Hamstring Tendon Harvest for ACL Reconstruction: Impact on Muscle and Function

by

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ABSTRACT

Background: Semitendinosus-gracilis (STG) autograft continues to increase in ACL reconstruction and a comprehensive study of the impact of what is essentially 'surgically induced tenotomy' of STG has not been undertaken.

Purpose: To examine longitudinal changes in muscle morphometry and physical activity (PA) in relation to strength, functional tests, and subjective outcomes.

Methods: Assessments at pre-, 2-weeks, 6- and 12-months post-surgery were performed on twenty moderately active adults undergoing ACL reconstruction. Participants were randomized to the Standard group (using STG tendon from the ACL deficient limb) or the Contra group (using STG from the opposite limb). Bilateral lower extremity MRI, Tegner, Lysholm, and IKDC scores, hop tests, and isovelocity strength testing in a seated and hip-neutral supine position were completed. PA was assessed using a tri-axial accelerometer (GTX3, Actigraph, Pensacola, FL).

Results: **S**ubjective scores significantly improved from pre- to 12-months post-surgery, although Tegner score was significantly less (-1.25 levels) than pre-injury scores at 12-months. ST and G CSA significantly declined in donor limbs to 41.5% and 65.5% of pre-surgery, respectively and there was a 5.7 (2.9) cm proximal shift in ST and a 4.2 (2.3) cm shift in G donor muscles. In the donor limb, nine of 17 participants for ST and one for G had more than an 80% reduction in volume. There was significant difference between donor and non-donor limbs in peak knee flexor torque, but only in the hip-neutral testing position. There were no differences in hop tests between legs regardless of reconstruction or STG tendon harvest. PA did not significantly improve from pre-surgery, but was comparable an age-matched normative population. This level was less than that necessary for a healthy lifestyle (10,000 steps). Morphological parameters were moderately or highly predictive of outcomes in subjective findings, single hop test, PA, and strength.

Conclusion: Changes in muscle morphology following tendon harvest of ST and G were found to be related to measured decreases in knee flexor strength, and post-operative deficiencies in objectively measured PA, hop tests, and subjective findings at 12-months post-surgery. PA did not increase in a statistically or clinically relevant degree consistent with a diminished self-report of function.

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INTRODUCTION

Anterior cruciate ligament (ACL) reconstruction using hamstring tissue was first described in 1939 by Harry B. Macey, but today's procedures bear little resemblance to that time.[1] Surgical ACL reconstruction using semitendinosus (ST) and gracilis (G) has evolved through the exploration of various aspects of the surgery including graft fixation devices [2–12], single- (two strands) versus double- (four strands) bundle techniques [13–21], anatomic ACL reconstruction [21–25], and different tunnel placement approaches. [26] Post-operative rehabilitation has also evolved with a shift towards 'evidence based' prevention and treatment strategies and implementing early, more progressive, and novel techniques such as the application of vibration, EMG feedback, and others to enhance neuromuscular control.[27–33] Hewett and colleagues recently described "a new approach to return-to-sport training after ACL reconstruction that is focused on resolution of neuromuscular deficits that are known modifiable factors that persist following reconstruction and rehabilitation." [27] Much of the work upon which this approach is based evaluates ACL reconstruction using bone-patellar tendon-bone autograft. Many aspects of rehabilitation will be the same regardless of graft choice, but in addition, well-designed and effective approaches that mitigate the impacts of STG graft harvest are critical for maximizing patient outcomes.

The use of hamstring tendon has been widely adopted as the standard for ACL reconstruction in Canada. A recent survey of Canadian Orthopaedic Association (COA) members found that 72% of orthopaedic surgeons chose the STG autograft.[28] This is a dramatic increase from a survey conducted in 1995 that reported only 12% of Canadian surgeons using STG.[29] There is also evidence of surgeons based in other countries preferring hamstring autograft. For example, the results of a survey of ten orthopaedic societies in 57 countries found 63% choosing hamstrings[30] and a study based on the Danish ACL registry reported 71% of ACL reconstructions between 2005 and 2007 incorporated hamstring autograft.[31] There may be a shift in the United States towards the use of hamstring autograft, but based on the most recent reports, bone-patellar tendon-bone autograft is still preferred.[32–34]

There is still a debate as to the benefits of STG autograft over other options (e.g., bone-patellar tendon-bone graft (BPTB)).[4,35–37] The primary criticism of using an STG graft has been reduced knee flexor strength post-operatively while anterior knee pain and knee extensor strength deficits are the primary concerns with BPTB. There is also ongoing exploration into other options, for example, quadriceps (Q) tendon, allograft, and synthetic graft material.[38–50] However, the use of hamstring graft continues to increase and a comprehensive study of the impact of what is essentially ‘surgically induced tenotomy’ of STG may provide insight into the enhancement of surgical and rehabilitation approaches to maximize patient outcomes.

Recovery after ACL rupture and subsequent surgery is multi-factorial. Following ligament rupture (but before surgery), there may be de-conditioning in one or both lower extremities, core muscles, cardiovascular systems, etc. There may be nociceptive inhibition of muscles in the lower limb due to pain and/or the anticipation of pain leading to apprehension, and then altered neuromuscular patterns due to pain or apprehension, in addition to limited range of motion, and muscle atrophy. As a result of the surgery, healing of the reconstructed ligament must take place, but additionally, the recovery from ST and/or G tendon harvest begins. Early research into the area of muscle morphology following STG graft harvest substantiated that tendon regeneration was possible.[51–55] It also emerged that tendon regeneration, at least the identification of tissue with tendon-like elements, does not happen in everyone, with studies of the rate of regeneration of ST ranging widely from 62 to 100%[52,54,56,56–63] These studies did not take into consideration tissue quality, point or quality of insertion, or functionality of the tissue. Studies of tendon tissue quality and re-attachment position of the regrown tendon have also been conducted, but the functional capacity of these muscles following graft harvest and the clinical relevance of changes in muscle morphology of ST and G remains ambiguous.[52,54,55,61,64] The tenotomy of ST and G muscles would obligatorily alter the lower limb sensory-motor systems, including loss of golgi tendon organs known to be housed at the musculotendinous junction and altered muscle spindle activity (change in line of action, length, and joints crossed). Ultimately, this would require changes in spinal cord neural connectivity as movement was re-acquired. As well, post-surgical nociception/pain would also be involved in altering neuromuscular control after tenotomy. To begin to understand the impact of surgical and post-surgical factors on neuromuscular function, it is important to establish the context in which muscle changes occur, and relate this to functional indices such as strength, performance, PA level, self-report, etc.

Depending on rehabilitation protocols employed and subsequent compliance, de-conditioning (neural activation and atrophy) may take place in the early post-operative phase. So, iterative re-learning of movement must take place with the ever-changing mechanical circumstances that evolve from the time of rupture to well after reconstruction surgery. Very few studies into the impact of harvesting STG have attempted to relate changes in muscle morphology to objective functional measures or even patient self-reported outcome. It is worthwhile to understand these impacts to determine if they result in negative change, if these changes can be mitigated through enhanced rehabilitation protocols and compliance, and if there are ways to advance surgical techniques to minimize the impact in the first place. This is a complicated scenario that requires studies that are longitudinal and that investigate the multi-factorial nature of the problem.

There have been a small number of studies examining hamstring graft harvest from the leg contralateral to the ACL deficient knee.[65,66] By conducting a study that includes both standard and contralateral approaches, it is possible to compare the impact of reconstruction and of graft tendon harvest in isolation, as well as allow for comparisons between unaffected and reconstructed/graft donor conditions.

The aim of this study is to undertake a comprehensive, prospective and longitudinal evaluation of changes in muscle morphology after ACL reconstruction surgery and relate them to PA, function, strength and self-reported measures. This study will provide evidence upon which to develop well-timed and effective approaches to ACL rehabilitation in order to address neuromuscular deficits that persist after surgery and current post-operative standard of care.

BACKGROUND

Muscle structure

Tendon regeneration

It is well documented that ST and G have the capacity for tendinous elements to regenerate following graft harvest.[51–55] The focus of these studies has been to detect the presence of tissue regeneration, regardless of functionality. Cross and colleagues randomly selected four patients from a group of 225 that had undergone ACL reconstruction on which they 'felt a thickened band of tissue' in the posterior-medial aspect of the knee.[51] Using MRI, it was confirmed in all four cases that these were regrown ST and G tendons that appeared to run from the muscle bellies to the medial popliteal fascia in a diffuse, fan-shaped insertion.

Biopsies of such regenerated tendons were conducted on six patients at 7 to 28 months post-surgery and collagen of similar type and formation to normal tendon was seen, with small scar-like areas present.[52] In a study examining the regenerative process in rabbits, wavy structures were identified within 2 cm of the normal attachment site of the original tendon at 3 months post-harvest, and by 6 months, the structures were no longer wavy and extended to the normal attachment site.[53] More detailed studies of the evolution of tendon regeneration indicated that this time-dependent process is ongoing in humans up to and possibly beyond 24-months post-surgery. Based on a longitudinal study of 40 patients using ultrasonography at 2 weeks, 1, 2, 3, 6, 12, 18, and 24 months post-surgery, Papandrea and colleagues found that it was not until the latter time points that regenerated STG tendon was similar to normal tendon with respect to thickness, width and ethnogenicity.[54] By that time point, the histology of the tendon was well organized, with densely packed, longitudinally aligned collagen bundles. Based on a biopsy taken from a single patient at 6-months post-surgery, Ferretti and colleagues identified only a small proportion of well-oriented collagen in the regenerated tissue.[55] However, a thin fibroblastic zone and two thicker collagenous regions along the longitudinal axis were present in biopsies taken from two patients at 24-months post-reconstruction.

As demonstrated in the studies above, STG tendon regeneration following graft harvest is possible, but it is not a certainty in all patients. Different rates of regeneration have been reported and are presented in Table 1.[52,54,56–63,67] These range from one small study reporting non-regeneration in 38% (3 of 8 patients) to other studies reporting substantially lower rates of 9% (2 of 23) and 11% (2 of 19 patients). In two studies, all participants demonstrated some regeneration by at least 12-months, one with 29 participants and the other with 40.[54,67] The years in which these studies were conducted spans from 1997 to as recent as 2012, and across that period, a variety of surgical techniques and approaches to rehabilitation would have been used. Yet, there does not appear to be any specifics related to surgical approach or any foreseeable differences between studies that would generate such variable outcomes. The protocol for imaging and analysis may play a role. For example, Simonian and colleagues reported one of the highest rates of non-regeneration (33%) having used MRI taken at 0.7 mm contiguous increments to visualize the tendons throughout their course, and recording the distal insertion relative to the medial knee joint compared to the uninjured knee.[63] One of the studies that reported that all participants had some form of tendon regeneration at 12-months post-surgery that was conducted by Nakamae and colleagues utilized three-dimensional computed tomography imaging. Their analyses were based on slices of 1.25 mm thickness with 0.63 mm overlap, resulting in between 350 and

450 slices from the proximal thigh to the proximal leg. This was also a longitudinal study including pre- and 6- and 12-months post-surgery which may have strengthened the ability of the evaluators to track the regrown tendon based on its position pre-surgery.

Table 1. Summary of non-regeneration rates of ST and G in previous studies.

Study	Year	Total patients	Time point	Patients with no ST regeneration	Patients with no G regeneration
Simonian[63]	1997	9	3-4 yrs	3 (33%)	0 (0%)
Eriksson[59]	1999	11	6-12 mos	3 (27%)	
Papandrea[54]	2000	40	24 mos	0 (0%)	
Eriksson[60]	2001	6	7-28 mos	1 (17%)	
Eriksson[52]	2001	16	3-24 mos	4 (25%)	
Rispoli[57]	2001	21	12- 32-mos	2 (18%)	
Nakamura[56]	2004	8	27-47 mos	3 (38%)	
Tadokoro[68]	2004	28	2 yr min	6 (21%)	15 (53%)
Williams[69]	2004	8	6 mos	2 (25%)	0 (0%)
Nakamae[67]	2005	29	12-mos	0 (0%)	0 (0%)
Nishino[61]	2006	23	12-43 mos	2 (9%)	
Okahashi[62]	2006	11	1 year	2 (11%)	
Ahlen[58]	2012	19	+6 yrs	2 (11%)	1 (5%)

The average rate of regeneration across all studies, regardless of tissue quality or tendon attachment point, was eighteen percent or approximately one in five patients that did not have tendon regeneration of ST. The rate of regeneration is only clinically meaningful if regeneration involves the presence of normal or functional tendon (at the cellular level) with a normal pattern of insertion, and capacity to transfer force from the muscle across the joint. Associations between tendon regeneration and actual contribution to knee function have yet to be performed.

The time course of regeneration has also been examined with various outcomes. Rispoli and colleagues examined 21 patients at a range of time-points between 2-weeks and 32-months post-reconstruction. Two of 2 patients at 2-weeks post-surgery had no regeneration, 1 of 3 at 6-weeks, and 3 of 10 between 4 and 15-months had no signs of regenerated STG tendon. Meanwhile, one participant who was 32-months post-surgery had regenerated tendon.[57] Although this study looked at regeneration at a range of time points, it was not longitudinal and therefore, the actually progression of regeneration could not be determined. Another study found at 6-months post-surgery that of 21 patients, two had no regeneration, 9 had hypotrophic tendons, 7 tendons appeared normal, and 3 were hypertrophic.[67] Then, by 12 months, all tendons had regenerated to some extent - 6 hypotrophic, 11 normal, and 3 hypertrophic. These findings provide evidence that tendon regeneration is a long-term process. That being said, the extent and time course of regeneration was variable, with some tendons continuing to exhibit failure to beyond two years post-surgery.

The failure rates of tendon regeneration also appear to differ between ST and G, but not in a consistent manner. In a study of 28 patients beyond 2-years after ACL reconstruction, six were found to have no ST tendon regeneration and 15 with no G regeneration.[68] In contrast, a smaller study found 2 of 19 patients had no regeneration of ST tendon, but only 1 of 19 with no regeneration of G.[58] The proximity of ST and G to other tissues which may be used as a scaffold upon which the tendons could regenerate may be a source of variability between individuals and between muscles.

