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Reconstructed ACLs have different cross-sectional areas compared to the native contralaterals on postoperative MRIs. A pilot study

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Abstract. – OBJECTIVE: The current trends in anterior cruciate ligament (ACL) reconstruction aim not only to restore the position and footprint of the native ACL, but also its shape and biomechanical function. The objective of our study was to determine whether the *in vivo* shape of the healed graft differs from the native ACL.

PATIENTS AND METHODS: We performed bilateral MRI examinations on patients with successful unilateral ACL reconstruction for an average period of 3 years. The imaging acquisitions were performed using 1.5T field strength and T2 FSE axial oblique sequence at 2 mm spacing. We than averaged the ratio between the maximum width and thickness as well as the surface area in pixels using ImageJ (National Institutes for Health) and compared it with the native ACLs using the paired *t*-test.

RESULTS: For both quadrupled hamstrings and B-PT-B neoligaments, the mid-portion area was significantly higher ($p < 0.001$) than the native contralateral ACL: 41.82/31.39 mm^2 and 37.05/32.08 mm^2, respectively. The surface area of the neoligaments mid-portion was on average 33.23% higher than the native ACL for the quadrupled hamstrings and 15.49% for the B-PT-B, respectively. The native contralateral ACL was also significantly thinner throughout the mid-portion ($p < 0.001$) than both B-PT-B and quadrupled hamstrings neoligaments, with a width-thickness ratio of 2.57 vs 1.97 and 2.57 vs 1.39, respectively.

CONCLUSIONS: Our study showed that, several years after successful anatomic single bundle ACL reconstruction using an ipsilateral autograft, the mid-portion shape and cross-sectional area are not restored compared to the uninjured contralateral knee. This effect was more prevalent with hamstrings and less prominent when B-PT-B were used.

Key Words:
ACL, Anatomic reconstruction, Hamstrings, Bone-patellar tendon-bone, MRI.

Introduction

Injury of the anterior cruciate ligament (ACL) is a common sports injury of the young, physically active adult population. The poor healing capacity, as well as the need of an anterior tibial restrain in order to return to preinjury sporting activity level, made the ACL the most frequently reconstructed ligament in the human body[1]. The techniques for reconstruction have constantly evolved over the last two decades. Trans tibial tunnel drilling and the double bundle approach have not proved superior to the anatomic single bundle using hamstrings or bone-patellar tendon-bone autografts (B-PT-B)[2]. Current trends aim, not only to restore the position and footprint of the native ACL, but also the shape and biomechanical function. Recent anatomical research[3] found the shape of the ACL mid-substance to be flat, with a ribbon like appearance and broad, fan like expansions on both tibial and femoral insertions. Another study[4] showed that conventionally prepared quadrupled hamstring autografts had a mid-portion cross-sectional area more than 20% larger than the native ACL. These are cadaveric studies that do not account for the potential remodeling that may occur during healing. We therefore questioned whether the *in vivo* shape of the healed graft will also significantly differ from

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the native ACL, as determined by cross-sectional area and width-thickness ratio on postoperative MRIs.

