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Quadriceps and hamstring muscles strength differences in adolescent and adult recreational athletes 6 months after autograft bone–patellar-tendon–bone anterior cruciate ligament reconstruction: A retrospective study

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ABSTRACT

Background: Knee muscle strength recovery after anterior cruciate ligament reconstruction (ACLR) is crucial for a safe return to sport (RTS) but it is poorly described in the adolescent population. Therefore, we compared the knee muscle strength at 6 months post-surgery in adults and adolescents. We hypothesized a greater muscular strength in adolescents 6 months after ACLR.

Methods: This was a retrospective analysis of 55 adolescents (13–18 years old) and 76 adults (19–39 years old) who underwent ACLR with autograft bone–patellar-tendon–bone (BPTB), subjected to isokinetic tests 6 months after surgery. The following outcomes were analyzed: (1) the maximum torque of hamstrings (H) and quadriceps (Q) during flexion and extension at 30°/s normalized by body weight; (2) hamstrings to quadriceps strength ratio (HQ ratio); (3) injured to uninjured leg muscle strength ratio (limb-symmetry index, LSI).

Results: Both adults and adolescents produced lower Q torque with the injured leg compared with uninjured, but similar H torque. In adolescents, the injured Q torque and the Q-LSI were higher compared with adults. In both populations, the Q-LSI was lower than the H-LSI and the HQ ratio in the injured leg was higher compared with uninjured. Adolescents showed a lower HQ ratio in injured legs.

Conclusions: At 6 months after ACLR both adolescents and adults did not recover Q strength in the injured leg. However, adolescents showed larger Q strength compared with adults. The HQ ratio analysis showed that 6 months after surgery both groups are not ready for a safe RTS.

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1. Introduction

During the last decade a rapid increase in the involvement of children and adolescents in sports activities has been observed [1]. This has resulted in increased incidence of injury in the skeletal immature population [2,3]. This trend has been described worldwide especially in the population between 13 and 17 years old, in particular knee sprains. Among various knee sprains, anterior cruciate ligament (ACL) lesion is one of the most frequently diagnosed injuries [4–6].

Depending on the characteristics of the patient and the type of lesion, two possible treatments are described in the literature for [7,8]: a conservative approach based on rehabilitation program, and an operative treatment followed by rehabilitation program [9]. The recent research focused on the best ACL reconstruction (ACLR) technique for skeletally immature patients, the type of graft that better matches the patient and surgeon needs [10,11]. Conversely, the literature poorly described clinical outcomes in skeletally immature patients after ACLR and only few focused on the return to play.

The time and criteria for a safe the return to sports (RTS) especially in skeletally immature patients are not well described. Thus far, the literature has suggested 6–9 months as the appropriate time for RTS after ACLR and adequate rehabilitation in general populations [12]. In recent years, however, numerous studies have shown that 6 months following ACLR surgery may not be enough to safe RTS [9], with patients at high risk of retear in the 2 years following surgery [13]. For the adolescent population, it was recently recommended by the International Olympic Committee Consensus Statement to establish post-surgical rehabilitation programs that allow RTS 9 months after surgery [9]. Additionally, it was also suggested to avoid pivoting movement until 1 year after surgery [9].

The review by Marom et al. [14] reported a high variability in the timing and criteria for RTS following ACLR, and no specific protocols to guide the RTS were identified in the literature. Among the criteria proposed for the RTS evaluation, many studies took into consideration the results obtained by isokinetic tests [13,15,16], a dynamic measure of muscle strength that provides an objective evaluation of rehabilitation progress [17]. The isokinetic test has been described as a useful tool in the hands of the surgeon and sports medical doctor to establish the right time for RTS in the adult population [18]. In fact, there are some studies in the literature which describe the results of isokinetic tests in the pediatric population after ACLR [19–21]. Therefore, this study focused on comparing the results obtained by adult and adolescent patients in the isokinetic tests performed during their rehabilitation phase to better understand the differences between the two groups in muscle recovery.

The aim was to evaluate quadriceps and hamstrings isokinetic strength at 6 months in adult and adolescent patients treated with an ACL reconstruction with bone–patellar-tendon–bone (BPTB), in order to evaluate whether or not adolescent patients follow the same timing of recovery as adults.

2. Materials & methods

This was a retrospective study in patients who underwent autograft ACLR surgery with BPTB between October 2009 and December 2020 at the same study institution. Institutional review board approval was obtained for this study and all participants signed written consent before the start of the study.

The inclusion criteria were: (1) age within the range 12–40 years old, (2) ACLR surgery using BPTB autograft technique with or without concomitant meniscal tears, (3) postoperative isokinetic tests (Technogym REV 7000 at a speed of 30°/s), (4) postoperative follow up at 6 months, (5) presence of a complete report on the characteristics of the injury and of the patient [22]. The exclusion criteria included: (1) previous contralateral or ipsilateral arthroscopic or open knee surgery, (2) patients with congenital ACL deficiency, (3) a knee movement below the requested range (from 5° to 90°) during the isokinetic testing, (4) the presence of neurologic or rheumatologic pathology, or the presence of diabetes mellitus (5) multi-ligamentous knee surgeries or patients with associated anterolateral ligament reconstruction, (6) associated chondral or osteochondral lesions, (7) complications after surgery such as arthrofibrosis, significant anterior knee pains, sepsis, (8) professional or competitive athletes (Tegner Activity Scale level of 9 or 10) [22].