Several studies have examined the distal insertion sites of the regenerated tendons. Papandrea and colleagues reported attachment to the medial popliteal fascia 4 cm proximal to the pes anserinus at the approximate level of the medial joint line.[54] Eriksson and colleagues noted 12 of 16 patients' tendons regenerated to the level below the knee joint line, while one fused to gastrocnemius (GA) and another fused to semimembranosus (SM).[52] In a small study of three patients, no tendons regenerated to the level of the joint line, but were 2-3 cm proximal adhered to the sheath of the medial GA.[55] Rispoli and colleagues reported on the sequential migration of the regenerated tendons of 20 patients from joint line at 3 months post-surgery to 1-3 cm proximal to the original tibial attachment site at 12-months, and 1-2 cm proximal at 32 months.[57] Burks and colleagues reported most regenerated tendons attaching to the fascia of GA or sartorius (SA) with one of nine patients tendons regenerating to the point of the original attachment site.[64] Another study found that all of the 21 of 23 patients whose tendons regenerated passed the knee joint line.[61] So, there are not only differences in the presence or absence of tendon regeneration, but also a difference in the attachment point of these tendons. A small number of surgical studies have described harvesting techniques to maximize the potential for tendons to regenerate to their anatomical origin or at least, to beyond the knee joint line, but this work is preliminary and further research is needed to understand the advantages and drawbacks of the proposed approaches.[70] Certainly the studies to date indicate that the regrowth is not resulting in re-insertion to a mechanical position consistent with pre-surgery.

One would expect reinsertion site to be a critical component with respect to function. Both ST and G are bi-articular muscles affecting motion at the hip and the knee. With tendon regrowth falling short of crossing the knee joint line, the muscles are left to solely contribute to hip flexion and SM, biceps femoris (BF), and gastrocnemius (GA) completely take over the role of knee flexion. Tendon re-insertion below the joint line, however, is not the only element affecting functionality of ST and G following surgery. The quality of the regrown tissue, the quality of the insertion itself, the contribution of the tendon to transmit force from the insertion site to actual muscle fibers, the line of action of the muscles, and proximal shift of the musculotendinous junction all must play a role in functionality. One of the earliest studies on the impact of graft harvest on the donor muscles reported a mean proximal shift in musculotendinous junction of 2.7 cm in ST and 4.7 cm in G at approximately 3 years post-surgery.[63] Williams and colleagues also found both the ST and G muscle bellies shorter by at least 1.5 cm compared to pre-surgery and to the unaffected side on 7 of 8 patients.[69] With shortening of the muscles, the change in length would necessarily mean the number of sarcomeres in series would be influenced and require a period of adaption as well, akin to rupture of an Achilles tendon or repair of gastrocnemius muscle.

Given the variability described above, it has been very difficult to study what functional contribution the regenerated muscles have. Classifications have been very basic, “tendon” or “no tendon” and some studies have utilized categorizations such as “absent, hypotrophic, hypertrophic or normal”. The connection between tendon regeneration and recovery of muscle size and function, as well as force generating capacity has not been established.

In summary, ST and G tendon regeneration is possible following tendon harvest, but is not a certainty (approximately 18% of patients for ST). Also, the location of tendon reattachment and the proximal shift in the musculotendinous junction varies dramatically between individuals further contributing to any potential knee recovery. Consequently, there is a likely impact on the size (CSA and volume), the force generating capacity, as well as the line of action of the donor and surrounding muscles around the joint(s) about which they function. The impacts of these changes on the biomechanics of the knee are unknown, especially when one considers the concurrent actions of the other muscles and the neural factors of activation during movement.

Muscle cross-sectional area

A summary of previous studies on the CSA of SM, ST, and G is presented in Table 2. The first study to look in detail at the impact of STG harvest on muscle cross-sectional area was a study of nine patients ranging from 36 to 48 months post-surgery.[63] Based on MRI, CSA at 10 cm proximal to the medial knee joint line of BF, SM and SA were not significantly different side- to-side. Although one of the study objectives was also to examine the course and CSA of ST and G, the authors were not able to report on CSA as MRIs were not taken proximal enough to capture either of the muscle bellies. Several studies have examined CSA of the thigh muscles on the operated leg relative to the non-operated leg based on a single MRI, CT or ultrasound image with varied results. Eriksson and colleagues found the mean CSA on the operated side of the 8 of 11 patients that had regenerated ST to be 91% of the non-operated limb, while for those with non-regenerated ST tendons, the CSA was 79%.[59] MRIs for this study were taken only at one time point, between 6 and 12 months post-surgery, and the anatomical region of the slice was not stated. In a second study by the same researchers, sixteen patients underwent MRI at 7 months post-surgery with comparisons of CSA of the entire thigh and of ST at 12 to 14 cm distal to the pubic bone.[51] Twelve of the 16 operated legs showed ST tendon regeneration. Mean CSA of all thigh muscles in the operated leg was 96% of the unaffected side and ST CSA of the operated side was 84% ($p<0.001$) of the non-operated side. There were no significant differences between legs in which tendon regeneration had taken place and in those it did not, which may lead one to question whether tendon regeneration is a requirement of muscle CSA recovery or maintenance. However, this point was not raised by the study authors. There were no statistical differences side-to-side in SM, but in patients that had no ST tendon regeneration, SM was relatively larger (126% of the non-operated side). This introduces the possibility that some degree of compensation by other hamstring muscles is possible, but once again, the triggers for this mechanism are unknown. The factors (surgical or rehabilitative) which facilitate recovery of muscle cross-section or conversely those that precipitate failure (atrophy) of ST and G are unknown.

In another study, side-to-side comparisons of CSA of ST, G, SM, and BF on nine patients at 12 to 16 cm proximal to the knee joint at 1 year post-surgery were conducted and a much more dramatic impact on the harvested muscles was seen.[64] ST CSA was 32% and G CSA was 54% of the non-operated leg. No significant side-to-side differences were identified in either BF or SM. Tendon regeneration was not taken into consideration. A larger study of 37 patients undertaken by Lindstrom also found a substantial impact of tendon harvest on the donor ST and G.[71] Using bilateral computed tomography (CT) to evaluate CSA of the thigh muscles at one-week pre- and 1-year post-ACL reconstruction, the CSAs of the operated leg relative to the non-operated leg at one year for SM, BF, and SA were nearly 100% while for ST it was 24% and for G it was 57%.

Table 2. Summary of CSA of harvested SM, ST, and G from previous studies.

Author	Year	Patients	Time point	Point of measurement	CSA
Eriksson[59]	1999	11	1 yr	Not stated	Regen ST 8/11 – 91% of non-op Non-reg – 3/11 – 79%
Eriksson[52]	2001	16	3-24 mos	12-14 cm below pubic bone	ST: Regen – 89% non-op Non-reg – 66% non-op Overall – 84% non-op SM: Regen – 103% Non-regen – 126% Overall – 105%
Burks[64]	2005	9	1 yr	12-16 cm above joint line	G: Op – 2.0 cm^2 Non-op – 3.7 cm^2 ST: Op – 2.1 cm^2 Non-op 6.6 cm^2
Lindstrom[71]	2011	37	1 yr	15 cm above joint line	ST – 24% G – 67% SM-105%
Snow[72]	2012	10	9-11 yrs	Peak CSA	G – 67% - non-op ST – 75% non-op

In short, the studies outlined above have reported post-surgery ST CSA ranging from 24 to 91% of the non-operated side, with a mean of approximately 63% across all studies. The majority of these reported follow-ups at 1 year or more and there did not appear to be a pattern between time of follow-up and magnitude of CSA. There was some variability between studies with respect to the position of the cross-section of the thigh upon which these studies were based (10-15 cm from the knee joint line); however, this difference would not account for the discrepancies in CSA reported. Muscle cross-sectional area is primarily based on response to stimulus, and so it is likely that the rehabilitation protocol or compliance or both were a major contributing factor to the differences in these studies.

Most previous studies suggest that ST is significantly more impacted than G. Although, a recent study of 10 patients found that at long-term follow-up (9 to 11 years post-surgery), G on the operated side was significantly more significantly impacted at 67% CSA of the non-operated side than 75% for ST.[72] Additionally, in an evaluation of 11 patients between 7 and 32 months post-surgery, G was significantly smaller than the non-operated leg (2.6 versus 3.9 cm^2; $p<0.001$) at 1 cm distal to the middle of the thigh while there was no difference in ST, SM, or BF CSA.[73] Once again this difference in post-operative recovery may be based on the stimulus to the muscles due to exercises and functional activities undertaken, or there may be a trigger to atrophy. Importantly, all of these studies compared reconstructed to non-reconstructed limb at post-surgery time points, none compared to pre-surgery or an activity matched control group. The non-reconstructed limb at post-surgery is not a true unaffected 'control' since the time to wait for surgery would leave muscles of both lower limbs in a de-conditioned state.

Muscle volume

Williams and colleagues conducted pre- to post- and side-to-side comparisons between the operated and non-operated legs pre- and 6 months post-surgery in muscle volume of total hamstrings, G, ST, Q, and GA.[69] On the 8 patients evaluated, there was a significant reduction in hamstring, G, and Q volume on the operated side from pre- to post-surgery as well as compared to the non-operated limb. Examining the contribution of changes in individual muscles, the lower volume of hamstrings was found attributable to losses in ST while the reduced Q were due to smaller volumes in vastus lateralis, likely due to training specific de-conditioning as there would have been no direct impact of surgery. There were no changes or differences in the volume of other hamstring or Q muscles or in gastrocnemius; therefore, no compensation seemed to take place.

In another study involving eight patients, total volume of hamstrings was also found to be less for the operated limb, at both 6- and 12-months post-surgery, based on within-subject comparisons.[74] The mean muscle volume of ST at 6-months on the injured side was 99 cm^3 compared to 134 cm^3 on the non-injured side. By 12-months, the volume of ST for the injured side was reduced to 72 cm^3 and for the uninjured side was 114 cm^3. Another study of 10 patients 9 to 11 years post-surgery found that the mean volume of G on the operated limb was 54% of the non-operated limb and of ST was 58.5%.[72] In short, little information is available on changes in muscle volume following STG tendon harvest, but from these previous three studies, volume appears to be dramatically reduced post-surgery relative to the non-operated side.

Subjective and functional testing outcomes related to muscle morphometry

A very small number of studies on muscle morphometry have included an evaluation of subjective outcomes.[58,63,69] For example, Simonian's early study of tendon regeneration stated patients' mean Lysholm score as 88% at approximately 3 years post-surgery.[63] The magnitude of this score is within a 'typical' range for post-ACL reconstruction and implies that patients reported full to mostly to full normal knee function.[38,75–77] A significant proximal shift in both ST and G tendons was measured in the same study, but no attempt was made to associate to the subjective findings. Another study by Williams and colleagues reported patients completing the Knee Outcome Score and the global knee rating-scale but did not report the findings. [69] A third study reported significant improvements from 4 (1.3) to 6 (0.7) in Tegner score from pre- to 6-years post-surgery. This result implies an overall positive outcome and yet, it does not account for the almost certain decline in activity from pre-injury to pre-surgery. Mean Lysholm scores also showed a significant improvement from 73 (14) to 85 (14.4), but neither subjective measure was discussed in relation to the concurrent changes in muscle characteristics.[58]

A more recent study attempted to relate changes in muscle to changes in subjective outcome.[71] Mean Tegner score improved from 2.8 at 1-week pre- to 5.5 at 12-months post-surgery, Lysholm improved from 68.7 (2.3) to 86.4 (1.9) and the KOOS sports and recreation score (SR) improved from 41.5 to 75.0. Pre-injury scores were not reported nor was the time from injury to surgery. The Tegner score and KOOS sports and recreation score at 12-months post-surgery were significantly correlated with the operated/non-operated ratio of CSA in Q (r=0.45, p=0.005 and r-0.34, p=0.04, respectively). The higher the side-to-side ratio (i.e., the closer to 1or as side-to-side Q CSA becomes equal), the greater association with improvement to subjective outcome was found. Conversely, this may have signified a training-stimulus effect where higher levels of participation in sport resulted in equalizing of Q between the two legs. In this particular study, tendon graft harvest did not result in any significant impact on ST or G CSA comparing the graft donor/reconstructed limb to the unaffected limb and no association of ST or G to subjective outcome scores was presented.

So far, it remains unclear what impact STG muscle morphology has on subjective ratings as no studies have examined this association. Pre-injury status was not reported in any of the aforementioned studies, and so, even though significant improvements in subjective measures were demonstrated over the post-surgical period, there is no indication of whether patients met or exceeded their pre-injury level of activity or function.

Muscle strength related to muscle morphometry

Strength has been studied in isolation or as one of a series of outcomes including subjective scores, functional tests, and so on.[66,78–84] Only a few studies have examined changes in both muscle morphology and strength. In four patients in which regenerated hamstring tendons had been identified by Cross and colleagues, three had a knee flexor strength deficit of less than 10% for the operated leg compared to the non-operated leg, and the fourth patient had 10% greater strength in the operated leg at 6-months post-surgery. This early finding was used by the authors to assert that not only can tendons regenerate, but that graft donor muscles were to some extent functioning.[51] In a study of nine patients, greater knee flexor strength deficits compared to the non-operated limb were reported at 60 deg/s than at 180 deg/s.[64] At 6-months post-surgery, there was a 26% and a 16% strength deficit at the two velocities and at 12-months, the deficits were 21% and 13%, respectively. Knee extensor deficits were also reported at 6-months post-surgery with a mean deficit at 60 deg/s of 32% and at 180 deg/s of 13%. At 12-months post-surgery, the deficits were 9% at both time points. Although this study was longitudinal, no pre-operative evaluations took place. A shortcoming of this study was that no attempt was made to relate strength deficits to the significant side-to-side difference in ST and G CSA also found. Comparable strength deficits were reported in a study of 60 patients conducted by Konishi and colleagues in which strength and muscle volume were evaluated in 18 participants at 6-months and 52 at 12-months post-surgery.[74] No examination of the relationship between strength and total muscle volume was undertaken; however, it was reported that there was no difference between ACL reconstructed and non-operated limbs with respect to mean knee flexor torque per unit volume of hamstring.