Patients and Methods

We performed bilateral MRI examinations on 12 asymptomatic patients (3 females) with unilateral ACL reconstruction. Six patients had quadrupled hamstrings neoligaments and 6 had reconstructions using B-PT-B ipsilateral autografts for an average of 2.66 (range 1-5) and 3.33 (range 1-5) years respectively. All patients were operated by the same surgeon in the same location using an anatomical single bundle technique[1]. After initial arthroscopic exploration, the ipsilateral autografts were harvested and prepared by a resident on the back table. The bone-patellar tendon-bone was harvested from the mid portion using a longitudinal incision. The semitendinosus and gracilis were harvested through a small oblique incision over the pes anserine bursitis using closed stripper. Five patients had a partial meniscectomy: four of the medial and one of the lateral meniscus while 6 patients had grade 1 or 2 Outerbridge chondral lesions. The femoral tunnel was drilled first through the anteromedial portal with the aperture centered in the native footprint. The tibial tunnel intra articular aperture was centered on the remnant stump and the bony attachment of the anterior horn of the lateral meniscus[5]. Femoral fixation used either absorbable interference screws (2 knees) or cortical button-suspensory loop (4 knees). Tibial fixation was done by absorbable interference screws augmented in one case by a staple. The imaging acquisitions were performed on a General Electric machine with 1.5T field strength using T2 FSE sequence at 2 mm spacing. We exported 6 DICOM images corresponding to the body of the ACL from each axial oblique sequence using RadiaAnt (Medixant, Poznan, Poland) DICOM Viewer 1.9.16 (64-bit Windows). We then averaged the ratio between the maximum width and thickness as well as the surface area in pixels using ImageJ (64bit for Windows, National Institutes for Health, Bethesda, MD, USA) and compared it with the native ACLs using the paired *t*-test (GraphPad/QuickCalcs).

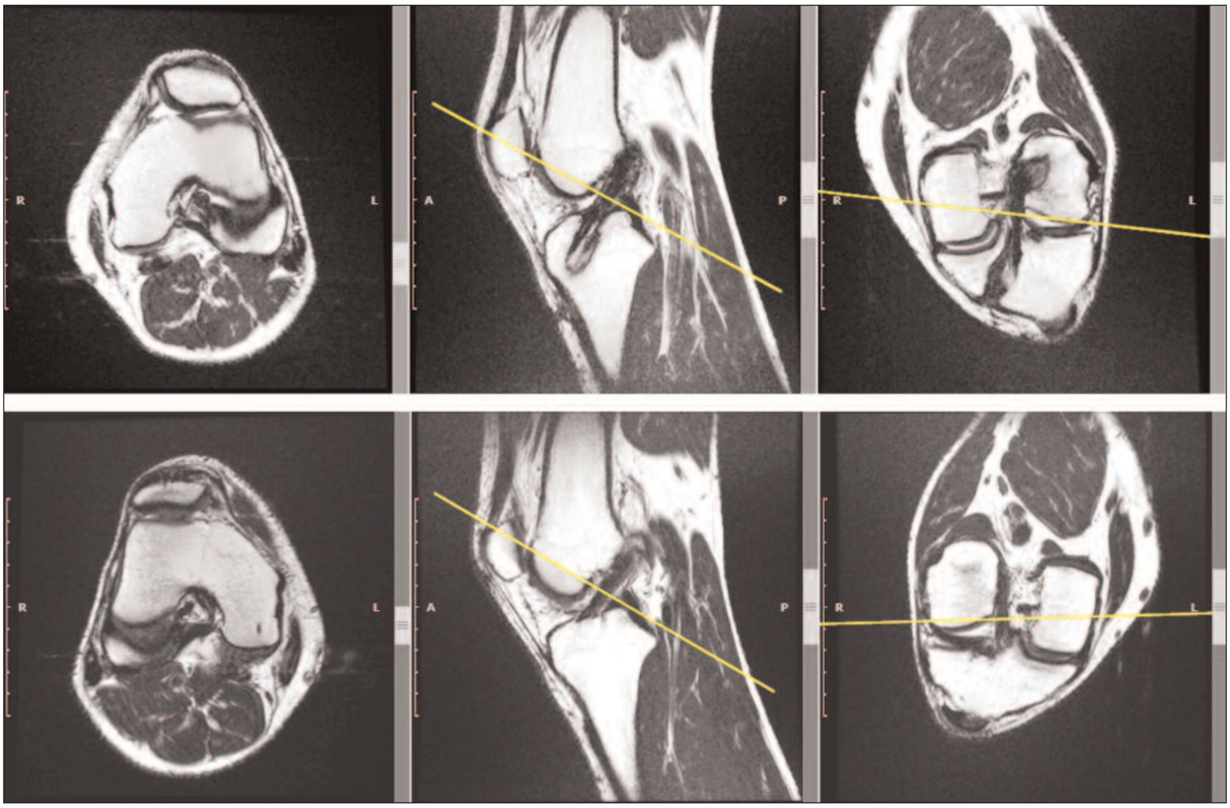

Figure 1. Screen capture of RadiaAnt viewer with the 3 sequences used to determine the neoligament/ native ACL shape from oblique AX, Sag and COR T2 FSE MRI acquisitions.

