Verona, Italy). Rehabilitation procedures were carried out in the Rehabilitation Center (Rehab Verona, Italy). Assessment procedures were performed at the Neurorehabilitation Unit of the University Hospital (AOUI of Verona, Italy). Subjects were recruited between 2015 and 2016. Follow-up assessments and data collection were performed from 2015 to 2017.

Participants

Consecutive patients with primary ACL reconstruction referred to the Orthopedic and Traumatology Unit, Hospital Borgo Trento (AOUI of Verona, Italy), for arthroscopic ACL reconstruction were eligible for inclusion. Inclusion criteria were: age between 18 and 65 years; diagnosis of ACL injury during sports activity; non-competitive sports activities; arthroscopic ACL reconstruction using the transtibial all-inside technique with a semitendinosus-gracilis (ST-G) graft; post-operative rehabilitation starting within 24 h after surgery; and discharge from rehabilitation between 4 and 6 months after ACL reconstruction. Discharge from rehabilitation was based on clearance by the attending physical therapist or the patient's decision to self-discharge. Exclusion criteria were: tibial plate fracture; ACL rupture of the other knee; ACL reconstruction using a ligament augmentation and reconstruction system [(LARS) Lars SA, Arc-sur-Tille, France]; neurologic or other orthopedic disorders causing gait and balance disorders; incomplete assessment; and rehabilitation program delivery with missing information. All patients gave their written, informed consent. The study was carried out according to the Declaration of Helsinki and approved by the local IRB (n. 1701N01A). Procedures are presented according to the Strobe Statement [22].

Surgical technique

Patients were operated under spinal or general anaesthesia by a single orthopedic surgeon with over 20 years of experience. A transtibial all-inside technique with anatomical reconstruction was utilized. A four-strand semitendinosus/gracilis autograft was harvested and doubled to reconstruct the native ACL. The tension was maintained on the graft, while it was fixed to the femur by Rigid-fix system. An interference screw was used to secure the reconstructed ligament in the tibial tunnel. The tunnel was positioned at the intercondylar notch on the inner face of the external femoral condyle, and the tibial one was performed with a specific guide after ligamentous withdrawal. Isometry was preserved by performing the femoral tunnel 2–3 mm posterior to the original ACL listing and positioning the knee on 50° of flexion; in this way, the two tunnels were aligned as much as possible to avoid angles.

Rehabilitation procedures

Rehabilitation was carried out in three phases. The first phase was before surgery and consisted of conservative therapy [weight discharge and pain control with nonsteroidal anti-inflammatory drugs (NSAIDs)] and exercises to

increase muscle strength, especially of the quadriceps. The second phase during hospital stay immediately after surgery was focused on a standardized post-operative rehabilitation program that emphasized early edema control and knee ROM. The third phase soon after discharge consisted of a structured, individualized rehabilitation program performed at the physiotherapy clinic. All patients attended the rehabilitation program three times a week for the first 2 months, and then twice a week for the following 4 months.

Assessment procedures

Demographic data (e.g., personal habits and sports activities) and clinical data, including results of the Lachman Test and the Anterior Drawer Test, were taken from the patient's medical chart. The patient-reported knee scoring system used in this study was the Lysholm Knee Scale [13]. This subjective report scoring system consists of eight items (limping, support, pain, instability, locking, swelling, stair climbing, and squatting). The score range is from 0 (worst performance) to 100 (best performance). Patients with knee instability score significantly lower than those with minimal or no instability (average scores 75.6 and 93.6, respectively) [13].

Instrumental assessment of balance and muscle morphometry was carried out at the Neurorehabilitation Unit (AOUI, Verona) according to standard practice. Follow-up assessment was performed at 3 (T0), 6 (T1), and 12 months (T2) after ACL reconstruction.

Balance and sensorimotor capabilities

Balance was evaluated using a stabilometric platform (Technobody©) (Website: <http://www.tecnobody.it>). This electronic monoaxial platform measures dislocation of the CoP, while the subject maintains standing position in different sensory conditions. The patient stands barefoot with arms alongside the body and feet in a standardized heel-to-toe position according to a previously tested protocol [6].