Larger knee flexor torque deficits were presented in a long-term follow-up (6-11 years post-surgery) study of 19 patients at 60 and 180 deg/sec.[58] Mean peak torques were 68 and 77% of the non-operated limb at the two velocities, respectively. Although tendon regeneration and CSA were also evaluated, once again no discussion of the association between muscle morphology and strength was provided.

Three studies were identified that did examine the relationship between changes in muscle morphometry following ACL reconstruction and strength. Although not examined statistically, the study conducted by Simonian and colleagues found that the magnitude of knee flexor strength deficit (when compared to the unaffected limb) differed between those patients who had regenerated tendons at or beyond 10 cm proximal to the knee joint (n=6; deficit = 1.8%) and those who did not show any tendon presence at the same level (n=3; deficit = 10.3%).[63] None of the ST tendons crossed the knee joint line, while 6 of 9 G tendons did. They found no difference in CSA between the two limbs with respect to SM, BF, or SA. In the study by Eriksson and colleagues, associations between concentric and eccentric hamstring peak torque and concentric Q peak torque and CSA of the entire thigh muscles in sixteen patients were examined at a minimum of 6 months post-surgery. [52] Strength deficits were found relative to the non-operated leg, 10% and 19% in hamstring concentric and eccentric peak torque, respectively, and 20% in Q concentric peak torque. Significant associations were found between concentric Q peak torque and total thigh muscle area which is expected based on previous research into knee extensor strength.[73,74] There were no associations in total thigh CSA and hamstring torque, but this may be attributable to diminished neuromuscular activation. In addition, no difference was found in strength between limbs with or without regenerated tendons.

A study of 29 patients compared peak knee flexor torque to the type of tendon regeneration and proximal shift of the musculoskeletal junction.[67] Tendons were categorized as absent, hypoplasia, normal and hyperplasia. Peak knee flexor torque was 68% and 83% of the non-operated side at 60 deg/s at 6- and 12-months post-surgery, and 74% and 82% at180 deg/s at the same two time points. There was no association between peak torque ratio (operated relative to the non-operated side) and the type of regenerated tendons identified at either 6- or 12-months post-surgery. There was, however, a significant negative correlation between peak torque at both velocities at 6-months post-surgery and the degree of proximal shift. That is, the greater the proximal shift of the musculotendinous junction of ST and G, the smaller the peak hamstring torque relative to the non-operative leg. This relationship did not hold true at 12-months. Many factors may have led to this shift over time, for example, some sort of compensation of SM and/or BF may have taken place, CSA of ST and G may have been recovered, neural adaptations may have taken place that maximized torque producing capacity of the knee flexors, and others.

Patients were categorized into one of three groups in a study by Nishino and colleagues based on the type of tendon regeneration and the length of ST (from the ischial tuberosity to the musculotendinous junction): Group 1 – regeneration of tendon-like structure confirmed on MRI and ST muscle length was the same as the non-operated limb; Group 2 – ST regeneration was confirmed but muscle was shorter than the non-operated side; and Group 3 – No tendon-like structure was identified.[61] These groupings were compared to the isometric knee flexor torques measured at 45 and 60° knee flexor in sitting. For the four patients in Group 1, there was no difference in peak torque between reconstructed and non-operated limbs. For the 17 in Group 2, there was a significant strength deficit at 90° only

(72% of the non-operated side). Finally, for the 2 patients in Group 3, there was a significant deficit in both knee flexor positions, at 57 and 44% of the non-operated side, respectively. These strength deficits were much greater than those reported in other studies. One difference in the strength testing protocol was that the patients were positioned prone with 0° hip flexion, not in the more common seated position. The bi-articular nature (crossing hip and knee joints) of the ST and G muscles coupled with any changes that may have transformed one or both into uni-articular muscles, may have magnified the effect on strength.

Typically, strength studies of knee flexion have been conducted in a seated position using a dynamometer. To examine the effect of hip position on knee flexion strength following ACL reconstruction, a study by Tadokoro and colleagues examined knee flexor isometric strength in three postures a minimum of two years post-surgery. In sitting, isometric peak knee flexor torque was 86% of the non-operative side while in prone at 90° and 110° of knee flexor, this deficit was increased to 55% and 49% of the opposite side, respectively. Regenerated tendons were unidentifiable in 6 of 28 cases for ST and 16 of 28 cases for G, and hamstring strength was found to be lower in the operated leg, regardless of degree of regeneration. One shortcoming of this study was the cross-sectional design. Second, only the normal attachment point of the tendon was examined, so one could not determine if the tendon was still attached at some location below the knee joint line with the potential to contribute to knee flexor torque. The study by Tadokoro contradicts the findings of the previously described work of Nishino and colleagues in which they found a relationship to tendon regeneration and strength. There are several possible contributing factors including a difference in categorization of tendon regeneration, imaging and analyses techniques, and/or the difference in strength as measured isokinetically versus isometrically.

In summary, there is some evidence of an association between tendon regeneration and strength following hamstring harvest for ACL reconstruction, but there were also studies with findings to the contrary. As strength is a fundamental aspect of ACL reconstruction used to evaluate patient outcome, it is surprising that more emphasis has not been placed on evaluating the broader scope of muscle changes induced by surgery, subsequent rehabilitation, and relationships to strength.

Physical activity related to muscle morphometry

No studies to date have examined objectively measured PA and related such outcomes to muscle morphometry post-ACL reconstruction surgery. PA can be viewed as a surrogate measure of function, as with most of the sports involving ACL rehabilitation (soccer, football, basketball), the intensity and duration of PA per day will be proportional to the level of performance in the sport.

Physical activity

There are numerous methods by which clinicians and researchers evaluate the outcome of ACL reconstruction surgery, for example, self-report of return to sport, functional testing (e.g., hop tests, balance, pivoting), laxity tests, strength, re-rupture rates, subjective questionnaires, and so on. A fundamental question that remains unanswered is does ACL reconstruction surgery impact a patient's level of PA?

Little to no research has been conducted to evaluate PA in the ACL deficient or ACL reconstructed population, particularly based on objective measurement. The Tegner Activity

Scale has sometimes been represented as a measure of PA; however, it is comprised of a self-reported response to a single question and is meant to complement a functional score (Lysholm score).[85,86] It categorizes the type of activity in which an individual participates, but does not quantify or describe day-to-day energy expenditure (EE). Level 1on the Tegner scale is defined as “Work – sedentary, e.g., secretary”, Level 5 is “Work – heavy labour (construction, etc.), competitive sports (cycling, cross-country skiing), recreational sports (jogging on uneven ground at least twice weekly),” and Level 10 is “Competitive sports (soccer, football, rugby (national elite).” Also, PA measures based on self-report have been shown to significantly overestimate activity by as much as 10 times, and thus it is important to examine other tools through which PA can be measured objectively in this population.[76–78]

Accelerometry can be used to objectively measure PA and was first demonstrated in the 1970’s and 80’s.[87,88] Known also as “motion sensors”, accelerometers are small, inexpensive (as low as $40), and non-invasive. With advancements in technology and resultant reductions in cost, accelerometers have become one of the most commonly used tools in PA measurement in the recent years. Accelerometry has been found to be a reliable, valid, and stable measure of PA in children, and in other patient populations (e.g., COPD; multiple sclerosis; lower-extremity osteoarthritis).[80,89–93] Several studies have validated the use of accelerometers in PA measurement, either with actual measurement of EE (e.g., using metabolic cart systems or portable gas systems measuring actual VO_2), using the doubly labeled water technique, or direct observation.[94–98]

Some accelerometers incorporate pedometry data collection into their functionality, that is, they record the number of walking steps taken. Walking generates vertical accelerations that are plotted against time and as the acceleration curve crosses zero, a step is counted.[99] Pedometry has been validated as a suitable measure of PA in many populations, including middle-aged adult men and women, pregnant women, adolescents of different ethnic backgrounds, obese, overweight children, and normal weight children, elderly men and women, and others.[100–103] Pedometers are limited in their accuracy in measuring locomotor movements at slow speeds and where ground reaction forces are low (cycling, elliptical, etc.). The advantage of incorporating both accelerometry and pedometry data into study analyses is that there are more population normative data and existing studies using pedometry to which the current study data can be compared. A focus of ACL recovery research has been to examine specific functional outcomes, such as strength, hop tests, agility, etc. However, PA is a fundamental measure of function that, to date, has been overlooked in ACL rehabilitation. Changes in PA may also be associated with changes in post-surgery strength or vice versa, and this important relationship has yet to be explored. Importantly, the amount and type of PA may be a determinate of muscle changes (tendon, cross-section, shift, etc) post-surgically. So PA is critical to assess to aid in understanding factors aiding or abating in restoration of muscle properties.

PURPOSE, OBJECTIVES AND HYPOTHESES

The purpose was to examine longitudinal changes in muscle morphometry and PA following ACL reconstruction using ST and G autograft in relation to changes in strength, functional performance tests, and subjective outcomes. The primary objectives were as follows:

1. To describe the impact of graft harvest on muscle morphometry of ST and G. The evaluation of impacts of graft harvest and of reconstruction are possible as a result of the defining four limb conditions based on the Standard approach to ACL (i.e., tendon harvest and reconstructed conducted on same limb) and the "Contra" approach (i.e., tendon harvest conducted on limb opposite to ACL reconstruction). Hypotheses associated with this objective were the following:
    - ST and G CSA (cm^2) at 50% between ischial tuberosity and knee joint line are reduced at 12 months post-surgery relative to pre-surgery;
    - There is greater preservation of muscle volume (cm^3) on the graft non-donor side than the donor side at 12-months post-surgery;
    - There will be compensatory growth of non-harvested hamstring muscles on the STG harvest side to account for loss of ST and G CSA.
2. To relate muscle morphometry of ST and G to subjective, functional, PA and strength measures. Hypotheses associated with this objective were the following:
    - Muscle morphometry (CSA at 50% of thigh length of ST, G, All Hamstrings, proximal shift of ST and G (cm), volume of ST and G (cm^3)) is related to knee flexor strength (peak torque (Nm)) across all velocities and contraction types (eccentric and concentric).

- Muscle morphometry (CSA at 50% of thigh length of Q) is related to knee extensor strength (peak torque (Nm)) across all velocities and contraction types (eccentric and concentric);
- Muscle morphometry (CSA at 50% of thigh length of ST, G, All Hamstrings, proximal shift of ST and G (cm), volume of ST and G (cm^3)) is related to Tegner scores at 12-months post-surgery;
- Muscle morphometry (CSA at 50% of thigh length of ST, G, All Hamstrings, proximal shift of ST and G (cm), volume of ST and G (cm^3)) is related to single leg hop, single-leg triple hop, single leg triple hop, and 6m timed single-leg hop;
- Muscle morphometry (CSA at 50% of thigh length of ST, G, All Hamstrings, proximal shift of ST and G (cm), volume of ST and G (cm^3)) is related to mean daily step count and energy expenditure.

3. To objectively evaluate the PA of patients undergoing ACL reconstruction from pre-surgery to one-year post-surgery. Hypotheses associated with this objective were the following:
    - Mean daily step count is greater at 12-months post-surgery than pre-surgery;
    - Mean energy expenditure is greater at 12-months post-surgery than pre-surgery;
    - There is a clinically relevant difference (minimum 2,000 steps) in PA between pre- and 12-months post-surgery;
    - Mean daily step count of non-elite athletes undergoing ACL reconstruction will meet or exceed the recommended 10,000 step minimum for achieving a healthy lifestyle; and

- Daily step count and energy expenditure are predicted by a combination of subjective, functional, strength, and muscle morphometry measures.

METHODS

Study design

This was a longitudinal, balanced randomization (1:1), parallel group study conducted at a single orthopaedic surgery facility from June 2009 to July 2012. Approval was granted by the research ethics board prior to enrolment (Appendix II; BREB - B2009: 036).

Study participants

Participants were identified by one of two participating fellowship-trained surgeons based on pre-surgery consultation. They had been referred to the surgeon due to the presence of an isolated anterior cruciate ligament tear, confirmed on MRI. If individuals agreed to be contacted, they were approached by a research assistant who proceeded through the consenting process (Appendix III).

Men and women between the ages of 18 and 50 with a complete ACL tear awaiting surgical reconstruction and who had no other ligament injuries requiring surgical intervention were candidates for inclusion. Exclusion criteria were as follows: recent or current use of ergogenic or performance enhancing drugs, previous lower limb surgery (other than arthroscopy), significant injury to either lower limb requiring surgery, history of arthritis, inability to comply with study follow-up or rehabilitation protocols (because of language, geography, physical barriers), pregnant females, collagen disease (e.g. Ehlers-Danlos), ongoing workers' compensation claims, or other medical conditions which precluded participation.

Randomization

Study patients that agreed to participate and signed an informed consent form were randomized to one of two study groups: 1) Standard treatment group (Standard) who would undergo anterior cruciate ligament reconstruction using ST and G tendon graft harvested from the patient's own ACL-deficient leg; or 2) Contralateral harvest group (Contra) who would undergo ACL reconstruction using STG graft harvested from the ACL-intact leg (i.e., leg contralateral to the torn ligament). Prior to the consenting of any patients, a series of sealed envelopes containing allocation to one of these two study groups was created based on computer-generated random numbers. Randomization took place intraoperatively, once the ACL tear was confirmed and an arthroscopic examination was completed. Due to the nature of the study with harvest site being evident, none of the surgeon, patient, or clinical evaluator could be blinded to the assigned intervention.