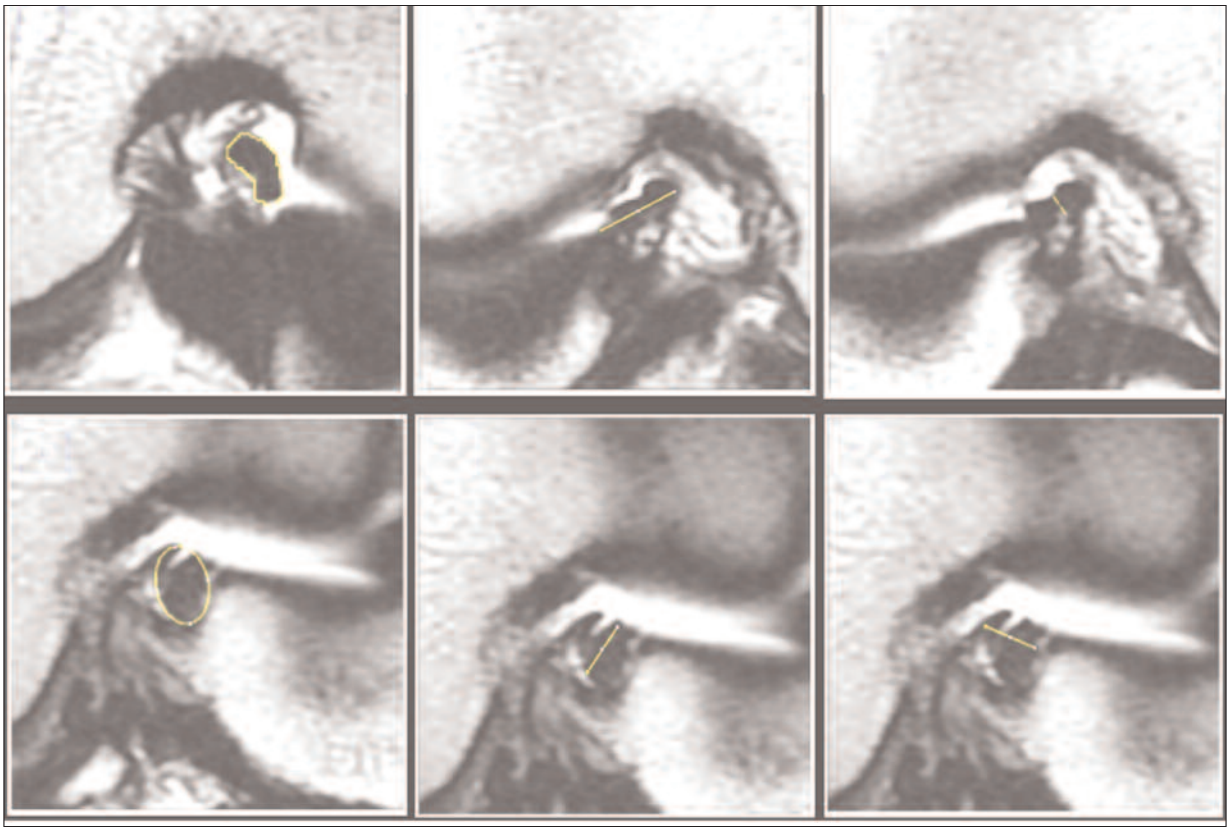

Figure 2. The lengths and widths of the ACLs were determined using the standard ImageJ tools and the measurements for the area were made using the elliptical or brush selections, free hand positioned, alternatively by two authors, on the chosen images at 400% magnification for better delimitation.