The initial database included 198 patients who underwent isokinetic tests after ACLR surgery; 67 of these candidates were excluded (37 candidates were eliminated due to incomplete reports on injury and patient history, and 30 did not meet the inclusion/exclusion criteria).

The remaining 131 patients met the inclusion criteria and were included in the study. The patients were divided in two groups according to age at time of ACLR: adult patients (n = 76, from 19 to 40 years old) and adolescent group (n = 55, from 13 to 18 years old).

2.1. Surgical procedure

Surgery was performed following the standard ACLR procedure with autograft BPTB technique, with the patient in the supine position, with tourniquet at the proximal injured thigh. Arthroscopic diagnostic evaluation was performed around all joint structures to assess whether concomitant lesions were present. Any necessary meniscal or chondral procedures were performed before ACLR surgery. Routine removal of residual ACL tissue and preparation of the notch were performed. For the graft collection a W-shaped skin incision was made, centered on the patellar tendon; the central third of the tendon with associated bony insertions was collected preserving the peritendon. Tibial tunnels were drilled with the guide set between 50° and 55° medially to the anterior tibial apophysis. Transtibial femoral socket was performed in both adult and adolescent patients. We opted for transtibial drilling technique to obtain more central femoral tunnels and to reduce the physeal area of injury in comparison with anteromedial portal techniques [23,24]. Femoral socket was drilled with a depth that was 5 mm greater than the length of the patellar bone block (30 mm of length as maximum) and the graft was positioned and fixed proximally with two resorbable pins and distally with a resorbable screw. Lavage and stability and motility tests were performed through full range of motion several times for tensioning the graft and to reach any graft impingement, particularly in full extension.

Compared with adults, the specificity of knee arthroscopy in adolescent patients was due to reduced joint size and nearby growth plates [25]. It was a feasible surgery even on adolescents, but precautions were required because lower limb growth is mostly restricted around the knee: (1) small-size equipment (forceps, shaver, radiofrequency electrodes, drill guides, fixation material); (2) in some cases a 2.7-mm optic oriented at 30° instead of the traditional 4-mm optic; (3) gentler exposure maneuvers for joint opening (both valgus/varus and traction) to avoid iatrogenic damage; (4) tunnels avoiding the periphery of the physis and the area of Ranvier and being as small as possible in diameter (<9 mm) and as vertical as possible; (5) interference screws not exceeding the growth plate but being epiphyseal or metaphyseal, using the smallest possible diameter; (6) fluoroscopy only in patients with closing physis during surgery to check the tunnel trajectory and the position of rigid fix in respect of the periphery of the growth plate.

2.2. Rehabilitation program

All patients followed an identical post-surgical rehabilitation regimen and underwent periodic reassessments to monitor their progress. This protocol involved initial non-weightbearing using two crutches with a hinged knee brace locked in full extension for 1 week, alongside cryotherapy, a 5-day course of non-steroidal anti-inflammatory drugs (if not contraindicated and depending on patient's weight) and anti-thromboembolic prophylaxis until weightbearing was permitted [26,27]. Anti-thromboembolic prophylaxis was prescribed in adolescents after menarche for girls and after a Tanner grade 3 for boys. The brace was maintained for 3 weeks postoperatively to reduce complications: providing better pain control, improving patient confidence during the first period of the rehabilitation program reinforcing quadriceps muscle, maintaining better control over leg extension after surgery [27].

Starting from the first day after surgery, all patients commenced a 3-hour daily regimen on a continuous passive motion (CPM) machine, operating at minimal speed with a range from 0 to 70°, with a 10° increase every 2 weeks. After 1 week, weightbearing was gradually reintroduced with the brace, without range of motion restriction. Simultaneously, patients were permitted to initiate kinesiotherapy and hydro kinesiotherapy after stitch removal. The brace was removed after 3 weeks.

Post-surgery, patients engaged in isotonic, proprioceptive, and strength training exercises to enhance functionality and limb strength. Specifically, at 3 months postoperatively, they were cleared to start running and undertake sport-specific rehabilitation, with the aim of resuming pivoting activities at the 6–12 months according to age, clinical evaluation, single-leg hop tests, dynamic knee valgus control, adequate movement quality in landing during hop and isokinetic tests.

2.3. Isokinetic test

The isokinetic test was part of this periodic re-evaluation protocol; the test was composed of five phases: (1) warm-up, (2) treadmill exercises, (3) press exercises, (4) isokinetic test and (5) proprioceptive test. The study focused only on the results obtained with the isokinetic test [28].

