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Human Kinetics
ORIGINAL RESEARCH REPORT

Differential Effects of 2 Rehabilitation Programs Following Anterior Cruciate Ligament Reconstruction

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Context: The muscular function restoration related to the type of physical rehabilitation followed after anterior cruciate ligament reconstruction (ACLR) using autologous hamstring tendon graft in terms of strength and cross-sectional area (CSA) remain controversial. ***Objective:*** To analyze the CSA and force output of quadriceps and hamstring muscles in subjects following either an Objective Criteria-Based Rehabilitation (OCBR) algorithm or the usual care (UCR) for ACL rehabilitation in Spain, before and 1 year after undergoing an ACLR. ***Design:*** Longitudinal clinical double-blinded randomized controlled trial. ***Setting:*** Sports-medicine research center. ***Patients:*** 40 recreational athletes (30 male, 10 female [24 ± 6.9 y, 176.55 ± 6.6 cm, 73.58 ± 12.3 kg]). ***Intervention:*** Both groups conducted differentiated rehabilitation procedures after ACLR. Those belonging to OCBR group were guided in their recovery according to the current evidence-based principles. UCR group followed the national conventional approach for ACL rehabilitation. ***Main Outcome Measures:*** Concentric isokinetic knee joint flexor-extension torque assessments at 180°/s and Magnetic Resonance Imaging (MRI) evaluations were performed before and 12 months after ACLR. Anatomical muscle CSA (mm^2) was assessed, in Quadriceps, Biceps femoris, Semitendinous, Semimembranosus, and Gracilis muscles at 50% and 70% femur length. ***Results:*** Reduced muscle CSA was observed in both treatment groups for Semitendinosus and Gracilis 1 year after ACLR. At 1-year follow-up, subjects allocated to the OCBR demonstrated greater knee flexor and extensor peak torque values in their reconstructed limbs in comparison with patients treated by UCR. ***Conclusions:*** Objective atrophy of Semitendinosus and Gracilis muscles related to surgical ACLR was found to persist in both rehabilitation groups. However, OCBR after ACLR lead to substantial gains on maximal knee flexor strength and ensured more symmetrical anterior-posterior laxity levels at the knee joint.

Keywords: ACL, MRI, muscle strength, objective criteria-based rehabilitation

Anterior cruciate ligament (ACL) rupture is one of the most severe and disabling injuries in the sport population.[1,2] Isokinetic dynamometry and magnetic resonance imaging (MRI) are the most commonly used methods to evaluate both muscle strength and morphology among the previously ACL reconstructed population. The peak torque for muscle force production and the cross-sectional area (CSA) of thigh muscles have been widely studied in this field.[3–5] Although there have been reported several methods for isokinetic hamstring muscle function assessment,[6] there is no consensus with respect to the influence of previous medial hamstring harvesting on successful returning to sports.[2] This fact has favored studies focusing on entire torque-angle curves as well as on the optimum angle for peak torque development among this population.[7] Inconclusive results have been reported, probably due to several factors such as differences in time from evaluation to prior surgery, the biological mechanisms associated with regeneration of the harvested tendon,[8] and divergences in the rehabilitation protocols followed that could play a key role in the recovery of hamstring musculature function.[9–12]

At the same time, anterior cruciate ligament reconstruction (ACLR) is a widely operation performed by orthopedic surgeons searching to restore knee stability and prevent the occurrence of further injuries of adjacent structures over time.[2,13,14] Autologous tendons remain the most frequent graft choice to perform the ligament repair.[2] Medial hamstrings grafts have been increasingly employed along these last years for ACLR due to its associated good material mechanical properties,

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minimal impact on the knee extensor mechanism and excellent postoperative outcomes.[9,15,16] However, some limitations have been described when this kind of graft is used. Greater knee laxity,[17] persistent knee flexor atrophy in terms of muscle size,[2,15] and strength deficits[15] have been reported along with a greater short-term risk for hamstring strain injury after returning to sports.[18–20] Several randomized controlled trials have found little or no differences, function or revision rates after ACLR was performed with the most frequently used autologous grafts (patellar tendon or hamstring tendons grafts).[21] However, increased rates of revision with hamstring tendon compared with patellar tendon grafts have been recently reported by the Scandinavian ACL registries.[13,15] None of these cohort studies[13,15] mention any data regarding the rehabilitation protocol followed after the ACLR.

In this sense, studies comparing different types of rehabilitation following ACLR during the past 25 years have favored the implementation of the so-called accelerated rehabilitation programs.[22,23] These protocols are mainly based on early weight bearing and joint mobilization after surgery as well as on a more intense strength and rehabilitation routines.[22,23] Early return to full activity levels, lower residual anterior-posterior knee laxity and lower postoperative complication rates have been described among subjects following this kind of rehabilitation routines with both patellar tendon or medial hamstring grafts.[22–25] Many clinical trials have been carried out comparing this methodology to conventional rehabilitation procedures.[22,26,27] However, there is not an accepted single standard for the definition of an accelerated rehabilitation program. Furthermore, objective progression criteria for patient management through the rehabilitation procedure in relation to ACL injury rehabilitation remains still a challenge for clinicians. In an effort to standardize the clinical management of ACL reconstructed patients and guide them by means of an objective criteria-based progression during the recovery process, Myer et al[20] published a step by step rehabilitation algorithm proposal for ACL injury rehabilitation following ligament repair. That way, the authors emphasized on the need to guide the patient by using different progressive objective evaluations through the rehabilitation process to optimize the successful outcome and return to sports participation. Briefly this rehabilitation algorithm required the patient to restore full range of motion and eliminate swelling. Later, more challenging goals for knee joint such as complete force restoration, running capability and finally the sports related agility task were allowed to perform if different functional evaluations were completed. Accelerated rehabilitation protocols have already been widely studied in the literature.[10,20,28,29] However, OCBR algorithms have not been studied to that extent despite having the potential for a more individual self-adapted recovery progression, and hence, a more suited clinical management.[20] In this context, to our best knowledge, there are not in the literature investigations focusing on the comparison of Objective Criteria-Based (OCBR) vs. usual care (UCR) rehabilitation protocols following ACLR with ipsilateral autologous medial HT graft with regards to muscle strength and morphology recovery rates.