The main stabilometric parameter was the mean magnitude of sway area (A) (mm²) with eyes open (EO) and eyes closed (EC) in two conditions: firm surface and compliant surface. Each assessment was performed on a firm (floor) and a compliant surface (foam mats). Each session lasted 30 s. Body sway and sensorimotor integration processes were evaluated by computing sway area with and without vision in the two sensory conditions and by calculating the percentage difference of sway (PDS) between EC and EO conditions [3]. Test–retest reliability of PDS investigated by Tjernström et al. reported more consistence in repeated measures than RQ [20].

Semitendinosus muscle morphometry

Muscle size and quality of the semitendinosus muscles were evaluated using a Logiq[®] Book XP portable ultrasound system (GE Healthcare; Chalfont St. Giles, UK). The ultrasound system has been reported to be a reliable technique for examining hamstring muscle size and quality [15].

The cross-sectional area (CSA), muscle thickness (MT), and elastic properties (% HDR) of the semitendinosus muscle were measured and compared between the affected and the unaffected leg [15]. Elastasonography allows evaluation of biological tissue stiffness. Shear wave elastography was performed using a multifrequency linear probe at a frequency between 4 and 15 MHz (SL 15-4). A physician evaluated the lower limbs from left to right. Measurements were taken on the semitendinosus muscle belly. The patient lay with face down and the thigh resting on the table in medial rotation and the leg medially rotated. The knee was flexed at about 45 degrees. The probe was placed at 50% on the line between the ischial tuberosity and the medial epicondyle of the tibia to obtain a transverse scan.

Statistical analysis

The scarcity of information on this topic hampers sample size calculation. The achieved statistical power, which refers to the probability of correctly rejecting the null hypothesis of no effects, was computed (achieved statistical power: 87%). Descriptive statistics as reported as the mean, standard deviation, and 95% confidence intervals for demographic and clinical outcomes. The Shapiro–Wilk Test was used to evaluate normality of data. Since the data were normally distributed, parametric tests were used for inferential statistics. The mean percentage difference in postural sway area (PDS) was evaluated by the ratio $[(RQ - 1)/(RQ + 1) \times 100]$, where the Romberg quotient (RQ) was measured by $[(\text{sway area score EC})/(\text{sway area score EO})]$ [3]. This ratio was used to quantify the influence of vision on postural control. Positive values reflect a larger sway in the EC than the EO condition [3], indicating a major contribution of vision in postural sway control. For the percentage difference of sway area (PDS) analysis, two-way mixed ANOVA was applied using “Time” as the within-group factor and “Condition” (firm/compliant surface) as the between-group factor. Muscle morphometry was analyzed by two-way mixed ANOVA using “Side” (affected/unaffected leg) as the between-group factor and the interaction of “Time × Side” to assess potential differences between the affected and the unaffected leg. Two-tailed Student's *t* test for paired data was used for post-hoc comparisons. A Pearson product-moment correlation was run to determine the relationship between PDS and muscle morphometry. Alpha was set at $p < 0.05$. Bonferroni's correction was applied for multiple comparisons ($p < 0.025$).

Statistical analyses were performed using SPSS 20.0 (IBM SPSS Statistics for Windows, Version 20.0. Armonk, NY, USA).

Results

A total of 39 patients (*M:F*; 29:10) were initially enrolled in the study. Baseline demographics and clinical characteristics are reported in Table 1. Fifty-eight percent (18/31) of patients underwent ACL reconstruction of the right knee and 42% (13/31) reconstruction of the left knee. Eight patients withdrew from the study after the first assessment. Four patients underwent reconstruction with a LARS artificial ligament and then excluded from analysis. The remaining 27 patients were prospectively followed (Fig. 1). No surgical complications occurred that could have affected physical rehabilitation. All patients regained complete knee ROM and knee stability, as measured by the Anterior Drawer Test and Lachman Test. All patients returned to sports activity between 4 and 6 months after surgery. A minimal-to-no functional limitation was reported by patients using the Lysholm Knee Scale (Table 1).