The test was performed with Technogym's REV 7000 at a specific speed of 30°/s that allows focusing on the maximum force of the examined limb reducing problems of coordination and muscle activation [16]. The patient sat with the tested leg locked to the seat of the machine to prevent movement during the exercise, while the ankle was fastened to the mobile arm that guided the movement and measured the applied force. The isokinetic test had a starting warm-up phase consisting of five repetitions, requiring a progressive increase in strength. After that the actual isokinetic testing procedure was performed consisting of five repetitions applying maximal force in the concentric phase of the movement both in extension and flexion: the maximum value obtained during repetitions was considered for the investigation. The machine increased the resistance to the patient's thrust proportionally to the applied force. The reference range of motion of the machine was between 5° and 90°. The patients underwent five repetitions at maximal force to optimize the test and accurately determine peak torque values: this approach aligns with established literature, which suggests that at least four repetitions are necessary to achieve reliable results without excessive workload or time consumption [29].

We measured the maximum torque produced by hamstrings (H) and quadriceps (Q) muscles (i.e., muscle strength) during flexion and extension movements at 30°/s. These data were then normalized by body weight to avoid biases related to weight difference between the two groups. We then calculated the limb-symmetry index (LSI) for both quadriceps and hamstrings, as the ratio of the maximum torque between the injured and the non-injured leg. As suggested by Sugimoto et al., an LSI > 90% may be one of the criteria to define when an athlete is ready to RTS [30]. We therefore calculated the percentage of patients that overcame that threshold in the adult and the adolescent populations. Finally, we calculated the HQ ratio, which is the ratio of flexor muscle (H) to extensor muscle strength (Q) in both injured and uninjured leg: its value was indirectly proportional to the risk of ACL rupture [31].

2.4. Statistical analysis

Continuous variables were reported as mean ± standard deviation, and range, while for categorical variables both absolute and percentage values of the population were reported. The population was divided into adults (age ≥ 19 years) and adolescents (age < 19 years). The body mass index (BMI) of these two sub-populations were compared using unpaired *t*-test. Potential non-random associations between gender and age categories were evaluated using Fisher's exact tests.

We evaluated potential correlations between age and muscle strength (i.e., weight-normalized maximum torque) using Pearson's correlation. Linear mixed effect models (LMEM) were used to analyze all variables of interest (weight-normalized maximum torque, LSI and HQ ratio), using the 'nlme' package in the R environment. The assumptions of independence and normality of residuals and random effects were confirmed by visually inspecting the distributions using QQ-plots and histograms, as well as by means of the Shapiro–Wilk test. After fitting the LMEMs, we performed analysis of variance (ANOVA) on the fitted models. If the model parameters associated with age category (adult/adolescent) and leg (injured/non-injured) were significant, we performed multiple comparisons to evaluate statistical differences between adults and adolescents (for both injured and non-injured leg) as well as statistical differences between injured and non-injured leg (for both adults and adolescents) on the dependent variable under investigation, using two-tailed z-tests and adjusting the *P*-values using Bonferroni corrections. Significance level was set at $P < 0.05$.

We fitted an LMEM to the weight-normalized maximum torque for each muscle group (hamstrings/quadriceps), using age (adults/adolescents), leg (injured/non-injured) and their interaction as fixed-effects. Further, we considered subject-ID as a random effect on the model intercept to control for inter-subject variability and avoid pseudo-replication. The same model structure was used to fit an LMEM to the variable HQ ratio. Finally, we fitted an LMEM to the variable LSI, using age (adults/adolescents), muscle-group (quadriceps/hamstrings) and their interactions as fixed-effects, and subject-ID as random effect. In each of these models, BMI was introduced as a fixed effect to control for potential confounding effects of this variable on the results.

3. Results

3.1. Patient characteristics

Patient characteristics are shown in Table 1. A total of 131 patients were analyzed: 76 adults (58%, mean age of 25.39 ± 5.39 years; 21% female) and 55 adolescents (42%, mean age of 16.11 ± 1.44 years; 33% female). Adults had a mean BMI of 24.07 ± 2.98 kg/m^2, and adolescents had a mean BMI of 21.77 ± 3.07 kg/m^2. Of those, 33% of adults and 13% of adolescents had a BMI ≥ 25. The BMI of the two populations were statistically different ($t(123) = -3.96$, $P < 0.001$). However, there was no association between gender and age category according to the Fisher's exact test ($P = 0.16$).

3.2. Different quadriceps muscle strength in the injured leg between adults and adolescents

The maximum weight-normalized torques obtained during concentric isokinetic exercises of the quadriceps (extension) and the hamstring muscles (flexion) are summarized in Table 2, for each limb and age category. Quadriceps muscles produced lower torque in the injured than in the non-injured leg for both adults ($\Delta = -0.79 \pm 0.05$ Nm/kg, mean difference ± standard error, $P < 0.001$) and adolescents ($\Delta = -0.52 \pm 0.06$ Nm/kg, $P < 0.001$). Quadriceps torques produced by the injured legs of adolescents were higher than those produced by the injured legs of adults ($\Delta = 0.36 \pm 0.11$ Nm/kg, $P < 0.001$) (Figure 1).