A required sample size of ten participants in each study group was determined based on an expected mean difference in percent of CSA of STG in the reconstructed leg relative to the non-reconstructed leg and a standard deviation of 15%, $\alpha=0.05$ and $\beta=0.80$. This expected mean difference is relatively conservative compared to other studies that report difference of 25% or more.[64,72] Sample size in each group was calculated to be 9 participants, which was increased to 10 participants to allow for 10% loss to follow-up.

From the two study groups, four treatment conditions of the knee were created based on whether the knee was reconstructed or not (represented by R or NR); and whether the limb was used as a graft donor for ST and G tendon or not (represented by D or ND) as defined in Table 3. Based on these four conditions, there was no true 'control limb', as all conditions involved some alteration from the pre-injury state, whether it be due to ACL injury, tendon harvest, or, in the case of the NR-ND limb, time waiting for surgery.

Table 3. Abbreviations and definitions of limb conditions.

Study group	Treatment condition	Definition
Standard	NR-ND	Not reconstructed and not STG donor (i.e., “unaffected”)
	R-D	Reconstructed and STG donor
Contra	NR-D	Not reconstructed but STG donor
	R-ND	Reconstructed but not STG donor

Surgical intervention

The ACL reconstruction procedure was performed under spinal anaesthetic. After examination of the knee under anaesthetic, randomization took place. As per the group allocation, the STG graft was harvested from the ACL deficient leg or contralateral to the ACL deficient leg. An incision was made just medial to the tibial tubercle and the STG tendons were identified and the tendons cut and extracted using a tendon stripper (ConMed TS8850, Linvatec, Largo, FL; Figure 1). They were then prepared into a 10-centimetre long four-strand graft and graft size was measured using an Arthrex graft size determination device (Arthrex, Naples FL; Figure 2). Once reamed, the graft was brought through the tibial and femoral tunnels with the ends fixated using an Exobutton (Linvatec, Largo, FL) in the femoral tunnel and a bioscrew in the tibial tunnel.

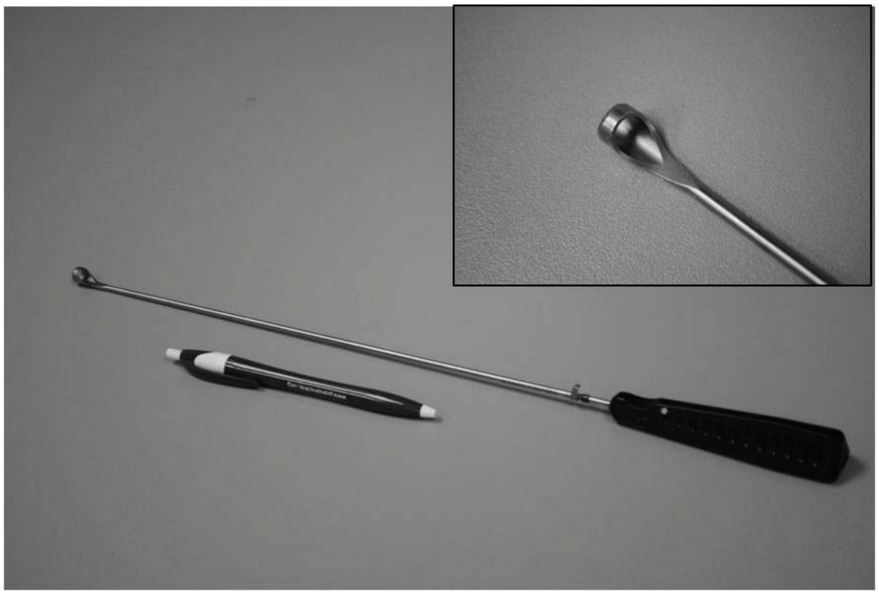


Figure 1. ConMed TS8850 tendon stripper.

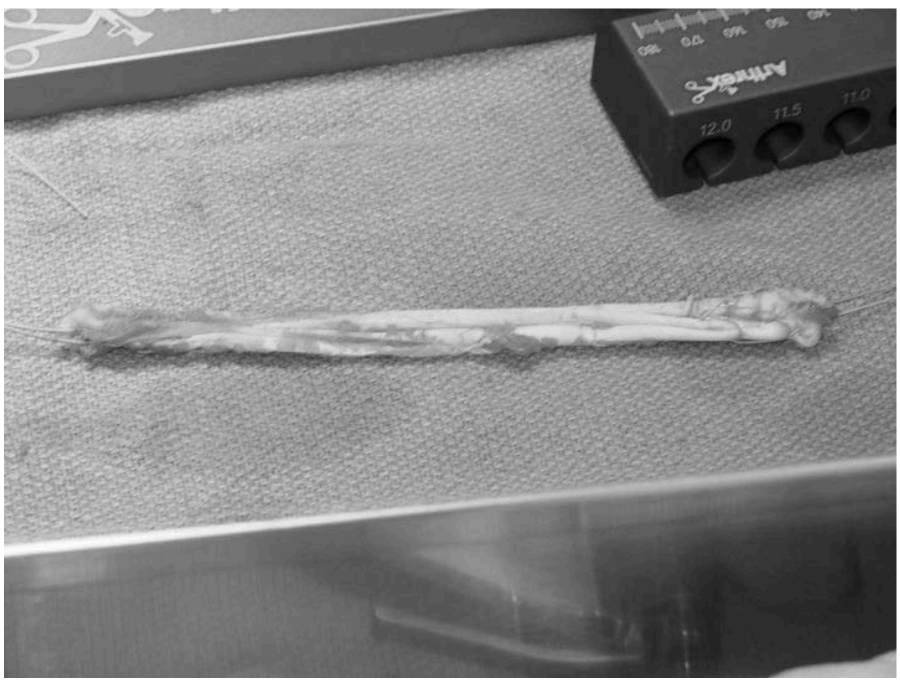


Figure 2. Prepared STG autograft (approximately 20 cm in length prior to being doubled over) and Arthrex graft size determination device.

Patients were discharged the same day as their surgery. A standardized post-operative rehabilitation program (Appendix 1) was provided that emphasized early swelling control and knee range of motion. Patients were instructed to weight bear as tolerated and initiate a physiotherapy or home exercise program. Hamstring curls and exercises involving quadriceps/hamstring co-contraction were recommended at 2 to 3 weeks. By 3-months post-surgery, goals included full range of motion (0 to 125 degrees) with no swelling, and exercise tolerance to 45 minutes of pain-free walking. Patients were allowed jogging and introductory plyometric training (e.g., box jumps, single and double leg bounding) at 3-months, higher-level activities including sport-specific training at 6-months with the goal of return to sport between 9 and 12 months. Patients attended follow-up visits with their surgeon post-operatively at 2 weeks, 3-, 6-, and 12-months, independent of the study assessment visits. No evaluation of compliance to the rehabilitation program was undertaken. Physiotherapy was not confined to one therapist or one facility; therefore, it was difficult to monitor or document compliance.

Study assessment protocol

Time points

Study assessments periods were set at two weeks preceding surgery, and 2-weeks, 6- and 12- months post-surgery. Assessments were: subjective questionnaires (International Knee Documentation Committee (IKDC) subjective assessment; Lysholm score, Tegner score), bilateral lower extremity MRI imaging, hop testing, strength testing, and PA monitoring. At 2-weeks post-surgery, only bilateral lower extremity MRI and PA monitoring were conducted.

Subjective questionnaires

At their initial visit, participants completed a form that included age, height, body mass, mechanism of injury, activity during injury, time of injury, and interventions to date.

The IKDC subjective assessment is a well-used region-specific instrument created from a committee of experts from the American Orthopedic Society for Sports Medicine (AOSSM) and the European Society for Sports Traumatology, Knee Surgery and Arthroscopy (ESSKA).[104] The IKDC subjective assessment is comprised of 18 questions on symptoms (e.g., pain, instability, weakness) and function (e.g., ability to walk, squat, run, pivot, etc.). The goal of creating the IKDC subjective assessment was to standardize documentation of patient outcome following treatment of knee conditions. It has been found to be reliable and has been validated for use with patients having a variety knee conditions which include ACL-deficiency and post-ACL reconstruction outcome.[104]

The Lysholm score is also a region-specific instrument comprised of 8 items related to self-report of function and symptoms. It was originally designed to be a physician-administered tool to evaluate patient outcome following knee ligament surgery.[105] The Lysholm score has since evolved into a well-used patient-administered instrument that has been found to be reliable, valid, and sensitive to change for use with those who are ACL deficient and those up to 24-months post-ACL reconstruction.[76,77]

The Tegner score was developed as an independent instrument to complement the Lysholm score with a focus on type of activity rather than on symptoms and function.[106] It is patient administered and asks the patient to evaluate their level of activity before injury and at their current status, choosing from 10 options, defined by a combination of type of sport/work (e.g., soccer, football, jogging) and level of participation (e.g., elite, competitive, recreational). This score has been found to be reliable and valid in participants with ACL rupture and following ACL reconstruction.[76]

Hop tests

Participants completed a warm up of 5-minutes of stationary cycling at a comfortable pace of their choice prior to testing. They then completed a one-legged hop testing protocol including a single hop for distance, a 6-m timed hop, a triple hop for distance, and four cross-over hops for distance.[107,108] This combination of tests were adopted in the early 1990's as a means to evaluate the "integrated effect of neuromuscular control, strength (force-generating capacity), and confidence in the limb."[108] Pre-operatively, all hop tests were only performed on the participant's uninjured side due to activity restrictions placed on them by their surgeon.

Bilateral lower extremity magnetic resonance imaging

Bilateral lower extremity MRIs were taken using a Siemens 1.5 Tesla Magnetom Avanto (Siemens Canada Ltd, Oakville ON). Images included the ischial tuberosity to 10 cm proximal to the lateral knee joint line with 5.0 mm slice-thickness and a 1.5 mm gap. Repetition time was 660 ms and echo time was 15 ms.

Muscle cross-sectional area (CSA) was determined by manually tracing the outer contour of a given muscle in an axial MRI slice and establishing the muscle boundary based on MRI intensity using a custom algorithm in MatLab 2012a (Mathworks, Natick MA; Figure 3). A threshold was used to exclude pixels arising from bone or fat, within the circumscribed region from the quantification of muscle cross-sectional area. The circumscribed region was then converted from pixels into cm^2. All digitization was conducted by a single rater blinded to the surgical procedure. Values for the following variables were measured or calculated: CSA of ST, G, BF, SM, SA, AD, and Q, and volume, taper, proximal shift, slope, and degree of atrophy of ST and G.

- CSA of ST, G, BF, SM, SA, AD, and Q: Measured on a single slice at 50% of the distance from the medial joint line to the ischial tuberosity;
- Volume of ST and G: CSA of ST and G was measured on every slice for the entire length of the muscle, then the CSAs were summed and multiplied by 6.5 mm (slice thickness plus slice gap) and converted to cm^3;
- Proximal shift: The difference in centimeters from pre- to 12-months post-surgery in the first slice in which CSA greater than 1.0 cm^2 was detected moving proximally from the knee joint;
- Slope of ST and G: The slope was calculated based on the line-of-best-fit for all CSAs of ST and G between the first slice in which CSA was greater than 1.0 cm^2 to the most proximal slice (level of ischial tuberosity);
- Degree of atrophy: Participants were categorized based on percent reduction in muscle volume from pre-surgery for ST and G: less than 5% reduction, 5 to 20%, 20 to 80 percent, and more than 80% reduction.

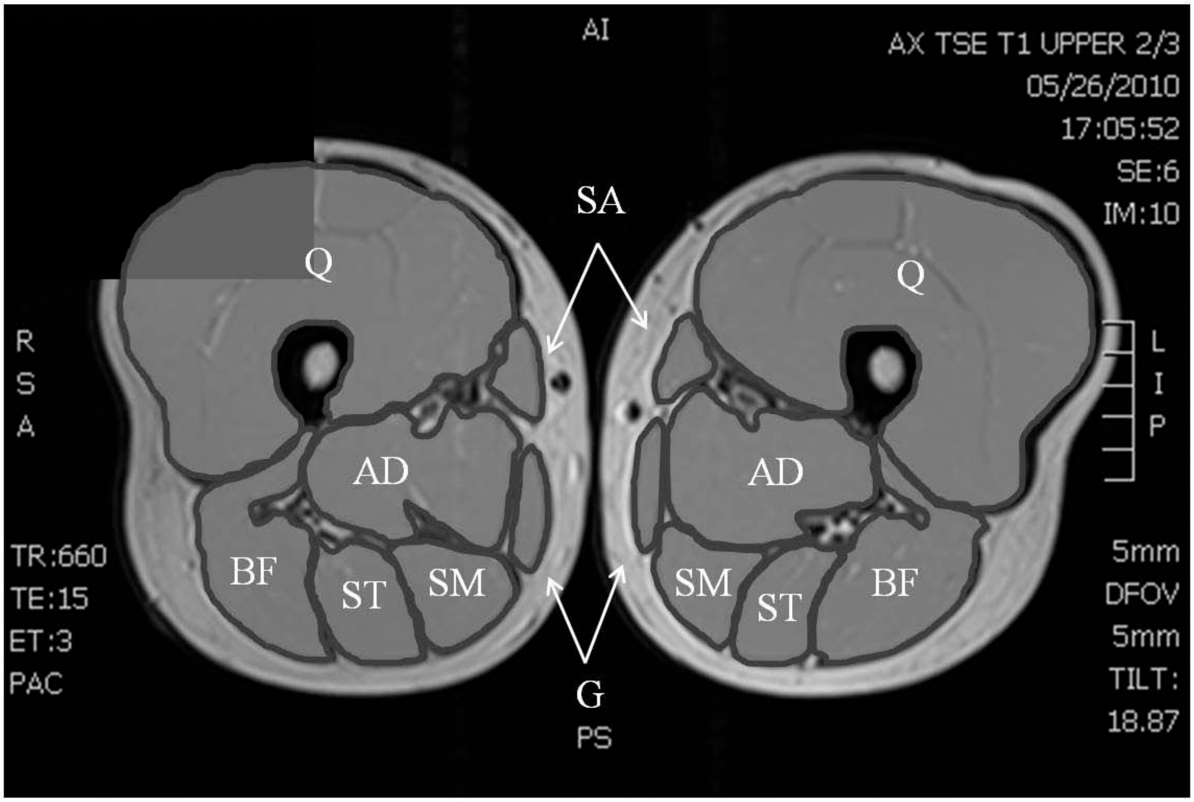


Figure 3. Sample slice of bilateral thigh muscles 50% proximal to medial joint line relative to ischial tuberosity.