Balance

A significant difference in PDS was observed over time ($p < 0.001$). The interaction “Time \times Condition” showed significant differences ($p = 0.021$), with worse performance on

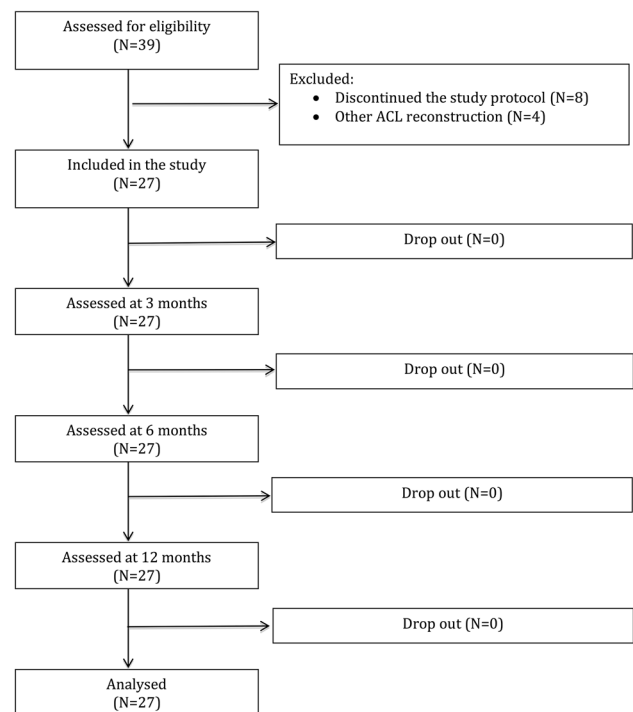


Fig. 1 Flow diagram of the study

the compliant surface. Significant between-condition differences were found for PDS ($p < 0.001$). Post-hoc comparisons showed that these differences were significant between T0–T1 and T0–T2 in the firm surface condition (Table 2; Fig. 2).

Semitendinosus muscle morphometry

There was a significant difference in CSA ($p < 0.001$), MT ($p < 0.001$), and %HRD ($p < 0.001$) over time. The interaction “Time*side” was significant for CSA ($p = 0.017$) and %HRD ($p = 0.01$). There were significant differences between the affected and the unaffected side for CSA ($p = 0.02$), MT ($p = 0.05$), and %HDR ($p < 0.001$) (Table 3; Figs. 3 and 4). Post-hoc comparisons are shown in detail in Table 3. There was a good, negative correlation between PDS on the compliant surface at 3 months and CSA at 3-month post-surgery, which was statistically significant ($r = -0.71$, $n = 27$, $p < 0.001$). There was a low, negative correlation between PDS on the compliant surface at 3 months and CSA at 3-month post-surgery, which was statistically significant ($r = -0.47$, $n = 27$, $p = 0.013$).

Discussion

The main finding of this prospective, observational study was that balance capability and changes in the sensorimotor system were correlated with time post-surgery. Most of the

Table 1 Baseline demographics and clinical characteristics

| | Mean (\pm SD) | Range |
|--------------------------|------------------|--------------|
| Age (years) | 29.6 (10.8) | 17 to 66 |
| Weight (kg) | 75.6 (12.7) | 48 to 105 |
| Height (m) | 1.76 (0.09) | 1.50 to 1.93 |
| BMI (kg/m ²) | 24.3 (2.6) | 20.0 to 29.3 |
| TLKSS | | |
| 3 months | 91.3 (9.8) | 70 to 99 |
| 6 months | 95.1 (8.4) | 72 to 100 |
| 12 months | 98.0 (4.5) | 90 to 100 |
| Range of motion | | |
| Knee extension | | |
| 3 months | -0.3 (0.9) | -3 to 0 |
| 6 months | -0.3 (1.1) | -5 to 0 |
| 12 months | 0 (0) | 0 to 0 |
| Knee flexion | | |
| 3 months | 106.4 (6.9) | 90 to 115 |
| 6 months | 113.8 (3.8) | 110 to 120 |
| 12 months | 117.0 (4.5) | 110 to 120 |

SD standard deviation, ROM range of motion, BMI body-mass index, TLKSS Tegner Lysholm Knee Scoring Scale

