Strength and Regrowth of Hamstring Tendons After Hamstring Autograft Anterior Cruciate Ligament Reconstruction

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Summary: Much controversy exists regarding the potential advantages and disadvantages of various graft choices for anterior cruciate ligament reconstruction. Advocates of hamstring autografts often cite the limited apparent morbidity associated with semitendinosus or semitendinosus and gracilis harvest, including evidence that hamstring tendons may regenerate after harvest. In this article, we attempt to summarize the functional, radiographic, and histologic studies to date that examine hamstring regeneration. Ultimately, it appears that tendon-like tissue regenerates in the vast majority of patients, but the anatomic location and biomechanical quality of the neotendon may be inferior. Regardless, functional deficits after hamstring harvest appear to be minimal in most individuals. **Key Words:** Anterior cruciate ligament—Hamstring—Regeneration—Tendon.

More than 100,000 anterior cruciate ligament (ACL) reconstructions are performed annually.[2] The majority of these procedures use autograft donor tissue, most commonly bone–patellar tendon–bone (BPTB) or hamstring tendons (either semitendinosus [ST] or semitendinosus with gracilis [STG]).[9,19] Much controversy exists regarding the potential advantages and disadvantages of these 2 graft choices. Advocates of hamstring grafts cite a number of potential drawbacks to BPTB use, including patellofemoral pain, patellar tendonitis, tendon rupture, patellar fracture, and permanent extensor weakness.[1,4,9,20] It has also been suggested, with growing evidence, that hamstring tendons may regenerate after harvest. Such a phenomenon may offer an additional advantage for the use of hamstrings in ACL reconstruction. In this article, we attempt to review and summarize the literature to date examining semitendinosus and gracilis regeneration after harvest from a functional, radiographic, and histologic standpoint. A number of papers reviewed included data in more than one category; each aspect of these papers is discussed in the appropriate section.

DISCUSSION

Functional Studies

A number of studies have been conducted evaluating hamstring strength after tendon harvest, not all of which can be reviewed here. Interpretation of this literature is somewhat more difficult because of the inevitable differences in follow up, rehabilitation protocols, and testing procedures found among the papers. In addition, some studies have evaluated patients after ST harvest, whereas others have evaluated STG harvest. Regardless, concern about postoperative leg strength after hamstring harvest has been a focus of study since at least 1982, when Lipscomb et al, after a retrospective analysis of 482 cases, found no significant loss of knee flexion strength at an average of 26 months after ST or STG harvest.[12] Hamstring strength averaged 99% of the normal knee when STG was used, and 102% of the gracilis was not harvested.

It was not until the early 1990s, however, that widespread interest in this subject developed, largely fueled by 2 somewhat contradictory studies. In Australia, Cross examined 4 patients 6 months after ACL reconstruction using ipsilateral STG grafts.[3] Three of the 4 patients

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demonstrated minimal decreases in peak flexion and extension strength, averaging less than 10% loss, whereas the fourth patient actually had improved strength parameters. Around the same time, Marder compared hamstring strength between patients with ipsilateral STG grafts and BPTB grafts and noted 17% lower isokinetic flexion strength in the former group.[15] Interestingly, Eriksson and colleagues noted significantly lower values of peak torque of both the hamstrings (approximately −25%) and quadriceps (approximately −50%), during both concentric and eccentric testing, when compared with the nonoperative leg in 16 patients 8 to 18 months after surgery.[4] Such global weakness may suggest insufficient postoperative rehabilitation, for which no specific details are provided.