Results

For both quadrupled hamstrings and B-PT-B neoligaments the mid-portion area was significantly higher (paired *t*-test $p < 0.001$) than the native contralateral ACL: 41.82/31.39 mm^2 and 37.05/32.08 mm^2 respectively. The surface area of the mid-portion neoligaments was, on average, 33.23% higher than the native ACL for the quadrupled hamstrings and 15.49% for the B-PT-B, respectively. The native contralateral ACL was also significantly thinner throughout the mid-portion (paired *t*-test $p < 0.001$) than both B-PT-B, as well as quadrupled hamstrings neoligaments, with a width-thickness ratio of 2.57 vs 1.97 and 2.57 vs 1.39, respectively. For the hamstrings autografts, the measured neoligament was also significantly smaller than the intraoperative size; 6.74 vs 7.21 mm (paired *t*-test $p < 0.001$).

Discussion

Our study showed that several years after trans AM (anteromedial portal) single bundle ACL reconstruction, using an ipsilateral hamstrings or B-PT-B autograft, the mid-portion shape and cross-sectional area are not anatomically restored compared to the uninjured contralateral knee. This is the first analysis of the anterior cruciate neoligament mid-portion shape compared to the native anatomy performed on human subjects, *in vivo*, after complete healing and integration. The results of our paper produced slightly different values from those reported in the literature (Table I) but do follow the same trends. The mid-portion area of both the hamstrings neoligament and the native ACL, as well as their percentual difference, are larger in our investigation compared to that of Pujol et al[4]. The cross-sectional area was smaller and the width-thickness ratio higher for

Table I. Results of the current study and comparison with the literature, analyzing the size of the ACL mid-portion in relationship with commonly used grafts.

Study	Type	Hamstrings ACLR mid-portion (mm)			B-PT-B ACLR mid-portion (mm)			Native ACL mid-portion (mm)		
		Area	Width	Thickness	Area	Width	Thickness	Area	Width	Thickness
Pujol et al 2013 Avg. (range)	Cadaver	35.3 (20-50)	6.7 (5-8) diameter	–	– –	–		29.2 (20-38.9)	6.1 (5-7) diameter	
Triantafyllidi et al 2013 Avg. 95% CI	Cadaver	–	8 diameter	–	–	–	5.8	35.4-39.4	7.41- 7.94	4.78- 4.96
Iriuchishima et al 2014 mean ± SD	Cadaver	64.4 ± 6.2	–		40.8 ± 6.7	–	–	46.9 ± 18.3	–	–
Current study mean ± SD	In vivo MRI	41.82 ± 2.17	7.84 ± 0.63	5.65 ± 0.48	37.05 ± 2.83	8.91 ± 0.48	4.53 ± 0.32	31.74 ± 2.14	8.95 ± 0.84	3.48 ± 0.37

the native ACL in our group, compared to a different paper[6]. Iriuchishima et al[7] also reported slightly higher values than ours for all surface areas. Such discrepancies, also present among the published materials, are within the expected range, due to several confounding factors. Particularly important is that all their determinations were made on cadaver specimens whereas ours were done using MRI of *in vivo* healed grafts.