Table 2 Percentage difference of Sway area (PDS) as measured by stabilometric assessment at 3-, 6-, and 12-month post-surgery

| | 3-month (T0) | | 6-month (T1) | | 12-month (T2) | | Mixed ANOVA | | Within-group Post-hoc comparisons | | | Between-group Post-hoc comparisons | | |
|-------------------|---------------|---------------|---------------|---------------------|------------------|--------------------|-------------|------------------|-----------------------------------|------------------|-------------------|------------------------------------|---------------------|----------------------|
| | Mean (SD) | Mean (SD) | Mean (SD) | Mean (SD) | Mean (SD) | Mean (SD) | Time | Time × Condition | T0-T1 | T1-T2 | T0-T2 | T0 | T1 | T2 |
| | Mean (SD) | Mean (SD) | Mean (SD) | Mean (SD) | Mean (SD) | Mean (SD) | p value | p value | p value (95% CI) | p value (95% CI) | p value (95% CI) | p value (95% CI) | p value (95% CI) | p value (95% CI) |
| Firm surface | 40.29 (13.86) | 20.55 (15.74) | 24.07 (14.85) | <0.001 (11.6; 27.8) | n.s (-11.6; 4.5) | <0.001 (8.4; 23.9) | <0.001 | 0.021 | <0.001 | n.s (-1.9; 12.1) | n.s (-7.1; 8.7) | n.s (-12.2; 0.4) | <0.001 (-29.1; -12) | <0.001 (-24.8; -7.6) |
| Compliant surface | 46.21 (8.73) | 41.10 (15.53) | 40.27 (16.71) | <0.001 | n.s (-1.9; 12.1) | n.s (-1.3; 13.21) | <0.001 | | n.s (-1.9; 12.1) | n.s (-7.1; 8.7) | n.s (-1.3; 13.21) | n.s (-12.2; 0.4) | <0.001 (-29.1; -12) | <0.001 (-24.8; -7.6) |

SD standard deviation, n.s. not significant, T0 3 months, T1 6 months, T2 12 months, PDS percentage difference of Sway, CI Confidence interval

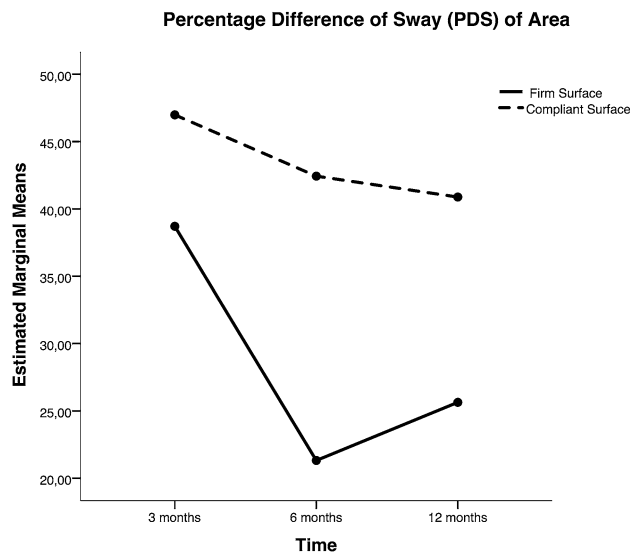


Fig. 2 Balance and sensorimotor capabilities changes at 3-, 6-, and 12-month post-surgery

improvements occurred within the first 6 months after surgery, while a slight decline was noted from 6 to 12 months. Evaluation of the postural strategies used in maintaining balance under different sensory conditions showed that the patients relied mostly on visual information to control their posture at 3-month post-surgery. Inversely, positive results reflecting a decrease in body sway in the EC condition were noted at 6- and 12-month post-surgery. The former could be interpreted as difficulty in processing (or loss of) somatosensory information coming from the lower limbs to maintain balance partially compensated by a major contribution of vision to achieve postural sway control. The latter may depend on a minor contribution of vision in postural sway control and improvement in sensorimotor strategies during balance. A similar trend was observed in both firm and compliant surface conditions, with worse performance measured on the compliant surface.