The objective of the current study was, therefore, to compare the effect of 2 differentiated rehabilitation programs (OCBR vs. UCR) on hamstring muscle strength and size 12 months after ACLR using a doubled (ie, 4 strand) Semitendinosus and Gracilis tendons autograft. It was hypothesized that better mechanical muscle performance (exerted peak torque) and muscle CSA would be improved to a greater extent among subjects following an OCBR rehabilitation program.

Methods

Patients

A longitudinal clinical double blinded (patients and evaluator) randomized trial was performed with 40 (30 male, 10 female) recreationally active athletes (Tegner activity scale 7) to analyze the effect of 2 different rehabilitation programs following ACLR (Table 1).

All patients were operated by the same orthopedic surgeon following identical surgical technique. Antero-medial portal was used in all cases to perform an anatomical ACLR. Autologous double bundle hamstring grafts were used for all patients. Tension was applied to all grafts for 10 minutes at 20 pounds before implantation to reduce residual graft laxity. Fixation of the graft was achieved with TightRope RT and Bio-Interference screw (Arthrex, Naples, USA) for femur and tibia, respectively. Subjects attended an outpatient clinic for clinical follow-up 10 days postoperatively and were evaluated before, and 12 months after ACLR. All patients were discharged from hospital within 24 hours from surgery. Cryotherapy and routine analgesia were prescribed for all patients as pain control. Elastic compressive stockings were prescribed for deep thromboembolism prophylaxis.

Patients with chondral injuries grade ≥ II or suffering from other knee ligament complete disruptions other than ACL were excluded from the study. There were 20 meniscus injuries treated, 9 external and 10 medial injuries (9 in UCR and 10 in the OCBR groups, respectively). Twelve of them were treated by meniscal body regularization, whereas the remaining 8 were treated by direct suture of the injury. Time from injury to surgery was consistent between groups (P = .47) (mean ± standard deviation [SD]; 199.5 ± 166.5 and 146.3 ± 147.4 days for both OCBR and UCR groups, respectively). Similarly, there were not significant differences (P = .23) on the number of days passed from surgery to 1-year follow-up evaluations between groups (Unpaired t test; 372.3 ± 9.3 vs. 374.5 ± 19.5 days for UCR and OCBR groups, respectively)

All participants were informed in detail about the experimental procedures and the possible risks and

Table 1 Anthropometric, Knee Joint Laxity and Optimum Angle for Peak Torque Objective Criteria-Based Rehabilitation (OCBR) and Usual Care (UC) Groups

				Age (y)	Body weight (kg)	Height (cm)	Knee AP laxity (mm)	Hamstring peak torque °	Hamstring work (J)
OCBR group	Before ACL reconstruction	Healthy	Mean (SD)	24.5 (6.9)	74.06 (11.7)	176.7 (5.8)	6.1 (2.7)*	35.9 (8.2)	9355.7 (3265.0)[a]
			95% CI				4.9–7.3	30.2–38.4	7615.9–11095.5
		ACL injured	Mean (SD)				8.5 (2.7)	36.2 (14.6)	7512.3 (3205.3)
			95% CI				7.3–9.8	30.2–41.7	5804.3–9220.3[+]
	12 months After ACL reconstruction	Healthy	Mean (SD)				6.1 (1.7)	35.3 (7.9)	11840.7 (2542.3)
			95% CI				5.2–7.1	32.2–38.4	10486.0–13195.4
		ACL injured	Mean (SD)				7.3 (2.8)	35.2 (7.8)	10871.4 (2352.3)*
			95% CI				5.8–8.7	33.7–36.4	9618.0 (12124.9)
UC group	Before ACL reconstruction	Healthy	Mean (SD)	23.5 (6.9)	73.1 (12.9)	176.4 (7.4)	7,5 (2.6)^	35.5 (8.1)	7474.4 (2488.8)[a+]
			95% CI				6.2–8.7	32.1–38.9	5970.4–8978.3
		ACL injured	Mean (SD)				9.5 (3.3)	35.8 (8.2)	7340.9 (3054.3)[a+]
			95% CI				7.8–11.1	32.4–39.3	5495.2–9186.6
	12 months After ACL reconstruction	Healthy	Mean (SD)				5.5 (2.6)[+]	33.4 (7.0)	9100.9 (2529.5)
			95% CI				4.2–6.8	30.5 (36.3)	7572.3–10629.4
		ACL injured	Mean (SD)				7.0 (3.0)	32.9 (7.1)	9440.3 (2695.0)
			95% CI				5.5–8.4	29.9–35.9	7811.7–11068.9

Abbreviations: AP, anterior-posterior; ACLR, anterior cruciate ligament reconstruction.

* Statistical difference ($P < .05$) with respect to ACLR limb of OCBR group pre surgery.

^ Statistical difference ($P < .05$) with respect to ACLR limb of UC group pre surgery.

[a] Statistical difference ($P < .05$) with respect to ACLR limb of OCBR group 12 months post surgery.

[+] Statistical difference ($P < .05$) with respect to ACLR limb of UC group post surgery.

benefits of the project. They all gave signed informed consent. The study was approved by the Ethical Committee of the local University and performed according to the Declaration of Helsinki. Informed consent was obtained from all participants included in the study.