Table 1
Pre-injured demographic characteristics of the analyzed population.

	Adolescent	Adults
Age, years	16.11 ± 1.44 (13–18)	25.39 ± 5.39 (19–39)
Gender, n	Male = 37 Female = 18	Male = 60 Female = 16
Weight, kg	65.43 ± 10.28 (45–86)	75.39 ± 13.15 (48–115)
Height, cm	173.33 ± 8.43 (150–190)	176.5 ± 8.86 (152–198)
BMI, kg/m^2	21.77 ± 3.07 (15.78–30.47)	24.07 ± 2.98 (18.50–35.49)

Variables are reported as the mean ± standard deviation and range. BMI, body mass index.

Conversely, there was no significant difference between the torques produced by the quadriceps muscles of the non-injured legs of adults and adolescents ($\Delta = 0.08 \pm 0.11$ Nm/kg, $P > 0.05$). Consistently with these results, quadriceps torques were negatively correlated with age (Figure 2) for both injured ($r = -0.35$, $P < 0.001$) and non-injured legs ($r = -0.19$, $P < 0.03$). However,

Table 2
Outcome measures of the isokinetic test at 30°/s, 6 months after surgery in adolescent and adult patients: hamstring and quadriceps torque (Nm/kg).

	Adolescents	Adults	P	Effect size (95% CI)
Injured quadriceps torque, Nm/kg	2.16 ± 0.60	2.16 ± 0.56	<0.001	0.36 (0.09; 0.63)
Uninjured quadriceps torque, Nm/kg	3.06 ± 0.61	2.95 ± 0.67	1	
Injured hamstrings torque, Nm/kg	1.64 ± 0.44	1.57 ± 0.39	1	
Uninjured hamstrings torque, Nm/kg	1.59 ± 0.38	1.55 ± 0.40	1	
Quadriceps LSI, %	83.97 ± 13.81	74.10 ± 15.88	0.04	−10 (−16; −3)
Hamstrings LSI, %	103.85 ± 16.28	103.15 ± 14.23	1	
Injured HQ ratio	0.65 ± 0.13	0.75 ± 0.15	0.002	−0.13 (−0.21; −0.04)
Uninjured HQ ratio	0.52 ± 0.09	0.53 ± 0.10	1	

HQ ratio, ratio of hamstrings to quadriceps strength; LSI, limb-symmetry index (ratio of muscle strength in the injured to the uninjured leg). Variables are expressed as the mean ± standard deviation. The *P*-values for the post-hoc tests comparing adults and adolescents are reported, along with the corresponding effect sizes and 95% confidence intervals (CIs) for the significant tests ($P < 0.05$).