Strength testing

Participants were seated on a Biodex III dynamometer (Biodex Medical Systems Inc, New York) at 85 degrees hip flexor with their upper body, hips, and test leg stabilized with straps (Figure 4). Knee flexor and extensor concentric and eccentric strength was measured through 90 degrees (5 to 95 deg flexion) range of motion for five repetitions each at ±60, 150, and 270 deg/s, with a two-minute rest period between sets. Negative velocities represent eccentric contraction and positive velocities represent concentric contraction of the prime movers. Prior to testing at maximal effort, participants completed a warm-up set of five repetitions at each velocity at approximately 50% of their maximal effort. At 12-months post-surgery time point only, strength was also measured with participants in a reclined position of 5º hip flexor (supine) using the same repetitions and velocities as in the seated position (Figure 5).

Figure 4. Testing position on dynamometer for knee flexor/extensor strength testing in sitting.

Data were extracted from the dynamometer as comma-delineated text files and compiled and synthesized using Matlab (Mathworks, Massachusetts) custom programming. Peak knee flexor and extensor torques (Nm) at each velocity in the two testing positions were derived. All torques were corrected for moment of the limb segment weight.

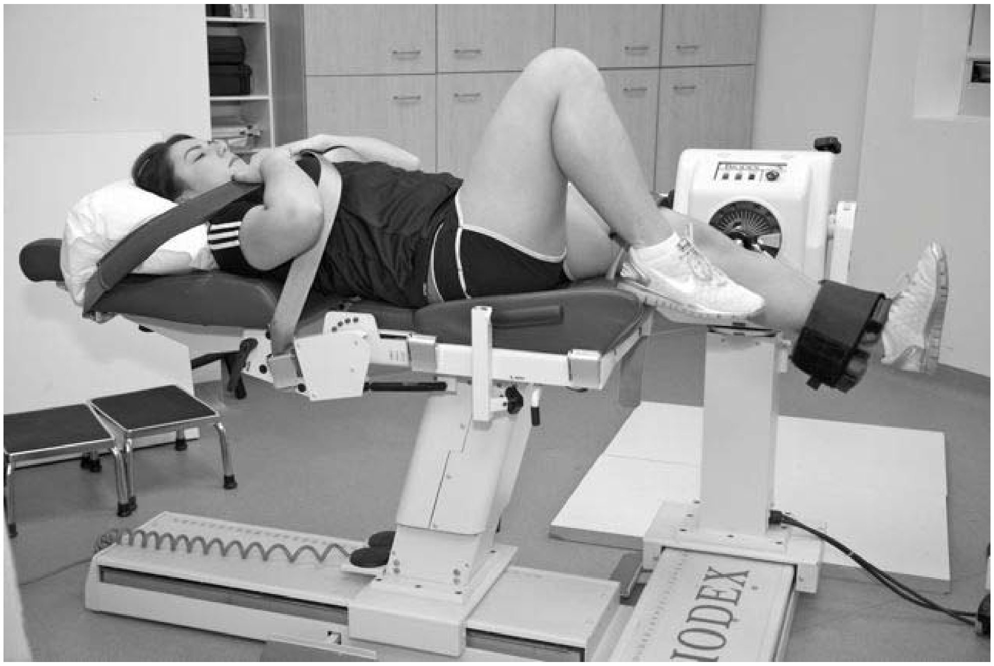


Figure 5. Testing position on dynamometer for knee flexor strength testing in hip neutral position.

Physical activity

PA was monitored using a tri-axial GT3X Actigraph accelerometer (Actigraph, Florida). Participants wore the GT3X on an elasticized waist belt with the unit positioned over the right hip for a 7-day period for all their time awake excluding any time in water (e.g., bathing, swimming). Data was collected in three planes at a sampling rate of 100Hz with summed acceleration (activity counts) recorded at 3-second epochs. The raw data (activity counts in three axes, step count, and orientation of accelerometer) were extracted from the accelerometer using Actilife software version 5.6.1 (Actigraph, Florida) in the form of comma-delineated text files that were then imported into MatLab (Mathworks, Massachusetts) for analysis.

Figures 6 and 7 present sample raw activity count data and daily steps data obtained from a study patient over a 20-hour period. The mean daily values for the following variables were extracted or determined from the raw output: wear time, hours active, activity count, EE, daily steps, time stepping, cadence, bouts of moderate to vigorous activity (MVPA), minutes of MVPA, number of bouts of MVPA greater than 30 seconds, and the proportion of participants with daily steps greater than 10,000 and greater than 12,500.

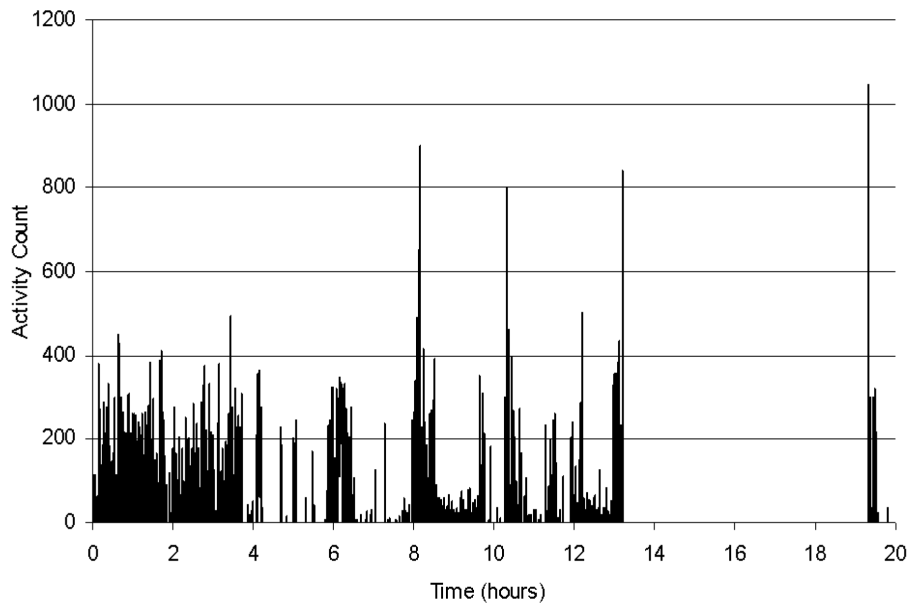


Figure 6. Activity count data from GTX3 accelerometer for 20-hour period.

- Wear time (hours/day): 24-hours less any period in which there was greater than 30 consecutive minutes of inactivity, thus excluding periods in which the accelerometer was not worn or in which there was extended (>30 minutes) complete inactivity;
- Time active (hours/day): The total time in a 24-hour period in which activity counts were greater than zero. Thus, hours active was always less than wear time;
- Activity count: the resultant of the activity counts for three axes using the Pythagorean Theorem;

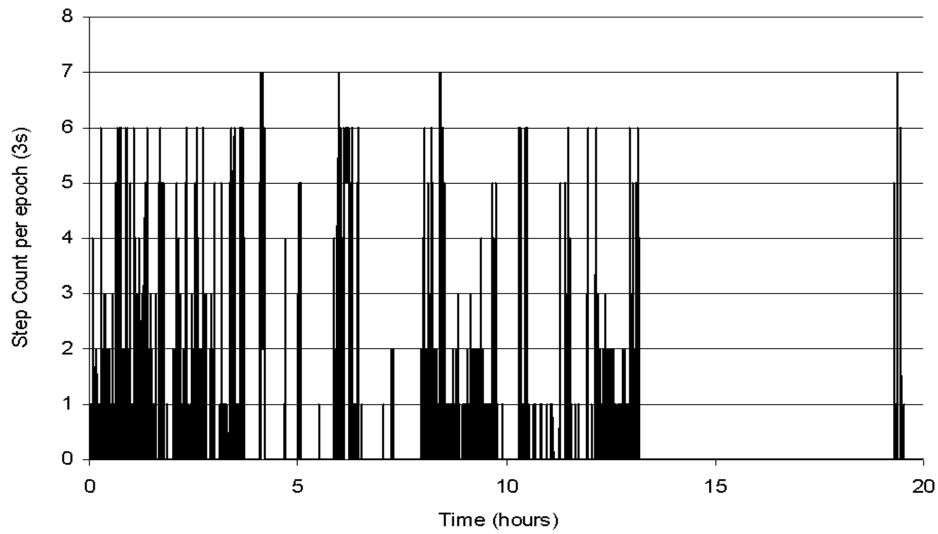


Figure 7. Daily steps data from GTX3 accelerometer for a 20-hour period (same participant as in Figure 6).

- EE (kcal/day): Calculated based on activity counts using the Work-Energy Theorem for low level activity and a modified Freedson equation for triaxial accelerometry (Actilife software, version 5.6.1).
- Daily steps (steps/day): Derived from the steps per epoch per day;
- Time stepping (hours): The total time in a 24-hour period in which a step was detected;
- Cadence (steps/min): Daily steps divided by time stepping;
- Bouts of MVPA: Number of epochs in which resultant activity count exceeded the threshold for MVPA, the energy expenditure equivalent of 3 METS;
- Minutes of MVPA: Regardless of the length of a bout of MVPA, the total number of minutes in which activity counts in an epoch exceeded the MVPA threshold;
- Number of bouts greater than 30 seconds in MVPA: A bout was counted if activity counts in sequential epochs were maintained above the MPVA threshold for 30 seconds or more;

- Daily steps greater than 10,000 or 12,500: Number of days a participant reached or exceeded these thresholds.

For data in a given day to be considered eligible for inclusion in statistical analyses, wear time in that day had to exceed 8 hours. The minimum criteria for a mean daily value to be considered ‘eligible’ was that it had to be based on at least 4 of 7 days wear time of 8 or more hours per day.

PA Comparison Data

To provide some context to the level of PA measured in the current study group, comparisons were made to age-matched normative data, a threshold for healthy living, and a threshold for highly active living. The source for the age matched normative data was a study by Colley and colleagues.[109] The PA of 2,832 participants ranging from 20 to 79 years was evaluated based on accelerometer data. Of those, 395 men and 509 women made up the 20 to 39 year old category. Mean daily steps were reported as 9,926 for men and 8,875 for women. The mean daily steps of 10,000 was used as a threshold for healthy living as it has been reported widely as the minimum number of steps recommended for adults.[110–114] It is important to note that the age-matched mean daily steps do not meet this 10,000 step criteria.

Mean daily steps of 12,500 has been established as a threshold for being considered ‘highly active’ and was also used to put the current data in context.[111] For within-person comparisons between pre- and 12-months post-surgery, a clinically relevant difference of 2,000 steps was used.[115–118] This threshold is based on the increase in daily step count required to improve overall well-being, for example, reduce risk of diabetes, heart disease, etc. The clinical relevance is not specific to improvement in an ACL injured population.

However, this increase in amount of steps is associated with an additional 1.6 km per day of walking, representing only a modest gain for an active group.

Data analysis

Descriptive statistics are presented for all outcome scores and functional tests overall, and by study group (Standard and Contra). Data were also described and compared based on the four limb conditions; NR-ND, R-D, R-ND, and NR-D. In order to examine the impact of reconstruction, outcomes were collapsed into two groups: R where ACL reconstruction was performed on all limbs, including donor and non-donor conditions (R-D and R-ND), and NR where ACL reconstruction was not performed, including donor and non-donor conditions (NR-ND, and NR-D). Similarly, to examine the impact of STG tendon harvest, outcomes were collapsed into two groups: D where STG tendon harvest was conducted, including reconstructed and non-reconstructed limbs (NR-D, and R-D), and ND where STG was not harvested, including reconstructed and non-reconstructed limbs (NR-ND and R-ND). The collapsing of groups was permitted statistically, as there were no observed differences in parameters between sub-groups. Further, this increased the power to detect differences between conditions.

Comparisons between time points were conducted using repeated measures ANOVA. Between group comparisons were performed using independent t-tests with the exception of comparing gender between groups, performed using a Fisher's exact test. For strength, general linear models were run with each strength measure as a dependent variable, velocity and limb as the independent variables, and pre-surgery as a covariate. For trajectory analyses of strength, and muscle morphology parameters, repeated measures ANOVAs were conducted for pre-, 2-weeks, 6-, and 12-months post-surgery. A repeated-measures ANOVA was performed to examine the trajectory of PA parameters across the four study time points; however, post hoc it was determined that there was some missing data at each time point. Data was unavailable or ineligible for the following reasons: inadequate time prior to surgery to conduct a 7-day activity monitoring period, technical difficulties with the accelerometer or data transfer, participant withdrawal from the study prior to the 12-month end point, lack of compliance either in days or hours per day worn, or loss to follow-up. In repeated-measures analyses, data for all time points must be present in order for it to be included. It was noted that because different participants were affected by ineligible data at each time point, list-wise exclusion of participants severely reduced the data maintained for analysis. Therefore, a series of relevant pair-wise t-tests were performed in order to include all eligible data collected. To compare PA outcomes to population normative data and published activity thresholds, one-sample t-tests were conducted. Bivariate Pearson product moment correlations were conducted to explore associations between hop test outcomes, between muscle morphology parameters, and between subjective scores. Interactions were performed based on two series of stepwise linear regressions with entry probability of 0.20, and 0.25 removal. The first series examined the predictive value of ten muscle morphology parameters: CSA of Q, ST, G, Hams less STG, and volume, proximal shift and slope of ST and of G. For outcomes that could be impacted by both limbs, such as PA and subjective scores, D and ND outcomes were included. For outcomes that were likely impacted by one limb, such as strength and hop tests, only outcomes for the involved side were included. The second series of regressions examined the predictive value of PA parameters: Daily steps, daily EE, cadence, minutes in MVPA, and bouts of MVPA. Significance was $p<0.05$ with no adjustment for multiple comparisons. A conservative interpretation strategy was employed to deal with the possibility of accepting Type 1 errors for the multiple comparisons performed.