Procedures

Rehabilitation Protocols. The patients were consecutively divided in 2 different rehabilitation groups after the operation. The allocation procedure was block randomized. Group 1 (the first 20 patients) followed the usual care for ACL reconstruction in Spain (UCR) and patients in Group 2 (the following 20 patients) were enrolled in an Objective Criteria-Based rehabilitation protocol (OCBR). The2 different rehabilitation programs were conducted in 2 different rehabilitation centers. Patients were not aware of the group allocation or follow-up examination results during the time course of the investigation.

The UCR group received traditional care for an ACLR rehabilitation procedure[30] (see Online Appendix). The main features of this protocol are 2 to 4 weeks of immobilization before free gait, delayed onset of strength training, and restricted return to sports activity up to 6 months postoperatively.

The OCBR group followed a standardized Objective Criteria-Based rehabilitation program based on that previously described by Myer et al[20] (see Online Appendix). The main features of this rehabilitation protocol include early full range of motion restoration, free gait, and specific strength training and agility drills introduced progressively as the patients surpassed several predefined objective functional goals through the rehabilitation program.

No knee braces were used after the surgical ligament reconstruction, during the rehabilitation program, or during the knee performance tests at the follow-up examinations. Patients who developed pain, swelling, or range of motion deficits during the rehabilitation programs underwent symptomatic treatments until the impairments were resolved. There were not statistically significant (P = .24) differences between groups with respect to the number of rehabilitation sessions administered (58.8 ± 22.0 and 67.6 ± 22.6 sessions in UCR and OCBR groups, respectively).

Isokinetic Strength Testing. The dynamic concentric knee extensor/flexor strength (180°/s concentric/concentric muscle action) was measured with each subject seated on an isokinetic dynamometer (Humac norm, CSMi solutions, Stoughton. Ma. USA). The trunk was attached perpendicular to the floor, and the hip and knee joints were placed flexed to 90°. Subject posture was secured with straps. Before each data collection set, a warm-up set consisting of 5 submaximal knee flexion/extensions for each leg at 180 °/s was performed. The testing session consisted of 8 knee extension/flexion (90–0° range of motion, 0° = to full extension) repetitions for each leg. Gravity-corrected flexor and extensor peak torques expressed in N·m were recorded for each leg. Isokinetic concentric strength evaluations of the Hamstring and Quadriceps muscle groups have previously demonstrated excellent reliability.[31] An automated data analysis procedure was implemented using Matlab 7.11 (MathWorks Inc; Natick, MA, USA) to determine the angle of peak torque for the Hamstring muscles on each testing repetition. In addition, the area under the torque-angle curve was also calculated (ie, mechanical work in J). This variable was calculated by means of the following formulae:

Muscle Imaging. MRI scans of the thigh were performed with a 1.5 T whole body image with surface phased-array coils (Magnetom Avanto; Siemens-Erlangen, Germany). For the magnetic resonance scans, subjects were positioned supine with their knee extended. MRI of the subjects' thighs was performed before and 12 months after surgery. The length of the right femur (Lf) was measured by the distance from the intercondylar notch to the superior border of the femoral head measured in the coronal plane (cm). Subsequently, 15 axial scans of the thigh interspaced by a distance of 1 / 15 Lf were obtained from the level of 1/15 Lf to 15/15 Lf. Every image obtained was labeled with its location (ie, slice 1 being closer to the coxofemoral joint and slice 15 closer to the knee). Great care was taken to reproduce the same individual Lf each time by using the appropriate anatomical landmarks as previously described.[32]

For the final calculation of the CSA of each muscle, slices corresponding to 8/15 and 12/15 of the total femur length levels (50% and 70% of the bone axial length) were used for all muscles examinations (Figure 1). T2-weighted transverse spin-echo magnetic resonance axial images [repetition time (RT) = 3250 ms, echo time (ET) = 32, 64, and 96 ms were collected using a 256 × 256 image matrix, with a 320 mm field of view and 10-mm slice thickness] were analyzed. This data were used to obtain the anatomical CSA of each Quadriceps, Biceps Femoris, Semitendinosus, Semimembranosus, and Gracilis muscles (Figure 1). The MRI files obtained were converted to a Digital Imaging and Communications in Medicine (DICOM) format and analyzed with image manipulation and analysis software (Slice Omatic, Tomovision, Canada). The same examiner performed all muscle perimeter measurements. The anatomical muscle CSA was calculated by drawing a region of interest and tracing the outline of the muscles on the previously prepared proton-density images (ET:32) as previously described.[32]

Knee Joint Laxity Assessment. Knee joint laxity was evaluated with the KT-1000 arthrometer (MEDmetric Corporation, San Diego, CA) at maximal pull (180-200 N) with anterior-posterior (AP) directed loads. The measurement continued until the value was reproduced. KT-1000 instrumented examination of knee laxity in the ACL injured leg shows high intratester reliability.[33]