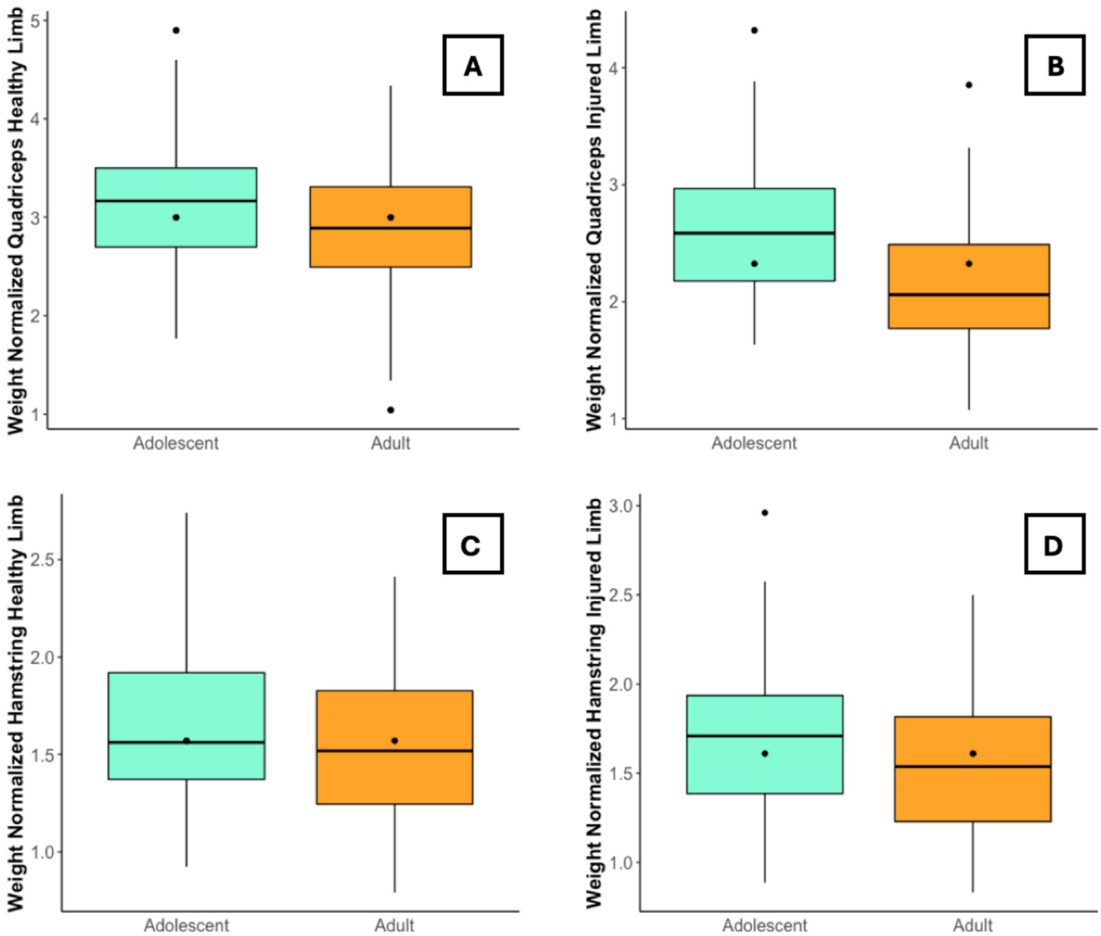

Figure 1. Box plot representing weight-normalized torques for healthy and injured limbs in adolescent and adult groups. (a) Quadriceps in healthy limb; (b) quadriceps in injured limb; (c) hamstring in healthy limb; (d) hamstring in injured limb. The median (horizontal line), first and third quartile, minimum and maximum values (vertical line), the mean (central point) have been plotted for adolescent and adult groups. Note: values outside this range are the outliers.

in the non-injured leg such a correlation was very weak, leading to no significant difference between adults and adolescents. The hamstring muscles produced similar maximum torques between legs for both adults (Δ = -0.02 ± 0.03 Nm/kg, $P > 0.05$) and adolescents (Δ = -0.05 ± 0.03 Nm/kg, $P > 0.05$), and similar maximum torque between adults and adolescents for both the injured (Δ = 0.07 ± 0.07 Nm/kg, $P > 0.05$) and the non-injured legs (Δ = 0.03 ± 0.07 Nm/kg, $P > 0.05$) (Figure 1). Consistently, hamstring torques were not significantly correlated with age for both injured ($P = 0.09$) and non-injured legs ($P = 0.12$).

3.3. Higher quadriceps LSI in adolescents than in adults

The LSI values are summarized in Table 2 and Figure 3. The quadriceps LSI was significantly lower than the hamstrings LSI for both adults (Δ = – 29 ± 2%, $P < 0.001$) and adolescents (Δ = -20 ± 3%, $P < 0.001$). However, while hamstring LSI was similar between populations (Δ = -1 ± 3%, $P > 0.05$), quadriceps LSI was significantly lower in adults than in adolescents (Δ = -10 ± 3%, $P = 0.04$). Accordingly, the percentage of adolescents who had a quadriceps LSI > 90% was higher than the percentage of adults who overcame that threshold (adolescents: 41.51%; adults: 14.5%). Conversely, a similar percentage of adults and adolescents had a hamstrings LSI > 90% (adolescents: 83%; adults: 84.2%).

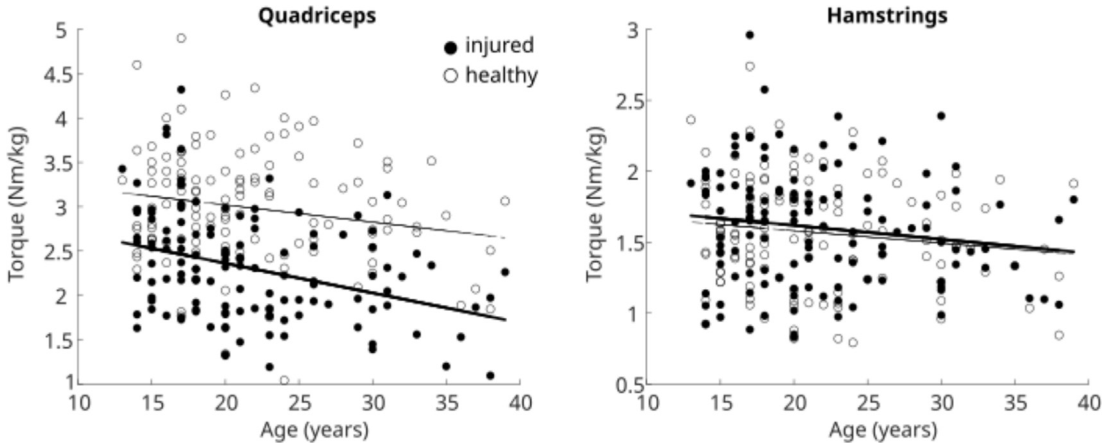

Figure 2. Weight-normalized maximum torques as a function of age, for quadriceps (left) and hamstrings (right) muscles of the injured (filled dots) and healthy (empty dots) legs. The lines represent the linear fits of each sub-population (tick lines for the injured, and thin lines for the healthy legs).