RESULTS

Participants

Fifty-eight patients were screened of which 20 were eligible and consented to participate (Figure 8). The primary reasons for patients being ineligible were the inability to comply with study follow-ups (level of time commitment, from out of town), being outside the eligible age group, or not interested. Participants were randomly assigned to either the Standard group or the Contra group with demographics presented in Table 4. One participant was excluded from the study post-randomization due to issues unrelated to the surgery. One participant was injured (multiple trauma unrelated to the knee) prior to subjective and functional assessment at 6 months post-surgery and was unable to complete participation. Purely by chance, the ACL reconstruction performed on the two patients that were excluded were the only two patients contributed by one of the participating surgeons. Therefore, the ACL reconstruction surgeries on the remaining participants were all performed by one surgeon. There were 14 males and 4 females that took part in the study with a mean age of 29.2 (SD 7.1). No significant differences were identified between groups with respect to sex ($p=0.141$), age ($p=0.529$), height ($p=0.588$), body mass ($p=0.686$), body mass index ($p=0.794$) or time from injury to surgery ($p=0.209$). Six participants ruptured their ACL while playing soccer, six while playing basketball, two at hockey, and four during other sporting activities. Four ruptured their ACL due to a contact injury, while the other 14 had a non-contact mechanism of injury. One participant was lost to follow-up at 12 months post-surgery.

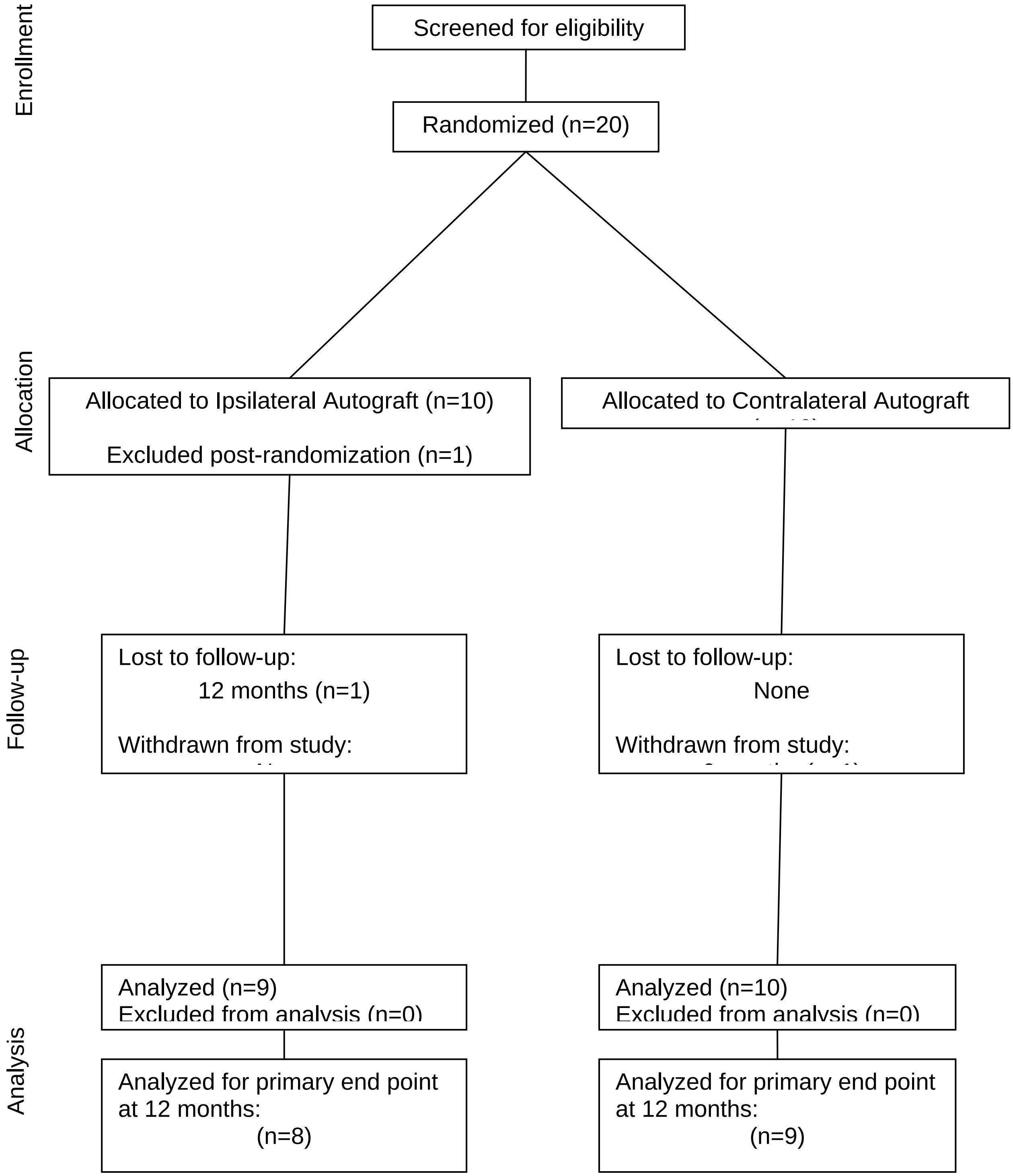


Figure 8. Flow diagram of subject progress through the phases of the study.

Table 4. Characteristics of participants at pre-surgery (mean & SD).

Variable	Standard	Contralateral	p-value	Overall
Sex (F/M)	9 (4/5)	10 (1/9)	0.141	20 (5/14)
Age (years)	30.3 (8.1)	28.2 (6.3)	0.529	29.2 (7.1)
Mass (kg)	83.2 (23.4)	86.5 (9.0)	0.686	84.9 (17.0)
BMI (kg/m^2)	27.0 (4.4)	27.6 (4.2)	0.794	27.3 (4.1)
Injury to surgery (days)	228 (86)	378 (288)	0.209	308 (225)

Subjective assessment

Subjective outcome scores are presented in Figures 9 to 11. Comparing means across all study patients, there was a significant improvement from pre- to 12-months post-surgery in each of the three subjective measures. The mean IKDC subjective score increased 20.8 (13.5) points to 87.6 ($p<0.001$), Lysholm score increased 14.1 (16.8) points to 88.9 ($p=0.003$), and Tegner score increased 2.3 (2.1) levels to 6.3 ($p<0.001$). At pre-surgery, patients reported their pre-injury Tegner score as 7.9 (1.1) which was significantly higher than their 12-month post-surgery scores ($p=0.010$) by a mean difference of 1.25 (1.7) levels. Seven of the 17 (41%) participants reported achieving their pre-injury activity level by 12-months post-surgery. There was a ceiling effect (proportion of patients scoring between 90 and 100%) in both Lysholm and IKDC scores, 64 and 41% respectively.

The trajectory of improvement from pre- to 6- and then 12-months post-surgery differed between groups. IKDC improved incrementally across the three time points while Lysholm improved significantly ($p=0.002$) from pre- to 6-months post-surgery and then leveled off with virtually no change between 6- and 12-months. In contrast, Tegner scores did not improve between pre- and 6-months surgery (p=0.99), and then significantly improved between 6- and 12-months. There were no significant correlations between the three subjective measures at 12-months post-surgery.

No pre-injury subjective evaluation of activity level was available; but patients were asked at pre-surgery and each post-surgery time point to recount their pre-injury Tegner score. There were no mean differences between time points as to the pre-injury activity level that was recalled within individuals (p=0. 893).

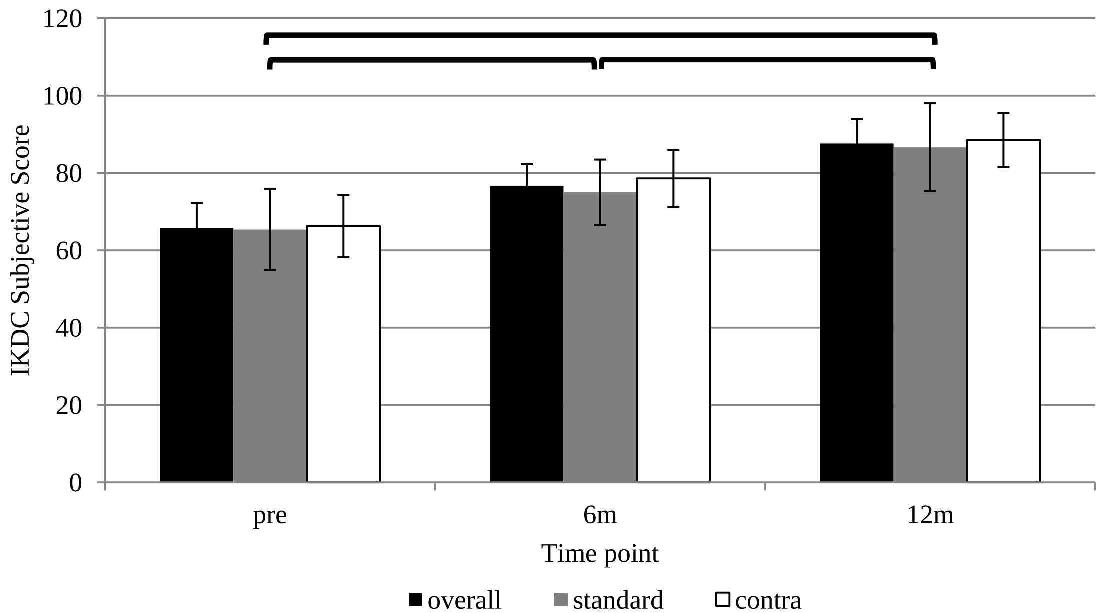


Figure 9. Mean (95% CI) IKDC scores overall and by group over time. Brackets indicate significant differences and apply to overall, standard, and contralateral comparisons.

There were no differences between Standard and Contra groups with respect to any of the subjective measures prior to surgery: IKDC subjective assessment (p=0.764), Lysholm score (p=0.612), Tegner score for ‘Pre-Injury’ activity level (p=0.734); and Tegner score ‘Current’ activity level (p=0.862). Furthermore, there were no significant interaction effects between group and time for any subjective measures.

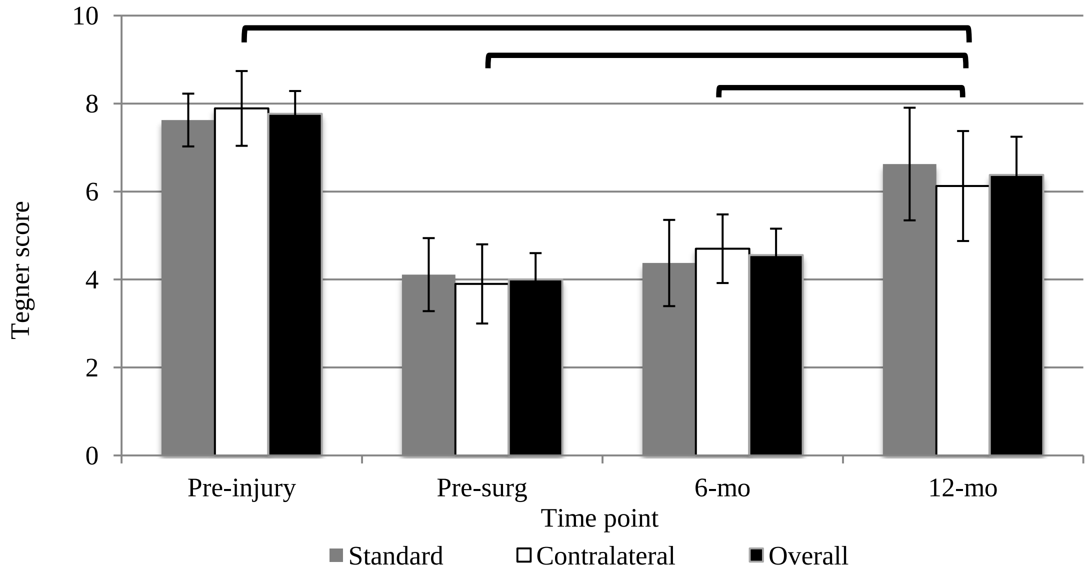


Figure 10. Mean (95% CI) Tegner scores overall and by group over time. Brackets indicate significant differences and apply to overall, standard, and contralateral comparisons.

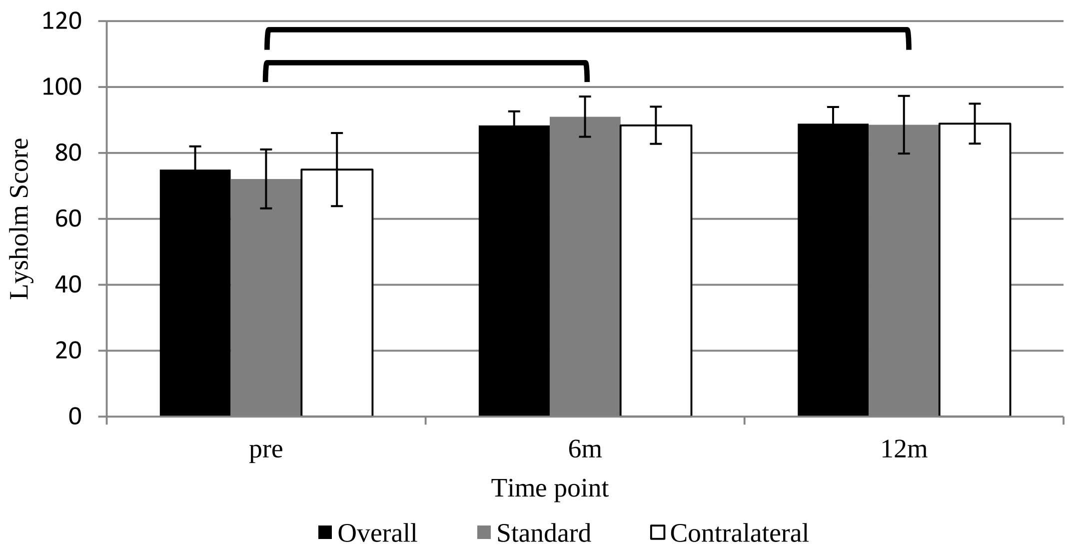


Figure 11. Mean (95% CI) Lysholm scores overall and by group over time. Brackets indicate significant differences and apply to overall, standard, and contralateral comparisons.