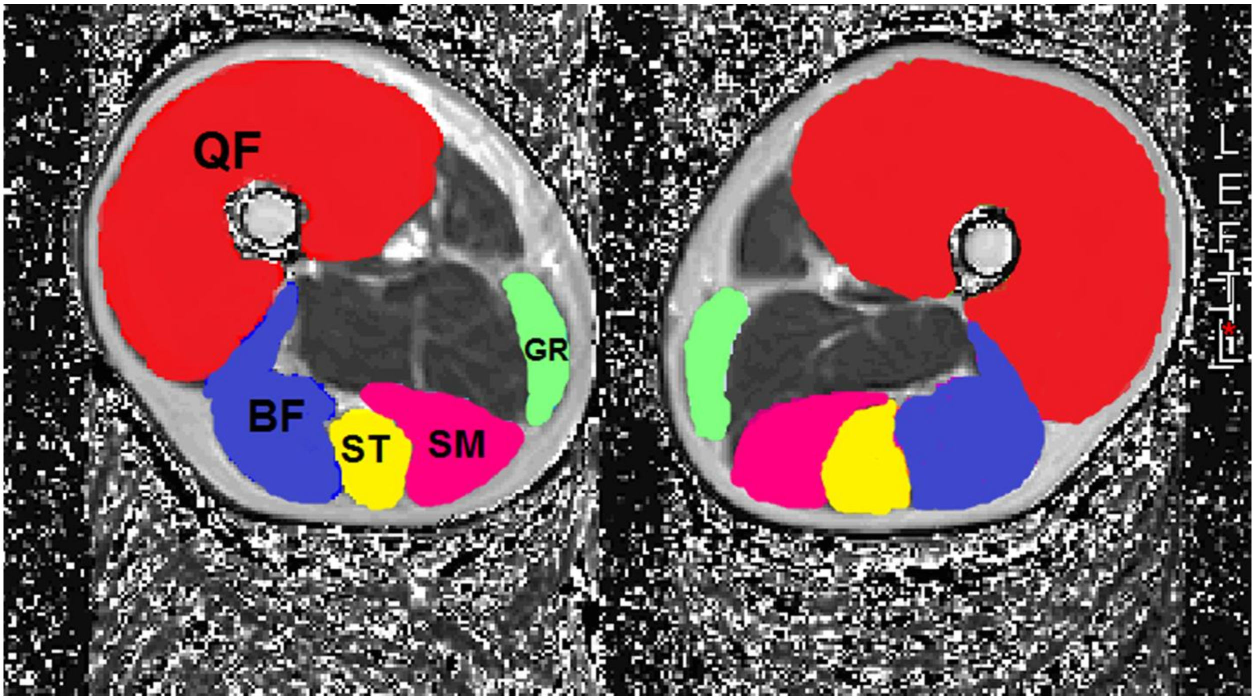

Figure 1 — Middle-thigh (50% length of the femur) cross-sectional area of a subject enrolled in Objective Criteria-Based Rehabilitation group 12 months after reconstruction (left side ACL reconstructed). Muscular structure fragmentation with fat suppression of knee flexors and extensors: Quadriceps femoris (Q), Biceps Femoris (BF), Semitendinous (ST), Semimembranous (SM), Gracilis (GR).

Statistical Analyses

Standard statistical methods were used for the calculation of means, standard deviations, and confidence intervals (CI). To check out the normality assumption of the analyzed variables, the Kolmogorov-Smirnov testing was applied revealing no abnormal data patterns. Variance homogeinity was verified using Levene test, which showed variance homogeneity between groups. The number of patients enrolled in the present investigation was based on a power analysis calculated previously in a similar study by Lindstrom et al.[34] They determined that the number of patients needed to detect a 4% change in hamstring muscle cross-sectional area with 80% statistical power was 37 subjects.[34]

A 3-way analysis of variance (ANOVA) [group (OCBR or UC) by time (pre or post ACLR) by limb (ACL reconstructed or healthy contralateral)] with 2 repeated measures (ie, time and limb) was used to compare between groups' mean comparisons. When a significant factors interaction was found, each factor was followed up separately using 1-way comparisons. The level of significance was set at $P < .05$. For between groups comparison regarding demographics, and for time from original injury to surgical reconstruction, as well as from surgical reconstruction to 1-year follow-up, an unpaired T-test with the alpha error level set at $P < .05$ was performed. SPSS statistical software (V. 20.0, Chicago, IL, USA) was used for all statistical calculations."

Results

No significant ($P < .05$) differences were found with respect to subjects' anthropometrics (Table 1). Similarly, there were not significant differences with regards to baseline muscle force or CSA measurements between groups (Tables 1 and 2).

Isokinetic Strength Testing

Non significant group by time by limb interactions were found neither for Quadriceps ($F = 0.33$; $P = .57$) nor Hamstrings ($F = 0.02$; $P = .88$) peak torque assessments performed.

However, significant group by time interactions were found with respect to isokinetic strength evaluation ($F = 14.17$; $P < .01$ and $F = 11.75$; $P = .01$) for Quadriceps and Hamstring muscles peak torque evaluation, respectively). In that way, subjects in the OCBR group demonstrated significantly ($P < .05$) greater knee extension peak torque 12 months postoperatively, in comparison with their UCR counterparts, in both ACL reconstructed and contralateral healthy limbs (Figure 2A). Moreover, Hamstring muscles peak torque values from ACL reconstructed limbs of OCBR patients at 12 months after ACLR, demonstrated to be greater ($P = .049$) than baseline values of ACL injured leg of subjects in the UCR group (185.5 ± 37.0 N·m; 95% CI: 167.1–203.9 N·m vs. 142.0 ± 52.0 N·m; 95% CI: 117.6–166.3 N·m for the reconstructed leg

Table 2 Muscle Cross-sectional Areas (mm^2; CSA) Before and After ACL Reconstruction in Objective Criteria-Based Rehabilitation (OCBR) and Usual Care (UC) Groups