Knee stability is provided by a combination of primary and secondary stabilizers [8, 25]. The ACL is thought to play a key role in the central somatosensory feedback loop by providing afferent inputs on knee joint position and movement [1]. Animal studies have shown muscular excitation in the hamstring when the ACL is pulled and activity of the gamma motor neurons of the muscles around the knee when the ligament is put under tension. Impulses from the sensory nerves in the ACL are activated during overstretching and combined knee extension and rotation. In humans, mechanical or electrical stimulation of the ACL elicits excitation in the hamstring muscles. During static isometric and isokinetic muscular activity (and also during gait), stimulation of the ACL inhibits ongoing activity. This long latency inhibitory reflex (60–120 ms) indicates that the ACL might

Table 3 Semitendinosus muscle morphometry properties at 3, 6, and 12 months after surgery

| | 3-month (T0) | | 6-month (T1) | | 12-month (T2) | | Mixed ANOVA | | | | Between-group Post-hoc comparison | | | | | |
|-----------------------------|--------------|--------------|--------------|-------------------|----------------------|---------------------|-------------|-----------|---------|--------------------|-----------------------------------|------------------|------------------|------------------|------------------|--|
| | Mean (SD) | Mean (SD) | Mean (SD) | Mean (SD) | Mean (SD) | Mean (SD) | Time | Time×side | Side | T0 | T1 | T2 | T0 | T1 | T2 | |
| | | | | | | | p value | p value | p value | p value (95% CI) | p value (95% CI) | p value (95% CI) | p value (95% CI) | p value (95% CI) | p value (95% CI) | |
| CSA (cm²) | | | | | | | | | | | | | | | | |
| Affected leg | 7.81 (1.13) | 8.06 (1.41) | 9.42 (1.37) | n.s. (-0.7; 0.2) | <0.001 (-1.8; -0.9) | <0.001 (-2.1; -1.1) | <0.001 | 0.017 | 0.02 | <0.001 (-2; -0.6) | n.s. (-1.7; 0.1) | n.s. (-1; 0.5) | | | | |
| Unaffected leg | 9.14 (1.43) | 8.87 (1.78) | 9.68 (1.43) | n.s. (-0.4; 0.9) | n.s. (-1.3; -0.3) | 0.004 (-1.1; 0.01) | | | | | | | | | | |
| MT (cm) | | | | | | | | | | | | | | | | |
| Affected leg | 2.26 (0.34) | 2.43 (0.37) | 2.66 (0.31) | n.s. (-0.3; -0.1) | <0.001 (-0.3; -0.12) | <0.001 (-0.6; -0.2) | <0.001 | n.s. | 0.05 | n.s. (-0.4; -0.01) | n.s. (-0.4; 0.1) | n.s. (-0.3; 0.1) | | | | |
| Unaffected leg | 2.49 (0.41) | 2.58 (0.56) | 2.78 (0.37) | n.s. (-0.3; 0.1) | 0.003 (-0.4; 0.02) | n.s. (-0.5; -0.1) | | | | | | | | | | |
| %HDR | | | | | | | | | | | | | | | | |
| Affected leg | 58.24 (5.83) | 54.85 (5.43) | 49.94 (3.38) | n.s. (0.4; 6.4) | <0.001 (3.05; 6.8) | <0.001 (5.6; 11) | <0.001 | 0.01 | <0.001 | <0.001 (4.9; 11.1) | 0.013 (0.8; 6.8) | 0.006 (0.8; 4.8) | | | | |
| Unaffected leg | 50.22 (5.48) | 51.01 (5.51) | 47.10 (3.90) | n.s. (-3.4; 1.9) | 0.015 (2; 5.8) | <0.001 (0.7; 5.6) | | | | | | | | | | |

CSA cross-sectional area, MT muscle thickness, HDR (%) percentage Hard density ratio, SD standard deviation, n.s. not significant, T0 3 months, T1 6 months, T2 12 months, CI Confidence interval