In general, however, recent studies that have examined knee flexion strength have documented minimal or no deficits in peak torque after ST or STG harvest.[13,14] Most notably, Yasuda prospectively evaluated peak torque after STG harvest from either the ipsilateral or contralateral leg.[27] In neither scenario did hamstring harvest appear to significantly decrease flexion strength past the immediate postoperative period. More detailed analyses, however, have found subtle differences in the torque pattern. Adachi et al assessed peak torque, peak torque angle, and total work in 58 patients at an average of 2 years after ACL reconstruction using ST, STG, or allograft.[1] Again, they found no significant differences in peak strength or total work between the groups, but the degree of flexion at which peak torque was generated did shift to a significantly shallower angle in the hamstring groups. Similarly, Ohkoshi also noted no differences in peak flexion torque before and after contralateral hamstring harvest (ST only) in 25 patients, but did find significant decreases of 11° to 15° in peak torque angle.[18] They proposed that decreases in peak torque angles result from compensation by flexor muscles that have lower peak torque angles than the hamstrings. Irie and Tomatsu also assessed 13 patients at 12 to 16 months after isolated gracilis or STG harvest.[10] Cybex testing of knee flexion found no differences in peak torque but did note 25% less total work performed at flexion angles greater than 75°.

More recently, in a study of 74 consecutive patients 2 years after surgery using ST or STG, Nakamura and partners also found recovery of peak flexion torque to be greater than 90%.[17] Once more, however, peak torque at 90° of knee flexion was deficient in both the ST and STG groups, but with no differences between the groups. Finally, in one of the only prospective, randomized analyses on the subject, Tashiro randomly assigned 90 patients to ACL reconstruction with either ipsilateral ST

or STG autograft.[24] At 6, 12, and 18 months after surgery, the groups did not differ significantly from one another in peak flexion torque, and overall, torque was decreased only slightly at the 6-month time point before returning to preoperative levels thereafter. Like in other studies, however, recovery was less at higher flexion angles, and significant decreases in hamstring strength of up to 30% were found at flexion angles greater than 70° in both groups.

Overall, it appears that deficits in postoperative knee strength—at least in terms of knee flexion—are minimal regardless of whether the ST or STG tendons are harvested, with the exception of somewhat lower strength at very high flexion angles. It is not clear, of course, whether overall maintenance of flexion strength is a result of hamstring regeneration or compensatory hypertrophy of other muscle–tendon units. Two recent studies suggest that a more important parameter for assessment may be internal tibial rotation torque. In 2000, Viola reported on 23 subjects who had undergone ACL reconstruction with STG.[25] At an average of 51 months after operation, internal tibial rotation torque (as compared with the contralateral limb) of approximately 10% to 15% was found at all velocities measured (60°, 120°, and 180°/sec). No differences in external torque strength were noted. Similarly, Segawa and associates compared internal tibial torque in 32 patients with ST and 30 patients with STG grafts 1 year after surgery.[21] Again, internal rotation strength was significantly less than the contralateral leg, especially if the gracilis was also harvested. The authors recommended harvest of the ST only, if possible, and the inclusion of specific rehabilitation exercises focused on internal rotation strength. Regardless, no studies have yet correlated deficits in either knee flexion or internal rotation strength with any functional impairment or effect on athletic performance. Some authors suggest that such differences should not produce significant clinical deficiencies except in certain high-performance activities requiring intense knee strength in deep-flexed positions such as judo, gymnastics, or wrestling.[17,23,24]

Radiographic Studies

Numerous investigators have also attempted to describe the radiographic appearance of the ST and gracilis tendons after harvest. Their studies have provided information not only on the extent of regeneration, but also on the location of regenerate tissue and the occurrence or absence of muscle atrophy. Cross, in the early case series mentioned in the previous section, also included magnetic resonance imaging (MRI) evaluation of the 4 patients.[3] In all scans, they were able to trace a tendon-like

structure from the hamstring muscle bellies to the medial gastrocnemius, in which insertion appeared to be diffuse into the medial popliteal fascia. Furthermore, electromyographic studies on these patients demonstrated normal hamstring innervation patterns and muscle activity. Simonian also described a more proximal insertion of the ST regenerate tendon, but found no significant hypertrophy of the biceps, semimembranosus (SM), or sartorius when compared with the nonoperated sides.[22]