			Muscle CSA (mm^2)	Quadriceps		Biceps Femoris		Semitendinosus		Semimenbranosus		Gracilis	
			% femur length	50	70	50	70	50	70	50	70	50	70
OCBR group	Before surgery	Healthy	Mean (SD)	6827.0 (937.3)	4278.1 (1735.3)	1379.0 (307.9)	1076.5 (367.1)	*^806. (237.1)	301.5 (324.0)	661.7 (106.4)	1143.5 (242.3)	434.6 (132.4)	*^171.1 (127.5)
			95% CI	6285.8–7368.2	3276.2–5280.1	1192.9–1565.1	864.5–1288.5	669.7–943.5	83.8–465.4	597.4–726.0	1003.6–1283.4	358.1–511.0	90.1–252.2
		ACL injured	Mean (SD)	6112.3 (969.1)	3910.6 (1918.6)	1422.5 (358.8)	1063.5 (366.6)	*^807.6 (178.1)	274.6 (284.0)	718.9 (164.7)	1120.2 (246.9)	401.0 (115.1)	*165.2 (130.9)
			95% CI	5552.7–7368.2	2802.8–5018.3	1205.6–1639.4	851.9–1275.2	704.8–910.4	83.8–465.4	619.3–818.4	977.7–1262.8	334.5–467.4	86.1–244.4
	12 months follow-up	Healthy	Mean (SD)	7412.6 (1300.4)	4362.7 (994.3)	1414.8 (345.8)	1117.6 (349.4)	*^879.0 (213.6)	204.4 (139.5)	737.6 (196.1)	1385.5 (431.9)	434.2 (182.0)	^155.1 (48.2)
			95% CI	6661.9–8163.4	3788.6–4936.8	1215.1–1614.5	915.8–1319.3	749.9–1008.1	104.6–304.2	624.3–850.8	1136.1–1634.9	329.2–539.3	124.5–185.7
		ACLR	Mean (SD)	6848.9 (1178.1)	4075.9 (888.7)	1423.6 (413.8)	1220.5 (340.3)	630.6 (158.2)	170.6 (247.8)	718.7 (204.6)	1378.8 (514.4)	347.1 (175.6)	76.7 (58.6)
			95% CI	6168.7–7529.1	3562.8–4589.1	1184.7–1662.5	1024.1–1417.0	539.2–721.9	–83.5 to 430.6	595.1–842.3	1081.8–1675.8	245.6–448.5	31.7–121.8
UC group	Before surgery	Healthy	Mean (SD)	7203.8 (1589.9)	4046.9 (1482.9)	1307.0 (476.3)	1149.0 (535.7)	*^840.8 (246.1)	276.2 (197.1)	668.1 (302.5)	1169.7 (357.9)	415.0 (115.7)	*^163.2 (96.4)
			95% CI	6323.4–8084.2	3190.7–4903.1	1043.2–1570.7	839.6–1458.3	704.5–977.1	157.1–395.3	500.5–835.6	971.5–1367.8	351.0–479.1	107.6–218.9
		ACL injured	Mean (SD)	6855.5 (1425.1)	3831.6 (1211.6)	1349.9 (432.3)	1145.9 (478.2)	*^861.9 (279.0)	234.7 (155.6)	701.1 (268.6)	1208.4 (337.7)	397.2 (147.3)	^140.9 (82.9)
			95% CI	6066.4–7644.7	3160.6–4502.6	1110.5–1589.3	881.1–1410.7	707.4–1016.4	140.7–328.6	546.1–856.1	1021.4–1395.4	315.7–478.6	93.0–188.7
	12 months follow-up	Healthy	Mean (SD)	7194.3 (1610.6)	4318.2 (1320.0)	1339.6 (453.6)	1331.3 (497.3)	*^858.4 (304.7)	426.3 (482.4)	757.8 (427.9)	1113.6 (562.8)	410.0 (129.2)	^155.6 (85.9)
			95% CI	6302.3–8086.2	3587.2–5049.2	1088.5–1590.8	1044.2–1618.4	689.7–1027.2	102.3–750.4	510.74–1004.8	801.9–1425.2	335.4–484.6	103.7–207.5
		ACLR	Mean (SD)	6850.0 (1508.0)	4024.5 (1044.6)	1358.0 (488.8)	1327.5 (393.3)	625.8 (208.4)	147.4 (166.5)	778.9 (397.5)	1260.0 (320.1)	348.3 (155.1)	63.4 (85.1)
			95% CI	6285.8–7368.2	3446.0–4603.0	1087.3–1628.7	1109.7–1545.3	510.4–741.2	28.3–266.5	558.75–999.0	1082.7–1437.2	262.4–434.2	9.3–117.5

Abbreviations: CSA, cross-sectional area; ACLR, anterior cruciate ligament reconstructed.

* Statistical difference ($P < .05$) with respect to ACLR limb of OCBR group 12 months post surgery.

^ Statistical difference ($P < .05$) with respect to ACLR limb of UC group 12 months post surgery.

of subjects in the OCBR group and the injured leg of UC group before ACLR, respectively) (Figure 2A and B). Finally, ACL reconstructed legs of subjects in the OCBR group also reported greater ($P = .01$) Quadriceps muscle peak torque values than ACL reconstructed legs of subjects in the UCR group at 12 months after surgical reconstruction (259.8 ± 52.7 N·m; 95% CI: 233.6–286.0 N·m vs. 189.6 ± 52.9 N·m; 95% CI: 164.1–215.1 N·m, respectively; Figure 2A and B).

Regarding within group analysis, a significant time effect was found for Quadriceps ($F = 7.81$; $P < .01$) and Hamstring ($F = 8.34$; $P < .01$) strength evaluations. 12 months after surgical repair, subjects in the OCBR group displayed greater Hamstring muscles peak torque values in their ACL reconstructed limb compared with their own baseline recordings obtained from both healthy ($P = .05$) and ACL injured limb ($P = .04$) [mean ± SD: 185.5 ± 37.0 N·m; 95% confidence interval (CI): 167.1–203.9 N·m vs. 143.0 ± 37.7 N·m; 95% CI: 126.2–159.7 N·m and 142.4 ± 38.5 N·m; 95% CI: 124.8–160.0 N·m for the postoperative ACL injured and preoperative ACL injured and healthy limbs, respectively]. Similarly, OCBR subjects also showed greater Quadriceps peak torque values in their ACL reconstructed ($P = .01$) and healthy ($P = .09$) legs 12 months postoperatively than those reported at baseline (259.78 ± 52.71 N·m; 95% CI: 233.57–285.99 N·m vs. 189.29 ± 65.59 N·m; 95% CI: 159.4–219.14 N·m and 189.31 ± 64.01 N·m; 95% CI: 160.94–217.70 N·m for the postoperative ACL injured, preoperative ACL injured, and healthy limbs, respectively) (Figure 2.A).