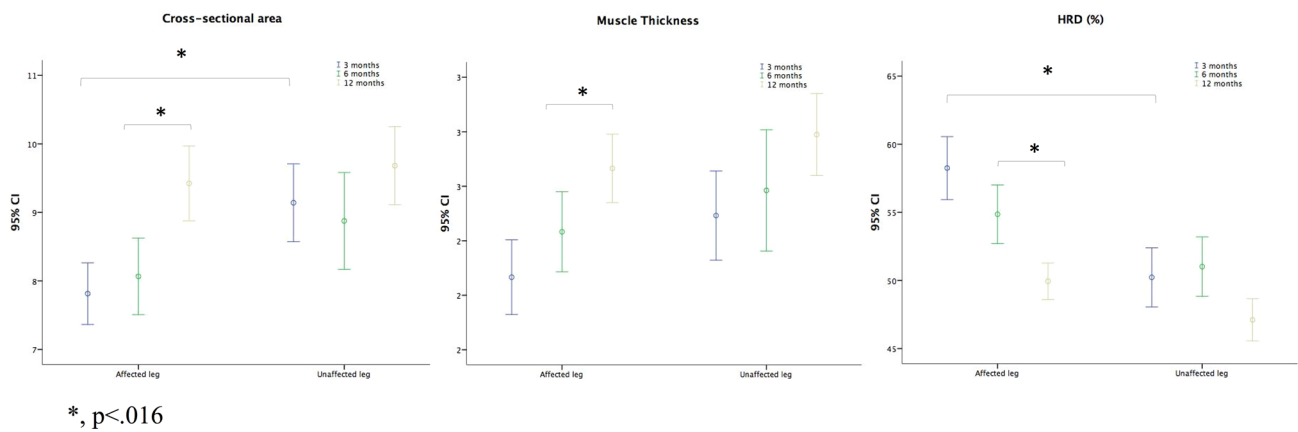
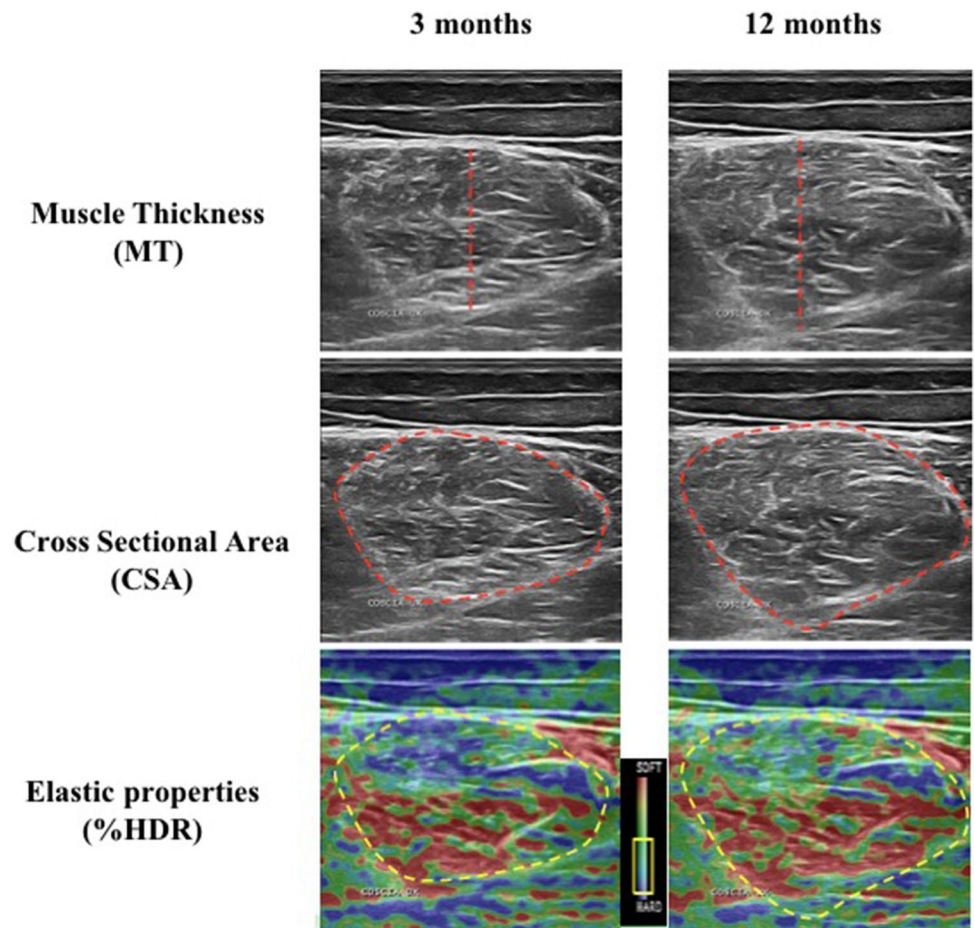


Fig. 3 Semitendinosus muscle morphometry changes at 3-, 6-, and 12-month post-surgery

Fig. 4 Semitendinosus muscle morphometry changes as measured by the ultrasound system



have an afferent function which, in turn, might influence knee dynamics [12].