Hop tests

Hop test outcomes were compared within participants for the NR-ND limb condition from pre- to 12-months post-surgery and no significant differences were found (single leg $p=0.826$; triple hop $p=0.205$; cross-over hop $p = 0.592$; timed 6 meter hop $p=0.797$). Because pre-surgery hop tests were not performed on the ACL-deficient side, a within leg comparison of pre- to post-surgery could not be conducted. Therefore, 12-months post-surgery hop test outcomes for the ACL reconstructed leg were compared to pre-surgery outcomes from the ACL intact leg. No significant differences for any of the tests were found ($p=0.193 – 0.934$). There were no differences between R and NR, D and ND, or the four limb conditions for any of the hop tests at 6- or 12-months post-surgery. Mean outcomes for the hop tests for D and ND at 12-months are presented in Figure 12.

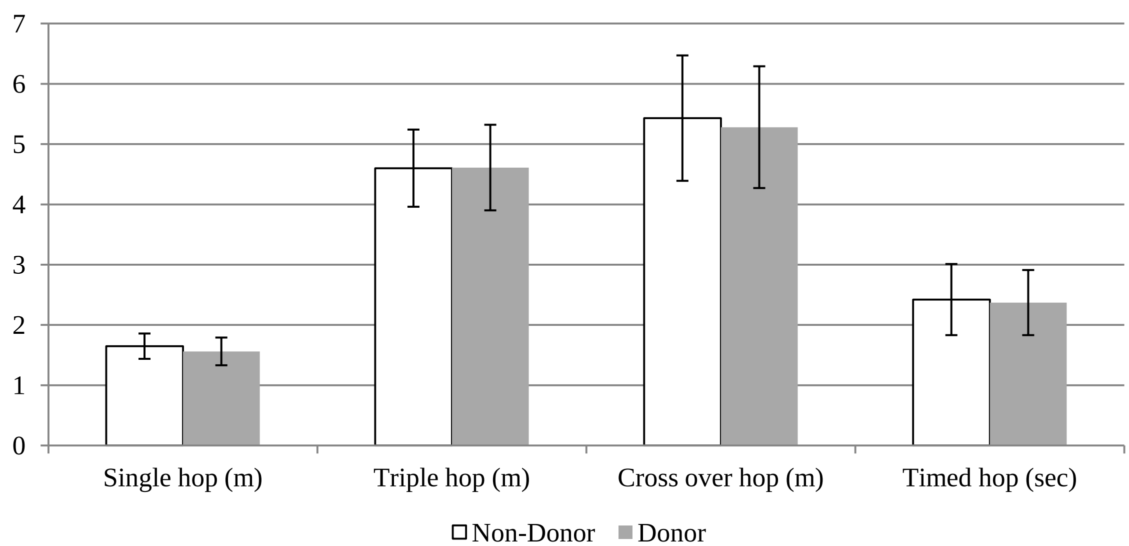


Figure 12. Mean (95% CI) hop test outcomes between ND and D at 12-months post-surgery.

The correlations of the four hop tests at 12-months post-surgery are presented in Table 5. All were significantly correlated for the ND limb. Single and Triple hop are highly correlated in both the ND (r^2=0.959; p<0.001) and D (r^2=0.962; p<0.001) limbs. The cross-over hop and timed 6 m hop tests are also significantly correlated for both limbs (ND – r^2=-0.864, p<0.001; D – r^2=-0.682; p=0.005).

Table 5. Correlations between hop tests for ND and D limbs at 12-months post-surgery. Shaded boxes indicate significant correlations.

		Single hop	Triple hop	Cross-over hop	Timed 6 m hop
Non-Donor	Single hop		0.959	0.851	-0.625
			<0.001	<0.001	0.013
	Triple hop	0.959		0.823	-0.546
		<0.001		<0.001	0.035
	Cross-over hop	0.851	0.823		-0.864
		0.013	0.035		<0.001
	Timed 6 m hop	-0.625	-0.546	-0.864	
		<0.001	<0.001	<0.001	
Donor	Single hop		0.962	0.389	-0.294
			<0.001	0.152	0.228
	Triple hop	0.962		0.489	-0.338
		<0.001		0.064	0.217
	Cross-over hop	0.389	0.489		-0.682
		0.288	0.217		0.005
	Timed 6 m hop	-0.294	-0.338	-0.682	
		0.152	0.064	0.005	

Side-to-side correlations between ND and D limbs were evaluated for each hop test at 12-months post-surgery, and r^2 ranged from 0.832 for single-hop to 0.960 for cross-over hop tests (p<0.001 for all).

Muscle morphometry

Compliance

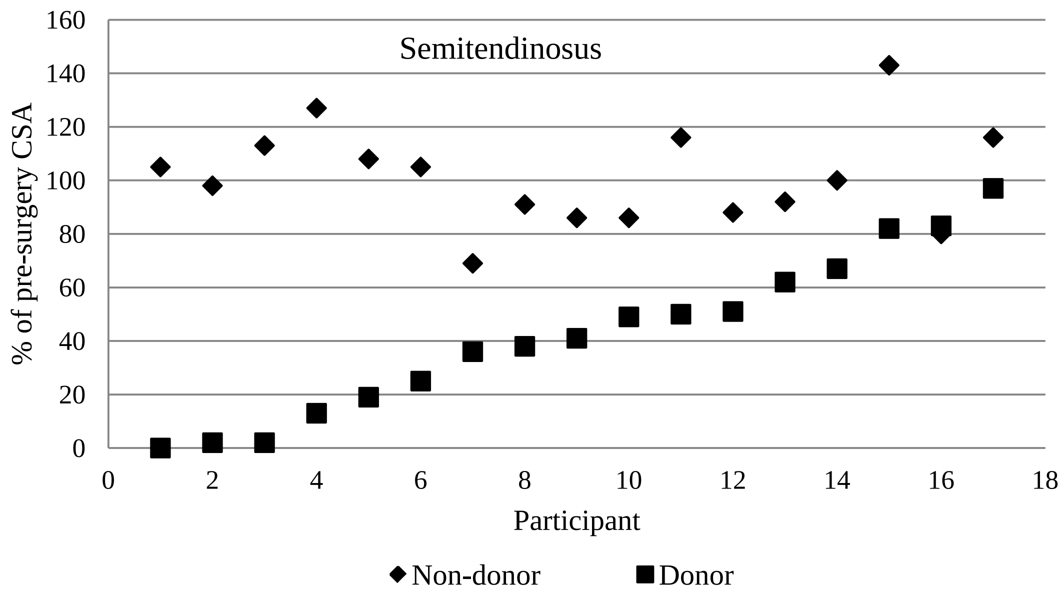
Compliance with MRI evaluation at each of the four study time points was very high (97%) with all examinations complete except for two participants at 12-months post-surgery, the one that was lost to follow-up and the other exited the study after the 6-month time point due to traumatic injury unrelated to the surgery.

CSA

Pre-surgery comparisons: No differences in CSA for any muscles pre-surgery were found between NR and R, ND and D, or between the four conditions, ND-NR, D-R, D-NR and ND-R (NR=not reconstructed; R=reconstructed; ND=non-donor; D=donor).

Pre- to 12-months post-surgery comparisons for ND and D: Percent CSA at 12-months relative to pre-surgery for each participant (sorted based upon loss of CSA) for D and ND limbs for both ST and G is presented in Figure 13. A within-subject comparison of pre-surgery to 12-months post-surgery CSA was conducted for ND and D (Table 6). For ND, CSA of SM was significantly greater at 12-months ($p=0.032$), and all other differences were not significant. For D, CSA of ST, G, and STG combined were significantly less at 12-months post-surgery ($p<0.001$). CSA of ST at 12-months post-surgery was 41.5% of pre-surgery CSA while G was 65.5%, and STG combined was 48.7%. All Hams CSA was significantly smaller at 12-months post-surgery ($p=0.038$). However, when taking into account the reduction in STG, Hams-STG was actually significantly greater at 12-months post-surgery (104.5%; $p=0.018$). No muscles displayed significant increases in CSA between pre- and 12-months post-surgery, but there were increases tending towards significance in CSA of BF (103.6%; $p=0.078$) and SM (106.3%; $p=0.054$) accounting for the increase in

Hams-STG. There was a significant reduction in CSA across all muscles to 89.2% of pre-surgery size.



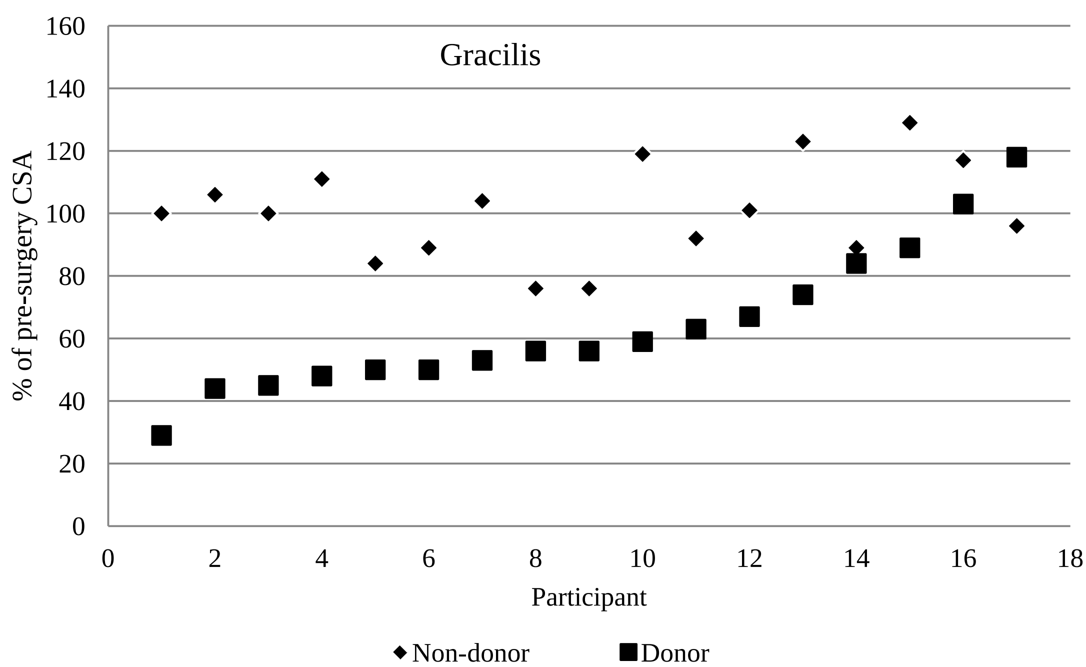


Figure 13. Percent CSA at 12-months relative to pre-surgery for each participant based on D and ND limbs for ST and G. Participants are sorted from greatest to smallest loss of CSA.

Pre- to 12-months post-surgery comparisons for NR and R: A within-subject comparison of pre-surgery to 12-months post-surgery was conducted for NR and R (Table 8). For NR, CSA for ST, G, and STG combined were significantly less at 12-months post-surgery, while SM significantly increased. ST decreased to 62% of pre-surgery CSA while G decreased to 80%. SM increased to 13% greater than pre-surgery. For R, only G was significantly less at 87% of pre-surgery CSA.

Pre- to 12-months post-surgery comparisons for four limb conditions: A within-subject comparison of pre-surgery and 12-months post-surgery CSA was conducted on the four study conditions (Table 9). There were no significant differences in CSA for any muscles in ND-NR. CSA of ST and G, and STG were significantly decreased in D-R (50, 71, and 56% of pre-surgery, respectively). Meanwhile, there was an 11% increase in BF and an 11% increase in Hams-STG. For D-NR there was a significant decrease in ST, G, and STG (34, 62, and 43% of pre-surgery area, respectively). No other muscles were significantly different 12-months post-surgery. For ND-R, there were no significant differences from pre- to 12-months post-surgery.

Between D-NR and D-R comparisons: There were no significant differences between CSA in D-NR and D-R at pre-surgery or 12-months post-surgery.

Between ND-NR and D-R: There was a significant difference (p=0.031) in CSA of ST between ND-NR and D-R, with D-R being a mean of 61% of the CSA of non-operated limb. The difference in CSA of G between ND-NR and D-R was not significant (p=0.067) with D-R being a mean 72% of the non-operated side.

Trajectory

***Within Donor and Non-donor*:** In ND, only SM is significantly different from pre-surgery by the 12-months post-surgery time point (110.1% of pre-surgery CSA; $p=0.032$; Table 6). However, all other muscles, with the exception of AD experienced an early post-surgery CSA reduction at 2-weeks from which they were essentially recovered by 6-months. With respect to muscles in combination, a similar pattern of early atrophy and then recovery by 6-months was seen in ‘All muscles less STG’, STG, and ‘hamstrings less STG.’ For D, early post-surgery atrophy was evident, and all muscles demonstrated recovery with the exception of ST reduced to 41.5% and G reduced to 65.5% of pre-surgery CSA.

Table 7 presents correlations of CSA of ST and G between time points for ND and D limb conditions. Pre-surgery ($r^2=0.638$; $p<0.001$) and two-week ($r^2=0.621$; $p<0.001$) CSA of ST in the ND condition was highly associated with the 12-month post-surgery outcome. But this did not hold true for CSA at pre-surgery of ST in the D condition ($r^2=0.118$; $p=0.178$). Two-week post-surgery CSA of ST was significantly associated with 12-month post-surgery CSA, as the impact of graft harvest continues to be present ($r^2=0.376$; $p=0.009$). Interestingly, pre-surgery CSA of G was highly associated with 12-month post-surgery CSA in both the ND and D conditions ($r^2=0.634$ and $r^2=0.607$, respectively; $p<0.001$). All associations between 2-weeks and 12-months post-surgery are maintained or increased when controlling for early post-operative daily steps.