Finally, there were not any group by time nor limb interaction with respect to their Hamstring muscles mechanical work production. Isolated time ($F = 6.71$; $P < .05$) and group ($F = 25.64$; $P < .01$) effects were present. In that way, subjects enrolled in the OCBR group, enhanced to a greater extent ($P < .001$) their hamstring muscles mechanical work exertion ability in their ACL reconstructed limb compared with baseline evaluation than their UCR group counterparts (Table 1).

There were not found any significant interactions between factors nor differences with respect to the angle for peak torque productions between groups at any of the time points analyzed.

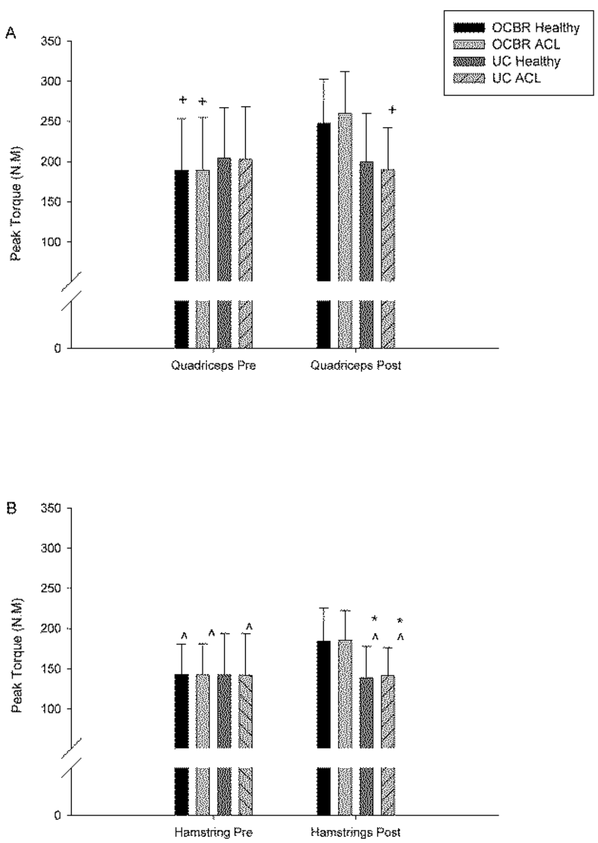

Figure 2 — Isokinetic muscle strength evaluation. Nm = Newtons per Meter. + statistical significance ($P < .05$) with respect to Objective Criteria-Based Rehabilitation (OCBR) group Quadriceps 12 months after surgery (A). * statistical significance ($P < .05$) with respect to OCBR Healthy Hamstrings 12 months after surgery. ^ statistical significance ($P < .05$) with respect to OCBR Hamstrings 12 months after surgery with respect to OCBR.

Muscle Imaging

With respect to muscle CSA evaluation, no significant group by time by limb interactions were found ($F = 0.59$; $P = .83$). However, there was a trend toward significant time vs. limb interaction in the Gracilis muscle at 70 ($P = .06$). In addition, there were significant main effect for limb in the Gracilis muscle at 70 ($F = 6.78$; $P < .05$), and Semitendinosus muscle at 50 ($F = 4.783$; $P < .05$). In addition, there were significant group effect in the Semimembranosus ($F = 5.28$; $P < .05$) muscle at 70, and Gracilis muscle at 50 ($F = 4.65$; $P < .05$).

In this sense, both the OCBR and UCR rehabilitation groups displayed significant ($P < .05$) GR muscle CSA reduction at 70% of the femur length level on their ACL repaired vs. their contralateral healthy limbs 12 months after ACLR (Table 2). Gracilis muscle sizes at this level were also found to remain diminished in both groups with respect to baseline measurements on the ACL reconstructed leg ($P = .01$) (Table 2). Semitendinosus muscles size measurements reported similar results to those observed on Gracilis muscle. In that way, comparing ACL reconstructed limb vs. contralateral healthy limb 12 months after the ACLR, Semitendinosus muscle CSAs at the 50% femur length level were also diminished in the ACL reconstructed limb in both OCBR and UC ($P < .05$) groups (Table 2). No additional factors interaction or main effects were observed in the imaging variables.

Knee Joint Laxity Assessment

Not significant group by time by limb interactions were found ($F = 0.26$; $P = .61$) in relation to knee joint laxity assessment over the entire follow-up period. In addition, there was a trend toward group by time interaction in the knee joint laxity was present ($F = 3.18$; $P = .07$). Moreover, significant main effects for time ($F = 9.81$;

$P < .01$) and limb ($F = 15.5$; $P < .001$) were observed, demonstrating greater knee joint AP laxity on their ACL injured limb with respect to that on their contralateral healthy knee at baseline evaluation for OCBR and UC groups ($P < .001$). Furthermore, 12 months after surgical reconstruction, the ACL reconstructed limbs of subjects enrolled in the UCR rehabilitation group still displayed greater knee AP laxity with respect to their contralateral healthy limb ($P = .03$). That difference with regards to intrasubject knee joint AP laxity values was not observed among subjects undergoing an OCBR program (Table 1).