Erikkson and partners have reported on the magnetic resonance imaging appearance of regenerate hamstring in a number of papers. The first, in 1999, reported regeneration of the ST to the level of the proximal tibia in 8 of 11 patients evaluated 6 to 12 months after surgery (ST harvest only), whereas in the other 3, the ST remnant fused to the SM tendon above the joint line.[6] Those patients with regenerate distal tendon demonstrated fusion of the ST and gracilis approximately 30 mm below the joint line with insertion into the pes anserinus as a conjoint tendon. (The authors do point out that the exact level of confluence, unless it is above the joint line, may be of minor importance.) The proximal cross-sectional area of the ST also differed, averaging 91% in those with distal regeneration and 79% in those without. Two years later, Eriksson studied 6 patients who had undergone ACL reconstruction 7 to 28 months earlier using only the ST graft.[5] In 5 of the 6 patients, magnetic resonance imaging showed regeneration of ST tissue to the pes inserting at an average of 3 cm below the joint line. The sixth patient, 24 months after surgery, had no evidence of new tendon. Concurrently, Eriksson and Hamberg published another magnetic resonance imaging study of 16 consecutive patients imaged between 6 and 12 months after ST harvest.[4] Seventy-five percent exhibited radiologic evidence of tendon regeneration, with neotendon fusing with the (nonharvested) gracilis 1 to 3 cm below the joint and inserting as a conjoined tendon into the pes. Some degree of ST atrophy was present in all patients but was significantly more in those without regenerated tendon, and in those patients, compensatory SM hypertrophy was greater. Unfortunately, no preoperative magnetic resonance images were used for comparison.

In a slightly different fashion, Rispoli et al attempted to provide radiographic documentation of tendon regrowth by performing a single magnetic resonance imaging on 21 patients, each at a different time interval (2 weeks to 32 months) after ACL surgery using STG.[20] They did not sequentially image any single individual. Fluid and edema were noted in the tendon tracts at the earliest time points, but by 6 weeks after surgery, tendon-like tissue had reached the level of the superior patellar pole. Appearance of tendon at and below the joint line

was variable, occurring anywhere from 3 to 12 months. This linear development was also documented by Papandrea in a study using sequential ultrasounds of 40 patients at 2 weeks, and 1, 2, 3, 6, 18, and 24 months after surgery using STG.[19] They observed a maturation process from ill-defined hypoechogenic tissue at the earliest time points, with hypertrophy occurring over the first year before development to a distinct, well-defined structure with normal tendon signal by 18 to 24 months. In all cases, the neotendon appeared to insert more proximally than normal into the medial popliteal fascia.

As recently as 2004, multiple investigators have continued to explore this process. Nakamura et al published a detailed retrospective study using magnetic resonance imaging and 3-dimensional computed tomography scans to assess ST regeneration in 8 patients, all of whom were at least 2 years postsurgery.[16] In 5 of the 8, discrete tissue was documented running in the same path of the native hamstrings but attaching distally into the medial popliteal fascia, whereas in the remaining 3, the ST remnant proximally fused into the SM muscle belly. Similar findings were apparently noted for harvested gracilis tendons as well, although a detailed description was not provided. Similarly, Tadokoro imaged 28 patients with magnetic resonance imaging at a minimum of 2 years after ACL reconstruction with STG.[23] Twenty-two of 28 ST tendons and 13 of 28 gracilis appeared to have regenerated, and no differences in muscle cross-sectional area were noted between those limbs in which tendon regeneration had occurred versus control limbs. Most interestingly, they found that although peak flexion strength in both supine and prone positions at high flexion degrees (90° and 110°) was less in the operated limbs, this strength had *no correlation* with the extent of morphologic regeneration. Williams and colleagues also performed magnetic resonance imaging on 8 patients before ACL reconstruction with STG and then again after return to sports (an average of 6 months after surgery).[26] In 88% of subjects (7 of 8), distinct tendons regrew, but the majority of tendons had not yet inserted on the tibia at the time of analysis. Furthermore, overall volume of the gracilis and ST muscles decreased by an average of 30% and, in contrast to Takadoro's study, appeared to correlate well with the degree of tendon regeneration. In addition, compensatory biceps femoris and SM hypertrophy also occurred.