A full review of the role of the ACL in proprioception is beyond the scope of this study. Overall evidence points out that ACL deficiency may affect knee proprioception [7]. The low methodological quality of existing studies calls for

more accurate methodologies that may help to revise current knowledge. Furthermore, new assessment tools to investigate the role of the somatosensory system in particular are needed [7]. What can be said is that the sensory afferent inputs from the somatosensory, vestibular, and visual systems are crucial for balance. The inputs are processed to

create the reference system on which balance is based [10]. For example, healthy subjects on a firm support base rely on somatosensory (70%), vision (20%), and vestibular (10%) information [10].

Stabilometric assessment of the afferent properties of the ACL has yielded interesting insights. Stabilometric assessment allows for determining balance by measuring the displacement of the center of pressure (CoP) on a force platform [6]. In quiet stance, the CoP reflects the position of the support base for the projection of the center of mass (CoM), and it reflects the activity of postural muscles [6]. From a biomechanical point of view, CoP displacement reflects the neuromuscular responses generated by the central nervous system to maintain balance. Static posturography has excellent sensitivity to detect differences in control of balance across the human lifespan [6]. It provides a measure of overall health and allows investigation of the underlying pathophysiological mechanisms by manipulating visual (i.e., eyes closed) and proprioceptive feedback (i.e., compliant surface) conditions. A recent review by Negahban et al. showed that balance is impaired in both legs during single-leg stance (without applying external perturbation) in patients with untreated ACL injury. The within-group difference in the eyes-open condition confirms the bilateral deficit of balance. However, the within-group difference during the eyes-closed condition indicates, again, that ACL injury affects the injured leg more than the uninjured leg [14].

In their systematic review, Howells et al. [11] selected studies that compared balance, as measured using a force platform, in patients following ACL reconstruction surgery with a control group. The results of ten studies ($n = 644$ participants; mean follow-up duration 29 months) showed that in static balance tasks there was a trend towards improved balance in the control group for the eyes-open but not the eyes-closed conditions. Only four studies evaluated dynamic balance and produced somewhat mixed results. Nonetheless, there was evidence to suggest impaired balance in patients following ACL reconstruction surgery when compared to controls, particularly for the more challenging tasks. Indeed, the eyes-closed condition of postural testing is more sensitive to evaluate integration of afferent (proprioceptive) inputs than the eyes-open condition and it allows estimation of the contribution of this information to maintaining balance [10].

At least six resources are essential for balance, including biomechanical constraints, movement strategies, sensory strategies, orientation in space, control of dynamics, and cognitive processing [10]. A disorder in any one of these resources can lead to postural instability, especially in the elderly [5]. Given the young age of patients who sustained an ACL injury, it is likely that the observed balance deficits depended mostly on defective sensory integration strategies [7]. The results of the present paper are shared by published

findings that balance deficit might be due to the loss of sensory information in patients with ACL reconstruction. Accordingly, vision appears to be dominant in compensating for the decreased contribution of the injured ACL in integrating afferent inputs [24].

Morphometric assessment of the semitendinosus muscle showed improvement in CSA mostly from 6 to 12 months (Fig. 4), as confirmed by within-group post-hoc comparison that showed no differences in the affected leg at T1. The negative correlation between percentage difference of sway area and semitendinosus cross-sectional area at 3-month post-surgery suggests that as the value of CSA variable increases, the value of the PDS (on the compliant surface) variable decreases. That is, better optimization of sensorimotor strategies is related to better viscoelastic muscle properties. Although the previous findings reported that hamstring muscle atrophy could persist for up to 9–11 years after ACL reconstruction [17], some factors could account for this discrepancy. First, the subjects involved in the present study returned to sports activity during the first year after reconstruction, which could have improved muscle recovery after the initial rehabilitation program. Moreover, the CSA was evaluated at 50% on the line between the ischial tuberosity and the medial epicondyle of the tibia, while in some previous studies, assessment was performed 7–16 cm above the joint line, which is distal to the muscle belly. Burks and et al. reported that at that level, the muscle was absent in many of their patients because of the window-shade effect [2]. This phenomenon can occur after tendon harvest, and it consists of a combination of distal hypotrophy and proximal retraction of the affected muscle [17].