Discussion

The current study aimed to compare the effect of 2 differentiated rehabilitation protocols (OCBR vs. UCR) on dynamic hamstring muscle strength and size 12 months after ACLR. Double bundle Semitendinosus and Gracilis tendon autograft was used in all cases. A novel finding of the current study was that thigh musculature strength was recovered to a greater extent in subjects undergoing an OCBR program compared with that observed after a usual care for ACL rehabilitation in Spain. In contrast, the muscle size in terms of CSA was not significantly ($P < .05$) different between the 2 groups. At the same time, although only a trend toward significant time vs. group interaction were found ($P = .07$), subjects in the OCBR group appeared to recover symmetrical values of KT1000 AP knee joint laxity 12 months after ACLR, while subjects in the UCR group did not. These results partially confirm our initial study hypothesis, which stated that greater improvements in mechanical muscle performance and muscle CSA would be found in subjects undergoing an OCBR protocol. To the best of our knowledge, this is the first study that has analyzed thigh muscle function and morphology among subjects who underwent 4 strand medial hamstring tendon ACLR and were subsequently exposed to 2 contrasting rehabilitation regimens.

Regarding the thigh strength recovery process, previous studies have reported varied results when assessing hamstring muscle strength after using Semitendinosus and Gracilis tendon harvesting for ACL repair.[4,5,8,11,12] The discrepancies in the results may be due to several factors such as the time from surgery, muscle size, hamstring strength evaluation methodology, proximal shifts of the newly formed musculotendinous junction (MTJ), and/or medial hamstring tendon regeneration.[2,35]

Previous investigations have documented long term-lasting (up to 2 years from ACLR) strength deficits in HT with respect to the contralateral healthy limb while assessing the torque generated at deep flexion values (more than 75° knee flexion).[8,12,36] However, other authors have found no differences in Hamstring muscle strength between 4-band hamstring graft ACL reconstructed limbs and the contralateral healthy extremities when measuring the absolute peak torque, which is produced at lower flexion angles (15–30°).[4–6,11,12,37] The differing results obtained between these methodologies could arise from the joint position at which the optimum mechanical advantage for the medial hamstrings is reached.[8] In the current study, it was found that subjects in the OCBR group recovered both Quadriceps and Hamstring muscle peak torque values to a greater extent than their UC group counterparts. In the authors´ opinion, these differences may be related to the more exhaustive and earlier implemented muscle strength training program performed by the subjects enrolled in the OCBR group that in fact, started on postoperative day 1. These results agree with previous researches focusing on the comparison of the strength recovery rates among accelerated rehabilitation and conventionally rehabilitated patients following prior ACLR.[23,24] However, to the best of the authors' knowledge such comparisons between OCBR and other rehabilitation programs are lacking in the scientific literature. It would be plausible that it is not only the time at which more exhaustive exercises are implemented from ACLR. Also which requirements must be fulfilled to allow loading the joint in a more aggressive manner could be crucial for a successful rehabilitation after ACL ligament repair.

Another proposed limiting factor for full recovery of the hamstring strength after medial hamstring graft based ACLR is the ability of the previously harvested tendon to regenerate.[4,5] Recently, Papalia et al[2] concluded in a systematic review including up to 400 subjects of both sexes, that tendon regeneration after harvesting occurs in the 85% of patients. However, they also reported persistent strength deficits among this muscle group mainly at deep knee flexion angles despite successful tendon regeneration had occurred. Janssen et al,[38] found no correlation between tendon regeneration and isokinetic hamstring muscles performance. In the current study both groups showed similar changes in medial hamstring CSA which has been shown to be directly correlated to tendon regeneration rates.[4,5,9] However, the fact that greater muscle peak torque values were exhibited by the OCBR group indicates that perhaps the type of physical training received after surgery and the requirements fulfilled (in relation to knee functional status) to allow different exercise intensities, could play a determining role in the neuromechanical hamstring function recovery.

The time from original ACLR has also been observed to be a significant contributor to medial hamstrings strength imbalances. Studies analyzing muscle short-term function up to 1 year after ACL surgical repair[35,38] have reported greater strength deficits than those targeting this issue after longer follow-up periods.[8,36] Our study results showed that the lasting muscle strength deficits were more evident among the UC group. These results are also in agreement with previous investigations targeting this issue.[23,24]

Lastly, muscle retraction after tendon harvesting have also been postulated as a limiting factor for full hamstring strength recovery rates.[2] This notion was based on potential medial hamstring moment arm reduction due to the MTJ retraction process.[7,12] Carofino and Fulkerson[7] argued that the muscle torque curve would be affected after medial hamstring tendon harvesting. Other authors have stated that the total area under the torque-angle curve, but most likely not the peak torque, would be decreased due to medial hamstring tendon harvesting.[39] Our results partially support this statement. The optimum angle for peak flexor torque was not different between groups. However, the Hamstring muscles total mechanical work (area under the torque-angle curve) and peak torque values were found to be greater among the affected limbs of OCBR subjects in comparison with the involved limb of their counterparts 12 months after ACLR. Thus, it seems that OCRB regimens have an important influence in the successful final hamstring functional recovery despite of medial hamstring-based ACLR.

With respect to thigh muscles radiological examinations, it has been widely reported that short and long-term (snow) medial hamstring muscle size reductions occur after ACLR with autologous ST and GR tendon grafts.[4,9,40,41] These results are similar to the results of the present investigation, despite only a trend toward significant time vs. limb interaction were observed in Gracilis muscle CSA at 70% of femur length. However, little is known regarding the functional recovery of this muscle group according to the rehabilitation process.[9] In this sense, previous studies have shown that an accelerated rehabilitation following ACLR with Semitendinosus and Gracilis tendons could lead to earlier improvements in muscle strength without affecting knee joint residual laxity.[25] These results are consistent with those reported in the present investigation. Furthermore, they contribute original data with respect to muscle morphology adaptations with regards to the effect of the implementation of an objective criteria-based rehabilitation algorithm such as the previously proposed Myer el al[20] following ACLR. A similar tendency was observed in the Q muscles, where better isokinetic muscle strength performance was found in the OCBR group at 12 months after reconstruction despite a lack of significant improvement in muscle CSA.