Histologic Studies

Despite the results of both functional and radiographic studies suggesting that harvested hamstring tendons regenerate in a similar location and with similar radiographic appearance as the native tendons, it was not until
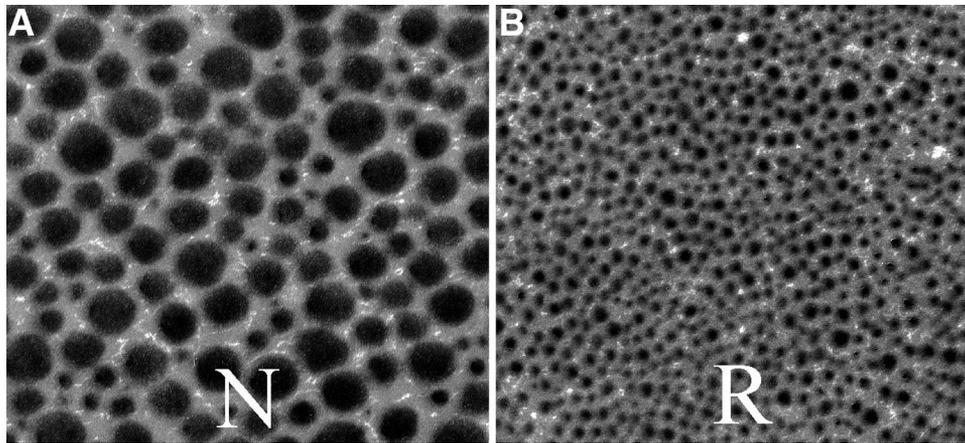
FIG. 1. Representative images at equal magnification comparing collagen fibril size in native (**A**) and regenerate (**B**) rabbit hamstring 28 weeks after harvest.

recently that any biomechanical or histologic assessment of the regenerate tissue has been performed. Eriksson and Hamberg, in their magnetic resonance imaging study, also obtained biopsies of the hamstring muscle body before and after surgery.[4] Although muscle fiber area exhibited a trend toward smaller values in the postoperative limbs, no differences were found in fiber-type composition or citrate synthetase activity. In a separate study from the same group, biopsies from the peripheries of 5 regenerate ST tendons were examined and compared with normal tendon.[5] The regenerate collagen fibers were of similar alignment and dimension as those in control tendons and uniformally stained for the appropriate forms of collagen. Small areas of irregularly oriented collagen and increased fibroblast and capillary formation, consistent with scar-like tissue, however, were noted.

Ferretti also histologically analyzed the regenerate tissue obtained from 3 patients at 6, 24, and 27 months after surgery during routine hardware removal.[7] In the earliest (6-month) specimen, microscopic examination demonstrated prominent fibroblastic proliferation and few vessels and little longitudinally oriented collagen. The 2 latter specimens, however, both contained thicker, well-oriented fibers with appearance similar to normal adult tendon.

Animal Models

Recently, papers examining rabbit models of tendon regeneration have been published, including 2 studies by the senior author of this paper (MDM). In the first study, 10 rabbits underwent magnetic resonance imaging, histologic and biomechanical analysis 16 or 28 months after ST harvest.[11] All animals exhibited radiologic evidence of tendon regrowth. On magnetic resonance imaging at 16 weeks, the regenerate tissue was wavy and could not be traced all the way to the tibia, but by 28 weeks, the neotissue appeared taut and inserted at the normal ST insertion. This maturation process was confirmed on histologic examination, because tissue at 16 weeks contained longitudinal but wavy collagen fibers, whereas at 28 weeks, the tissue was essentially indistinguishable from native tissue. Biomechanically, the tendons appeared to strengthen as they matured, although at both time points, the regenerate was weaker in maximum load to failure than native tendons (-77% at 16 weeks and -48% at 28 weeks).