A recent study by Suydam et al. [19] using continuous shear wave electrography investigated the viscoelastic properties of the regrown semitendinosus tendon post-ACL reconstruction. A positive correlation between time post-operative and shear elasticity was found in 13 patients between 6- and 24-month post-surgery. However, more than 12 months were necessary for the patients to regain a large percentage of the tendon's mechanical properties compared with the unaffected leg [19]. The recovery of mechanical properties indicates the possibility to restore the semitendinosus muscle–tendon complex function, which is essential for determining the potential strength of the semitendinosus muscle. Moreover, these improvements may parallel improvement in sensorimotor integration processes involved in postural sway control under challenging conditions (eyes closed on a compliant surface).

Rehabilitation is thought to play a crucial role in balance recovery after ACL reconstruction [7]. Cooper et al. [4] reviewed the effect of proprioceptive and balance training on outcomes in patients with ACL deficiency and ACL-reconstructed knees. Proprioceptive and balance training was associated with improvements in knee joint position sense,

muscle strength, perceived knee function, and hop testing in ACL-deficient knees. Only one study examined ACL-reconstructed knees and found improvements in quadriceps and hamstring strength as well as proprioception [4]. Our results are in line with the previous findings and highlight how balance improvements after rehabilitation might be limited to the training period. This suggests that knee surgery patients need to continue a specific program for reducing proprioceptive deficits also in the long term. Returning to sports activity cannot be sufficient for reducing such deficits. An open question is whether ACL injury causes a bilateral deficit of balance or pre-injury deficits predispose patients to ACL damage [14]. In addition, variations in rehabilitation protocols and sports activities may take into account possible central somatosensory changes which are crucial to the development of an effective strategy to stabilize the affected knee [7].

The main strength of the present study is the comprehensive instrumental assessment. In most previous studies, the outcomes were knee stability on physical examination, functional and patient-based outcomes, and radiographic outcomes. Physical assessment is the mainstay of the diagnosis and management of these patients. More attention should be directed to the use of standardized devices to yield more consistent results, in combination with patient-reported outcomes [8]. In addition, the instruments employed in this study are easy to use in the clinical setting: they provide a quick report of performance, unlike other expensive and time-consuming equipment (e.g., motion gait analysis). Other methodological strengths were the use of the same surgical technique in the majority of patients that the patients were homogeneous for the level of sports participation (non-competitive level), complied with the rehabilitation program, and returned to sports within 12 months after surgery. The methodological limitations included the lack of long-term follow-up and power calculation, rehabilitation was individualized, and patients were not blinded. This could have influenced patient performance positively or negatively.

As far as the clinical is concerned reference to consider a patient as a complex system with the interplay of physiological, biomechanical, behavioral, and psychological factors [23]. New findings on the precise role of changes in the sensorimotor system after ACL injury emphasized the development of specific assessment protocols. Given the feasibility and validity of the stabilometric assessment, stabilometry under different sensory conditions should be included in clinical to define physiological impairments after ACL injury better. It might be correlated with other contributing factors involved in ACL recovery such as muscle morphometry. The instrumental assessment of sensorimotor integration processes could be relevant in clinical practice as screening tests for primary and secondary preventions of ACL injury, to rethink evidence-based rehabilitation

protocols after surgery and to identify clinical predictors for recovery and return to sports activity.

Conclusions

Summarizing, balance was regained within the first 6 months after surgery, while morphometry of the semitendinosus muscle improved mostly between 6 and 12 months in patients who returned to sports activities. Comprehensive instrumental and clinical assessment may be useful to define the time course of postsurgical recovery and investigate the precise role of the changes in the sensorimotor system after ACL injury.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no competing interest.

Ethical approval All procedures performed in the study were in accordance with ethical standards of the IIRB and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. The Institutional review board approval for the study was provided (no. 1701N01A).

Informed consent Informed consent was obtained from all individual participants included in the study.

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