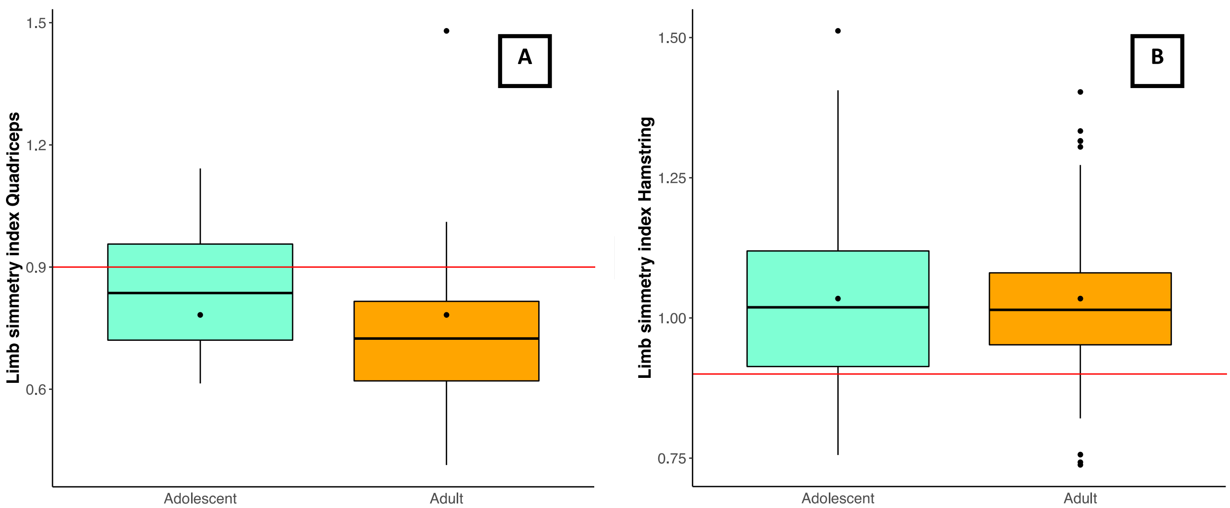

Figure 3. Box plot representing limb-symmetry index (LSI) values (ratio of muscle strength in the injured to the uninjured leg). (a) Quadriceps LSI; (b) hamstrings LSI. Quadriceps LSI of adolescents was higher than that of adults ($P < 0.001$), with no significant difference in hamstring LSI. Red line represents the 90% cut-off: few patients exceed the threshold for quadriceps (41.8% and 15.8%, adolescent and adults), while most exceed it for hamstrings (81.8% and 84.2%, respectively). The median (horizontal line), first and third quartile, minimum and maximum values (vertical line), the mean (central point) of the LSI values have been plotted for adolescent and adult groups. Note: values outside this range are the outliers. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