More recently, in Gill et al, the senior author of this paper reported a follow-up study with more comprehensive analysis of the regenerate rabbit tissue.[8] ST tendons appeared to regenerate in 26 of 31 animals at 9 to 12 months after surgery but were highly variable in size and tibial insertion site. The neotissue strongly resembled tendon in cellularity and immunolocalization of type I collagen, but fibril size was significantly smaller, fibril orientation less regular, and proteoglycan content significantly lower in the regenerate (Figs. 1 and 2). The authors also performed detailed biomechanical analyses and found markedly inferior maximum loads to failure and structural stiffness (approximately 25% of controls) in regenerate. Because the authors could not precisely compare the cross-sectional area of control or regenerate tendons, the inferior biomechanical results might be, at least in part, the result of smaller size, but the results strongly suggest substandard material properties of the regenerate tissue.

Future Directions

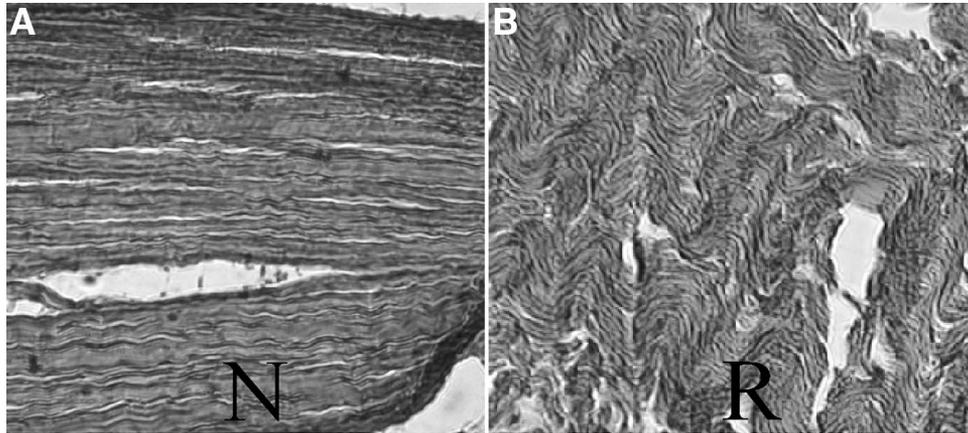It is not yet clear how regeneration occurs and what factors might increase the biomechanical properties of

FIG. 2. Comparable images of collagen fibril orientation in native (**A**) and regenerate (**B**) rabbit hamstring 28 weeks after harvest.

the regenerate. It is theorized that extrasynovial hematoma collects along fascial planes and may act as a scaffold for fibroblast precursors cells, with the regeneration process beginning at the more vascular proximal area and extending distally.[5,8,20] Despite these unknowns, reports are starting to appear proposing the possibility of reharvest of regenerate tendon for use in revision surgeries. Yoshiya and associates have published a case report from Japan in which the hamstrings were reharvested 8 months after a primary procedure and used for revision ACL reconstruction.[28] Biopsy of the tissue at the time of surgery showed significantly smaller collagen fibril diameter in the regenerate compared with normal tendon. Although follow up was only 6 months, the patient was reported to be doing well. Appropriately, however, the authors conclude that the feasibility of routine use of the regenerate tissue remains to be determined.

CONCLUSIONS

After a thorough review of the current literature, it appears well established that after harvest, the ST and gracilis tendons regenerate to some degree in the vast majority of patients, and the clinical impairment caused by hamstring harvest appears to be tolerable in virtually all patients. Nearly all individuals recover near-normal flexion strength with minimal residual functional deficit. This recovery is likely owing to a combination of ST and gracilis regeneration and hypertrophy of compensatory musculature. The extent of tendon regrowth, however, and especially the reinsertion site of the new tissue, is unpredictable in any given patient, because various authors have documented reattachment of the new tissue to the medial gastrocnemius and the popliteus fascia, as well as to the original anatomic insertion site. The

appearance and behavior of the regenerate tissue in the laboratory is also not ideal. The newly formed tissue closely resembles collagenous tendon, but appears to be less organized and biomechanically inferior to native tendon. Despite the low morbidity of hamstring harvest and the increasing body of work documenting regeneration of "tendon-like" tissue, it is not yet clear that reharvest of the regenerate tissue for revision surgical cases is feasible. Further work is necessary to determine the factors, both intrinsic and surgeon-controlled, that may improve regeneration of an effective and useful hamstring tissue.

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