We would like to comment the difficulties found in our investigation. There was present defect in measuring the sizes on MRI produced by the difficult detection of the ligament borders from the surrounding synovia. In order to reduce this effect, we acquired high resolution images closely spaced and used high magnifications; furthermore, the determinations were done by two experienced researchers, well familiarized with ACL MRI imaging and segmentation software. There was also imprecision in obtaining a true axial oblique orientation of the sequence which would produce a perpendicular cross-sectional area located over the mid-portion of the ligament. Both should have been mitigated by using an average size from 6 consecutive images. The use of an axial oblique sequence provided better evaluation of the ACL cross-sectional area but prevented a further comparison with the PCL, as determined from the same slice. By using pixels to quantify sizes there is an inaccuracy associated with the autocalibration and scaling; the effect disappeared when using ratios. The limited number of patients was compensated by using the paired *t*-test comparison with uninjured contralateral side and with the analysis of parameters with high predicted difference among groups. The lack of reported symptoms among our tested patients was considered an additional proof of quality reconstruction and appropriate healing. Without validated scores to backup, this may not always correlate with the surgical results[8]. Previous researches have focused on the use of cadaver samples, which provide a pertinent representation of the local anatomy. Nonetheless, there are several drawbacks with using human specimens. The age of the source is much higher than that of the young adult target population. Some cohorts also do not respect the predominance of males as is the case in the real ACL injured patients. However, the most important disadvantage with cadaver studies is, probably, that they cannot offer a true glimpse into the functioning of the healed neoligament and its properties *in vivo*. We chose the T2-weighted FSE MRI sequence for several reasons. It is a proved, noninvasive method to determine the position and the healing of the ACL graft[9,10]. The continuous structure, homogeneity and relationship of the graft, with the surrounding anatomic structures (coronal and sagittal inclination), tunnel size, aperture localization and absence of synovitis, were used as imaging criteria for successfully healed ACL reconstructions. In our study the patients were asymptomatic and have fully returned to pre-injury activity levels. A recent study compared the T2 MRI parameters of the reconstructed ACL with the mechanical properties of the *ex vivo* graft in a porcine model. The authors were able to prove that volume and combined grayscale values were strongly predictive for the biomechanical behavior of the tested healed grafts, accurately reproduced[11].

We consider that the shape differences above described may also have potential biomechanical implications. The native ACL is a complex three-dimensional structure, made up with bundles of fibers which fan out over the insertions and are twisted around the waistline[12]. These fibers have different length and orientation and undergo to separate group tensioning during flexion-extension and complex motions. The histological architecture is comprised of mid-substance fibers that have a separate insertion and trajectory from the surrounding fivers which extensively fan-out over the insertions[13]. This effect creates a much larger contact over the footprints and a nimble band-like cross-sectional area in the mid-portion with improved biomechanical behavior[3].

The mid-substance fibers can be recreated by the conventional reconstruction techniques and grafts[13]. The broader expansions over the footprint areas were attempted to be restored by the double bundle technique. However, this has not produced the expected biomechanical results except for large knees, where this double bundle effect was more prevalent[2]. Several authors have proposed the use of single bundle reconstruction with B-PT-B grafts fixed through rectangular bone tunnels. This configuration proved to have better *in vivo* kinematics compared to the round tunnels[14]. Compared to quadrupled hamstrings, the effect was also observed through round tunnels and cortical button-loop fixation by improved early flexion tibial control (simulated Lachmann and pivot-shift)[15]. We believe that both of these autografts have inherent peculiarities that will lead to idiosyncratic biomechanical behavior[16]. Both can be successfully used to closely recreate the native ACL function. However, the effects seen with the rectangular tunnel might be related to a more precise positioning that leads to a specific torsional pattern of the neoligament which more closely resembles the natural anatomy. This effect may be augmented by further refinement of the entire shape of the intraarticular portion of the reconstructed ACL. Extensive researches produced improvements from more biomechanically sound placements of the tunnel apertures in relationship to the natural footprints. In the same direction, we believe a better understanding of the functional behavior of the ACL body which will further improve the outcomes after ACL reconstruction.

Conclusions

Our study showed that several years after successful anatomic single bundle ACL reconstructions using an ipsilateral autograft, the mid-portion shape and cross-sectional area are not fully restored compared to the uninjured contralateral knees. This effect was more prevalent with hamstrings and less prominent when B-PT-B were used.

Conflict of Interest

The Authors declare that there are no conflicts of interest.

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