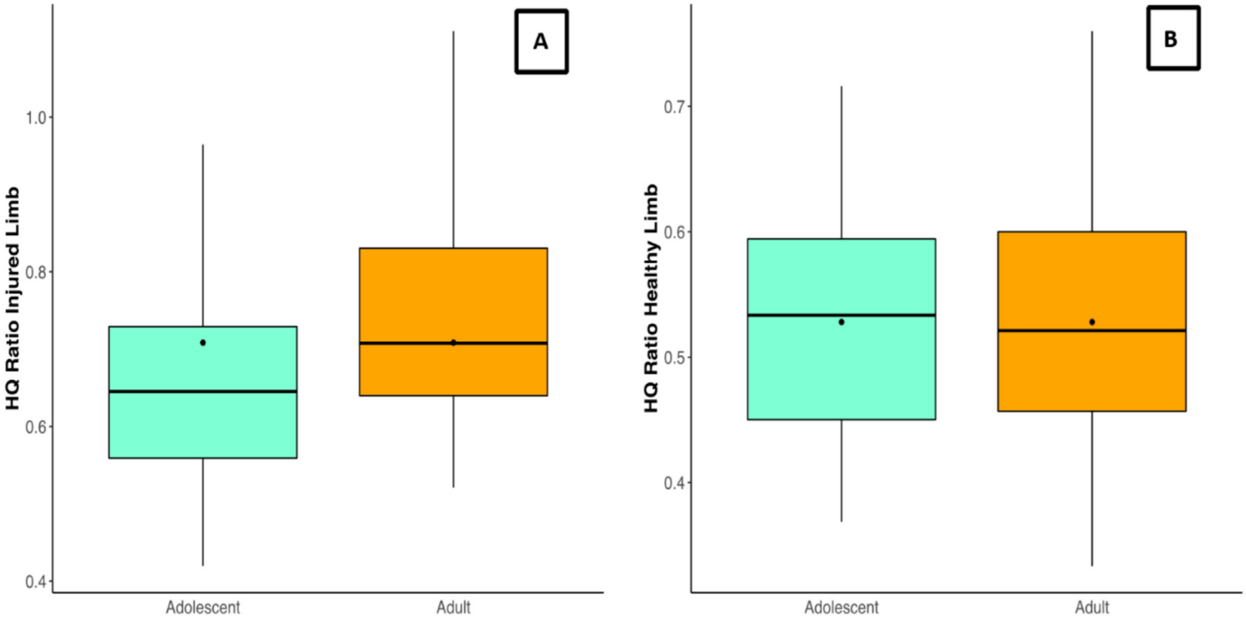

Figure 4. Box plot representing the hamstrings to quadriceps strength (HQ) ratio values in the healthy limb (a) and injured limb (b). HQ ratio is significantly higher ($P < 0.001$) in adults than in adolescents for the injured limb, while there is no difference in the healthy limb. The median (horizontal line), first and third quartile, minimum and maximum values (vertical line), the mean (central point) of the HQ ratio values have been plotted for adolescent and adult groups. Note: values outside this range are the outliers.

3.4. Lower HQ ratio in adolescents than in adults injured legs

The hamstring-to-quadriceps ratio (HQ Ratio) was calculated as the ratio of the hamstring to quadriceps strength values for both the injured and the non-injured limb (Figure 4). The HQ ratios in the injured legs were significantly higher than in the non-injured legs in both adults ($\Delta = 0.34 \pm 0.02$, $P < 0.001$) and adolescents ($\Delta = 0.22 \pm 0.03$, $P < 0.001$). However, in adolescents this measure was lower than in adults for the injured ($\Delta = -0.13 \pm 0.03$, $p = 0.002$), but not for the non-injured legs ($\Delta = -0.01 \pm 0.03$, $P > 0.05$).

4. Discussion

This study analyzed two cohorts: 55 adolescents (under 18 years old), and 76 adults who underwent a transphyseal ACLR with BTPB graft. The data confirmed our hypothesis: adolescents showed higher results of quadriceps strength and activation at 6 months after ACLR using a BTPB graft. The quadriceps torque delta between injured and uninjured leg was lower in adolescents compared with adults. The LSI analysis showed that at 6 months after surgery both adolescents and adults did not recover their quadriceps strength completely. At the same time quadriceps LSI value in the adolescent group was higher compared with adults, supporting the hypothesis that the younger population has better muscle knee strength at 6 months post-surgery.

The LSI was investigated by targeting an LSI value greater than 90% as indicated in the literature as an appropriate cutoff for the RTS [30,32,33]. Welling et al. [33] studied the value of LSI obtained in a group of adult soccer players after ACL reconstruction with either BPTB or hamstring. The interpretation of this result was used as a criterion to establish the different steps for a proper return to sporting activity. Specifically, with an LSI between 70 and 85%, a return to running without a change of direction was allowed; with an LSI between 85 and 90%, a resumption of some training activities avoiding contrasts was permitted, and a return to competitive activity was allowed with an LSI greater than 90%. Their study did not find significant differences in quadriceps between the injured patients and the control group at 7 months after surgery [33].

The current study shows that quadriceps LSI is significantly different between the two groups, with the adolescent group showing a better recovery compared with adults. These data may suggest a faster recovery in quadriceps strength after BPTB reconstruction. However, a prospective collection of isokinetic strength data after surgery is necessary to confirm these results. Sugimoto et al. [30] investigated the LSI value at 6–9 months using the same target of LSI > 90% in the pediatric population (under 15 years old) following ACLR showing that 75.2% of the candidates had a quadriceps LSI value > 90%, while 39.4% had hamstrings LSI values greater than 90%; their results could be explained by the use of hamstring grafts which weakens the flexors muscles more than the BPTB grafts.

However, in contrast with Sugimoto's study, in this manuscript only 41.8% of pediatric patients and 15.8% of adults presented a quadriceps LSI > 90%, supporting the hypothesis that an ACLR with BPTB weakens the extensors muscle more. In both groups the results are significantly lower compared with the values presented in adults and adolescents by Welling and Sugimoto, respectively. Shorter follow up time (6 months) and the use of only BTPB graft for ACLR could explain the differences in muscle torque and LSI values between the present study and the literature.

Our data (41.8% of adolescents and 15.8% of adults with quadriceps LSI > 90%) are comparable to those in the study by Riesterer et al. [32] which showed 80 patients aged between 14 and 51 years after ACLR performed with hamstring autograft. LSI value was described as > 90% in only 43% of patients for quadriceps analysis and 38% for hamstrings at 6-month follow up. These findings show that despite different ACL reconstruction techniques both groups did not reach an adequate LSI for a safe return to sport and support the theeory that at 6 months after ACLR both adolescent and adult groups are not ready for a return to competitive activities confirming evidence that recommend a return to play 1 year after surgery to reduce the risk of reinjuries [9,34].

Conversely, our study does not show a significant difference in the hamstrings LSI between adolescents and adults, and it highlights a significant percentage of patients with LSI above 90% in both groups: 84.2% of adults and 81.8% of adolescents. These values appeared higher than the results obtained in the compared studies. Riesterer's results [32] showed that only 38% of patients have LSI for hamstrings greater than 90%. Similarly, Sugimoto [30] described patients who underwent ACLR using hamstring or iliotibial band grafts had lower hamstring values compared with our results. Interestingly our study supported the evidence that graft selection and surgical techniques could induce specific muscle group weakness.