Abundant evidence exists with respect to neural factor-derived strength gains when no objective hypertrophy is observed.[42] In relation to ACL injury several authors have observed neural pathways –dependent force production attenuation in relation to ACL injury both in the short and long terms after ligament injury. In that sense, Jordan et al[3] found a late rate of torque development attenuation among alpine skiers with previous ACL reconstruction at 2 years follow-up after surgery. Furthermore, Mirkov et al[5] found a significant rate of force development reduction in the short term among 19 men athletes 4 months after ACL repair. Similarly, several investigations have identified different thigh muscles electromyographic alterations subsequent to ACL injury, such as failure on Quadriceps activation in the acute phase postinjury[4] as well as in the long term after ligament repair concomintant to a greater hamstring muscles coactivation associated with worse knee joint overall function.[6]

The observed strength-related gains through non-hypertrophy-derived pathways could have been achieved by a neural drive optimization effect in subjects undergoing the OCBR rehabilitation program. In this sense, the current study could be the first to report neural but not hypertrophy- derived muscle strength gains among previously ACL-reconstructed patients following an OCBR rehabilitation program in both the harvested and antagonist musculature. This hypothesis should be further corroborated by electromyography recordings and/ or rate of force development assessments to address this issue.

This study has a number of potential limitations that should be addressed. The first one is related to the body positioning for Hamstring strength evaluation. Tadokoro et al[36] found that strength deficits compared with the contralateral healthy limb varied depending on the position at which the subjects were placed for evaluation. They found 14%, 45%, and 51% deficits when assessing hamstring isokinetic function in a sitting position at 90° knee flexion and in a prone position at 90° and 110° of knee flexion, respectively. With this in mind, we decided to measure the absolute peak torque for Hamstring muscle strength, which was not restricted to deeper knee joint flexion angles. We did it this way because it is known that the Hamstring muscles strain at near full extension knee joint positions.[43] It is also accepted that ACL integrity is most challenged in this position but in closed kinetic chain efforts.[1] Secondly, we cannot asseverate that neural factors derived strength gains were observed among ACL reconstructed patients following and OCBR, since no neuromuscular examination was performed in the present research. Furthermore, despite not significant ($P = .24$), patients allocated in the OCBR group received more rehabilitation sessions than their CON group counterparts. Controversy exists in relation to the minimum number of rehabilitation sessions needed to promote a clinically significant functional improvement on the knee when rehabilitating from an ACL reconstruction after repair. Furthermore, what kind of rehabilitation could be the more effective in terms of muscle force, neuromuscular control and anterior-posterior knee joint laxity recovery is still a cornerstone for both clinicians and researchers worldwide. Based on recent investigations, it seems that more functional and more intense rehabilitation programs have better outcomes after ACL reconstruction.[7] Indeed, it has also been highlighted the special focus the clinician should pay on the coexisting concomitant injuries to promote adequate healing times and avoid non desirables swelling and or knee joint overloading episodes.[28]

However, a concrete number of rehabilitation sessions expected as well as the effect a lack of a number of them on the knee joint functional outcomes after rehabilitations is in the authors opinion lacking. Beynnon et al 2005[22] found no differences in terms of patient self-satisfaction, knee laxity, activity level and function when comparing and accelerated vs. a nonaccelerated RHB programs lasting for 19 and 32 weeks respectively. In the same way, Risberg et al 2009[44] found similar results with respect to Cincinnati knee score when comparing a Neuromuscular training vs. Strength training based rehabilitation protocols following ACL reconstruction.

Furthermore, the neuromuscular training group reached better performance values regarding improved knee function and reduced pain during activity. The Strength training group reported non- significant but greater values when comparing total of participation weeks on the RHB program, hours spent at outpatient physiotherapy clinic, hours spent doing other exercise and additional exercise sessions. Thus, the authors of the present investigation humbly considerate that this kind of researches such ours, reporting specific rehabilitation programs and its comparison in terms of functional recovery reporting the exact number of rehabilitation sessions developed, could significantly contribute to the field to clarify this issues.

Another issue that must be taken into account before drawing definitive conclusion from in the basis of the results provided from this investigation, is the time passed from original ACL rupture to surgical reconstruction, Non significant (P = .47) but greater (near 50 days) amount of time passed from ACL injury to surgery among ACBR group of patients. the authors considered as it has been previously described in the literature[28] presurgical rehabilitation could have more impact on the long term outcomes after ACL reconstruction rather than the time passed from injury to surgery itself. Factors such as swelling, range of motion, force exertion capability of the knee surrounding muscles at the time of surgery can to a greater extend affect the final results of the process apart from time course.

In summary, objective atrophy of the implicated musculature (Semitendinosus and Gracilis) related to the surgical reconstruction persisted in the reconstructed limb 1 year after medial hamstring ACLR, regardless of whether OCBR or UCR rehabilitation protocols were used. Surprisingly, subjects following the OCBR protocol demonstrated greater muscle strength gains despite persisting reductions on muscle size. At the same time no differences were found with respect to the optimum angle for peak torque production between groups. However, larger flexion mechanical work values were found in the harvested musculature among OCBR participants. Selective retraining of the Hamstring musculature and quantitative evaluation of the knee joint function and status for allowing progression through the rehabilitation program intensity (OCBR group) after ACLR, seems necessary to counteract the persisting knee flexor strength deficits and restore AP knee laxity to normal levels.

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