Rehabilitation should be personalized for each patient considering the surgical approach, the biomechanical properties of different grafts [35], and the muscle extensor or flexion strength reduction after different ALCR technique [36].

The HQ ratio frequently guides rehabilitation strategies aimed at achieving optimal limb strength before resuming sporting activities [37]. Myer et al. [38] demonstrated that decreased hamstring strength could increase the likelihood of ACL injury. The HQ ratio analysis in our groups of patients showed that in both adults and adolescents the values were higher in the injured leg compared with the healthy side. This result may be due to a lower quadriceps strength caused by the surgical technique with BPTB which influences this ratio. This indicates that both groups presented a muscular deficit at 6 months after surgery, and consequently are not ready for a safe return to play at that time [21,38,39]. Therefore, HQ ratio is a helpful parameter that could guide the rehabilitation program but cannot be considered singularly because different variables could influence this ratio. Bram et al. also described in their manuscript a higher HQ ratio after ACLR with quadriceps tendon (QT) compared with ACLR with hamstring tendon (HT) due to a lower strength in the extensors muscle group. However, as also highlighted by Bram et al., ensuring a high HQ ratio requires adequate quadriceps recovery, as weakness in the quadriceps muscle can also heighten injury risk [21].

This consideration regarding the quadriceps strength influence on HQ ratio is also noted comparing the two groups because adolescents presented a lower HQ ratio compared with adults. Given that hamstrings torque was similar between the groups, the difference is due to the higher quadriceps strength at 6 months in the adolescent group. More studies to analyze in which adolescent variable conditions these higher outcomes are needed for a better understanding of the results.

This study has some limitations. It is a retrospective study, and some patients were excluded due to the impossibility to recover postoperative clinical data. The groups were not randomly selected, population characteristics (e.g., BMI) could represent another limiting factor. Preoperative sports activity levels could influence both rehabilitation motivation and the prescribed rehabilitation protocol while factors such as postoperative pain, knee swelling, or anterior knee pain might influence variations in strength recovery. However, for this study, we decided to focus on pure evaluation and comparison at 6 months in recreational athletes without analyzing data from professional athletes or from patients with significant anterior knee pain. Moreover, we decided to include isokinetic data at 6 months of follow up because at this postoperative time patients' characteristics (pain, strength, patient-reported outcome measures, quadriceps activation capability) are more homogeneous than in the previous period.

There are several studies in the literature that use isokinetic testing as a criterion for assessing return to sport [12,40]. However, there are not many manuscripts that focus on tests on the adolescent population and compare these results with the adult studies. Furthermore, most studies have analyzed isokinetic tests at 60, 120, 180, or 300°/s [40–42]. Our study involves isokinetic tests with a velocity of 30°/s. In the literature, tests with this velocity have not been widely used. However, it has been observed that muscular strength assessed at low velocities allows a greater number of motor units to be collected, thus allowing for a better representation of the maximal work performed by the muscles studied [16,42,43]. For this reason, we routinely perform isokinetic tests at 30°/s; however, strength data at this velocity are less frequently reported in the literature.

5. Conclusions

Our data demonstrated that at 6 months after surgery neither adults nor adolescents are ready to resume sporting activity. However, adolescents proved to have a greater quadriceps strength than adults. These results could suggest that adolescents suffer less quadriceps strength deficit with ACL BPTB reconstruction at 6 months. Quadriceps torque value and LSI could be useful parameters to determine whether the patient is ready to resume sporting activities. HQ ratio analysis suggested that faster quadriceps recovery could be related to higher reinjury risk. Future studies on clinical follow up and reinjury rate after ACLR in adolescent patients are mandatory to better understand whether a patient is ready to resume sporting activities.

CRediT authorship contribution statement

Marco Turati: Writing – review & editing, Resources, Project administration, Methodology, Investigation, Conceptualization. **Erik Benedettini:** Writing – original draft, Visualization, Investigation, Formal analysis. **Dai Sugimoto:** Writing – review & editing, Validation, Methodology, Conceptualization. **Marco Crippa:** Writing – review & editing, Resources, Project administration, Methodology, Investigation, Conceptualization. **Cristiano Alessandro:** Methodology, Formal analysis, Conceptualization. **Valentina Bacchin:** Visualization, Methodology, Formal analysis. **Massimiliano Piatti:** Resources, Investigation, Conceptualization. **Fabio Albanese:** Resources, Investigation, Conceptualization. **Franck Accadbled:** Writing – review & editing, Validation, Methodology, Conceptualization. **Luca Rigamonti:** Writing – review & editing, Resources, Methodology, Investigation, Conceptualization. **Giovanni Zatti:** Supervision, Resources, Project administration, Methodology, Investigation. **Marco Bigoni:** Writing – review & editing, Resources, Project administration, Methodology, Investigation, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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