Table 6. Within-subject comparison for ND and D of CSA across study time points. All post-surgery values reflect percent relative to pre-surgery as baseline. Shaded boxes indicate significant difference from one time point to the time point immediately before with p-values in brackets.

	Pre-surgery (%)	2-weeks (%)	6-months (%)	12-months (%)	Pre-12mos p-value
Non - Donor					
G	100	93.9 (0.032)	103.9 (0.001)	97.4	0.824
ST	100	93.0 (0.031)	101.3	102.0	0.648
BF	100	94.3 (0.040)	99.8 (0.029)	96.6	0.914
SM	100	101.0	112.3 (0.024)	110.1	0.032
Q	100	91.6 (<0.001)	100.0 (<0.001)	98.5	0.970
SA	100	96.4	107.0 (<0.001)	104.0	0.117
AD	100				
All Hams	100	93.5 (<0.001)	100.8 (<0.001)	98.0	0.875
STG	100	93.3 (0.018)	102.1	100.6	0.656
All muscles	100	93.4 (<0.001)	100.9 (<0.001)	98.2	0.825
Donor					
G	100	86.3 (0.004)	71.9 (<0.001)	65.5 (0.001)	<0.001
ST	100	81.4 (0.002)	51.4 (<0.001)	41.5 (0.036)	<0.001
BF	100	92.9 (0.001)	102.3 (<0.001)	103.6	0.078
SM	100	91.6	111.8 (0.002)	106.3	0.054
Q	100	91.2 (<0.001)	99.9 (<0.001)	98.3 (0.841)	0.762
AD	100	101.0	99.7	92.1	0.716
SA	100	93.1	105.0 (0.001)	105.6	0.189
All Hams	100	91.8 (<0.001)	96.7 (0.002)	93.7	0.038
STG	100	82.9 (0.001)	57.5 (<0.001)	48.7 (0.015)	<0.001
Hams-STG	100	92.4 (0.005)	106.0 (<0.001)	104.5 (0.997)	0.018
All Muscles	100	90.9 (<0.001)	92.8	89.2	0.001

Table 7. Correlations of CSA of ST and G between time points for ND and D limb conditions.

Muscle	Limb	r^2 (p-value)		
		Pre-12 mos post-surgery	2 wks-12 mos post surgery	2 wks – 12 mos post controlling for 2-wk daily steps
ST	ND	0.638 (<0.001)*	0.621 (<0.001)*	0.612 (0.001)*
	D	0.118 (0.178)	0.376 (0.009)*	0.526 (0.003)*
G	ND	0.634 (<0.001)*	0.588 (<0.001)*	0.658 (<0.001)*
	D	0.607 (<0.001)*	0.790 (<0.001)*	0.845 (<0.001)*

*Significant correlation at p<0.05.

Within Reconstructed and Non-Reconstructed: In NR, SM is significantly greater from pre-surgery by the 12-month post-surgery time point (111% of pre-surgery CSA; p=0.023; Table 8). In contrast, ST and G were significantly reduced by 12-months at 63 (p=.002) and 77% (p=.010) of pre-surgery values, respectively. Both muscles are significantly impacted at 2-weeks post-surgery and CSA continues to decline at the final time point. CSA of All Muscles was verging on being significantly reduced, but this can be attributed to reductions in ST and G, as there are no other CSA that were significantly reduced post-surgery. For R, a similar pattern appears although the changes in CSA only reach significance with respect to G. Reductions in CSA of ST and G are trending towards significance and an increase in SM CSA was also noted.

Table 8. Within-subject comparisons for NR and R of CSA across study time points. All post-surgery values reflect percent relative to pre-surgery as baseline. Shaded boxes indicate significant difference from one time point to the time point immediately before with p-values in brackets.

	Pre-surgery (%)	2-weeks (%)	6-months (%)	12-months (%)	Pre-12mos p-value
Non – Recon					
ST	100	85	70	63	.002
G	100	89	83	77	.010
BF	100	94	102	100	.254
SM	100	95	112	111	.023
Q	100	96	103	99	.804
AD	100	99	97	87	.230
SA	100	94	105	105	.130
All Hams	100	95	100	95	.290
STG	100	86	74	67	.002
Hams-STG	100	94	106	104	.033
All muscles	100	94	97	93	.063
Recon					
ST	100	89	82	79	.064
G	100	91	92	85	.043
BF	100	93	100	100	.394
SM	100	97	112	105	.076
Q	100	87	97	98	.577
AD	100	97	97	92	.589
SA	100	95	107	105	.172
All Hams	100	90	98	96	.414
STG	100	90	85	81	.044
Hams-STG	100	95	104	102	.109
All muscles	100	90	96	95	.162

Within Four Limb Conditions: Even though no graft harvest took place on the ND-NR limb, ST was significantly reduced in CSA to 95% at 2-weeks post-surgery (p=0.046; Table 9). This CSA increased to 96% of pre-surgery magnitude by 6-months making the change relative to pre-surgery no longer significant. At 6-months post-surgery, quadriceps demonstrated a significant 5% increase in CSA (p=0.017) that was reflected in an overall 3% increase in total CSA of all the muscles combined (p=.037). In spite of these differences in trajectory between muscles, there were no significant changes in muscle CSA from pre- to 12-months post-surgery in the ND-NR limb.

In the D-R limb, there was an increase in CSA of both SM and BF by 6-months post-surgery (113 and 103% of pre-surgery CSA; p=0.005 and p=0.041, respectively) with the change in SM increasing to 7% greater than pre-surgery by 12-months (p=0.038). ST showed a significant decrease in CSA at 2-weeks post-surgery (86%; p=0.020) and continued to decline to 48% of pre-surgery magnitude by 12-months (p=0.007). Meanwhile, the reduction in G CSA did not become significant until 12-months post-surgery (70%; p=0.011). These changes culminated in an overall significant decrease (55%) in STG CSA and a significant increase in ‘Hams-STG’ (106%) relative to pre-surgery CSA by 12-months.

In the D-NR limb, there was a significant decrease in CSA for all muscles except AD at 2-weeks post-surgery. All muscles recovered to the same, or beyond, their pre-surgery values by 6-months with the exception of ST that continued to decline to 36% (p<0.001) and G that decreased to 62% (p=0.001) by 12-months post-surgery.

For the ND-R limb, there was an initial significant reduction in the CSA of G and Q at 2-weeks post-surgery, but by 12-months, all muscles had returned to their pre-surgery level.

Table 9. Within-subject comparison for NR-ND, R-ND, ND-NR, and R-D of CSA. Post-surgery values reflect percent relative to pre-surgery. Shaded boxes indicate significant difference from one time point to time point immediately before (p-values in brackets).

Limb condition	Muscle	Pre-surgery (%)	2-weeks (%)	6-months (%)	12-months (%)	Pre-12mos p-value
ND-NR	AD	100	0.94	1.01	0.80	.302
	BF	100	0.98	1.02	0.98	.234
	G	100	0.97	1.03	0.95	.848
	Q	100	0.98	1.05 (.017)	0.98	.413
	SA	100	1.02	1.11	0.99	.389
	SM	100	1.08	1.14	1.16	.096
	ST	100	0.94 (.046)	0.96	0.96	.608
	All Hams	100	0.98	1.04 (.023)	0.97	.546
	STG	100	0.95 (.049)	0.98	0.96	.728
	Hams-STG	100	1.01	1.06	1.04	.085
	All Muscles	100	0.98	1.03 (.027)	0.97	.614
D-R	AD	100	0.97	1.04	0.91	.961
	BF	100	0.95	1.03 (.041)	1.07	.038
	G	100	0.91	0.79	0.70 (.012)	.011
	Q	100	0.88 (.001)	0.98 (.002)	0.97	.835
	SA	100	0.99	1.11	1.01	.487
	SM	100	1.00	1.13 (.005)	1.05	.235
	ST	100	0.86 (.020)	0.57 (.030)	0.48	.007
	All Hams	100	0.91 (.006)	0.97 (.025)	0.94	.556
	STG	100	0.88 (.009)	0.63 (.026)	0.55 (.034)	.003
	Hams-STG	100	0.97	1.07 (.001)	1.06	.033
	All Muscles	100	0.91 (.003)	0.93	0.90	.127
D-NR	AD	100	1.03	0.93	0.93	.556
	BF	100	0.91 (.005)	1.03 (.005)	1.01	.670
	G	100	0.82 (.014)	0.66 (.002)	0.62 (.034)	.001
	Q	100	0.94 (.044)	1.01 (.031)	0.99	.500
	SA	100	0.89 (.016)	1.01 (.004)	1.09	.219
	SM	100	0.86 (.042)	1.11 (.023)	1.07	.163
	ST	100	0.77 (.030)	0.47 (.000)	0.36	.000
	All Hams	100	0.92 (.006)	0.97	0.94	.014
	STG	100	0.79 (.019)	0.53 (.000)	0.44	.000
	Hams-STG	100	0.89 (.009)	1.06 (.003)	1.03	.249
	All Muscles	100	0.91 (.005)	0.92	0.89	.002
ND-R	AD	100	0.97	0.91	0.92	.393
	BF	100	0.92	0.98	0.95	.219
	G	100	0.91 (.040)	1.05 (.006)	1.00	.914
	Q	100	0.86 (.000)	0.96 (.003)	0.99	.358
	SA	100	0.92	1.04 (.005)	1.08	.195
	SM	100	0.95	1.11 (.039)	1.05	.227
	ST	100	0.92	1.06	1.08	.317
	All Hams	100	0.90 (.000)	0.98 (.002)	0.99	.614
	STG	100	0.92	1.06	1.05	.378
	Hams-STG	100	0.93	1.02	0.99	.871
	All Muscles	100	0.90 (.000)	0.99 (.003)	0.99	.795

Proximal shift

From pre- to 12-months surgery, there was a 5.7 (2.9) cm proximal shift in ST (Figure 14) and 4.2 (2.3) cm in G (Figure 15) in the level at which muscle CSA could be detected in the D limb condition, and no proximal shift detected in the ND limb condition. There was no difference in proximal shift in ST or G between time points when evaluating NR and R limb conditions (Figures 16 and 17).

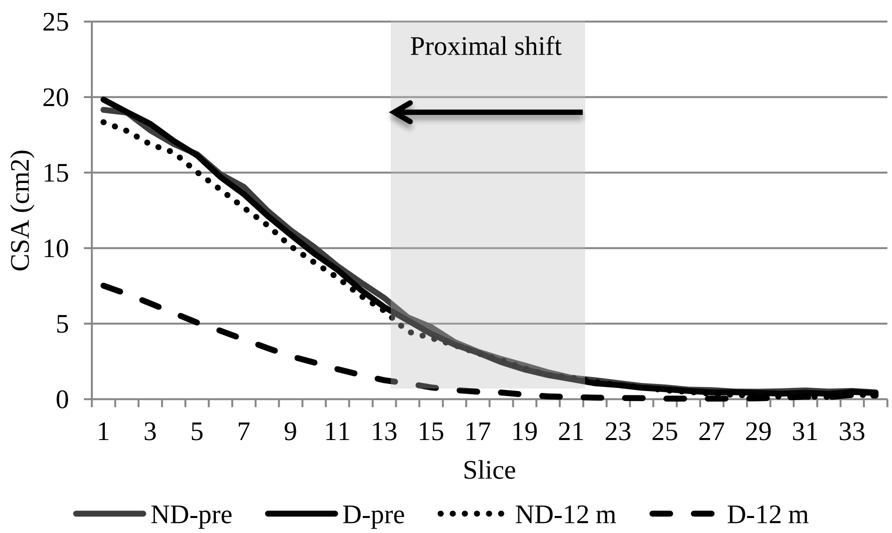


Figure 14. ST CSA by slice at pre- and 12-months post-surgery for ND and D limbs. Slice 1 is the most proximal image (ischial tuberosity) and Slice 33 is the most distal image (knee joint line).

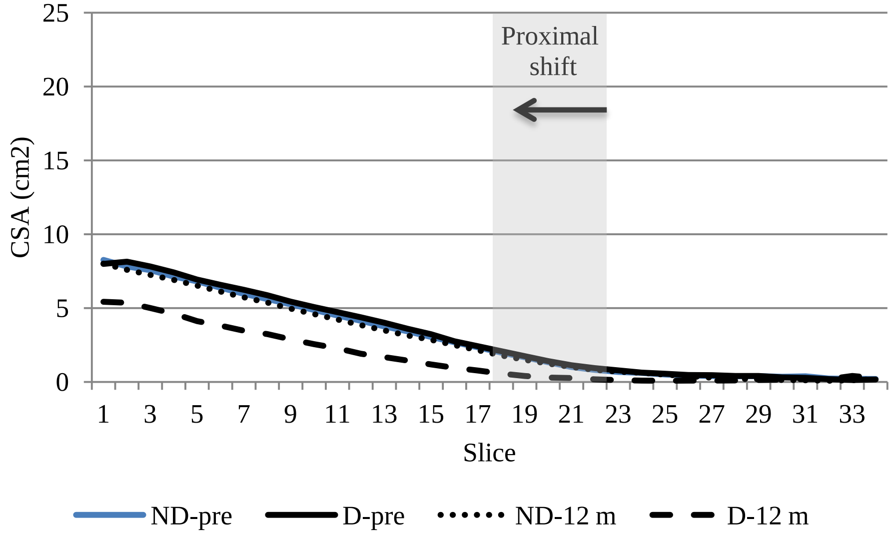


Figure 15. G CSA by slice at pre- and 12-months post-surgery for D and ND limbs. Slice 1 is the most proximal image (ischial tuberosity) and Slice 33 is the most distal image (knee joint line).

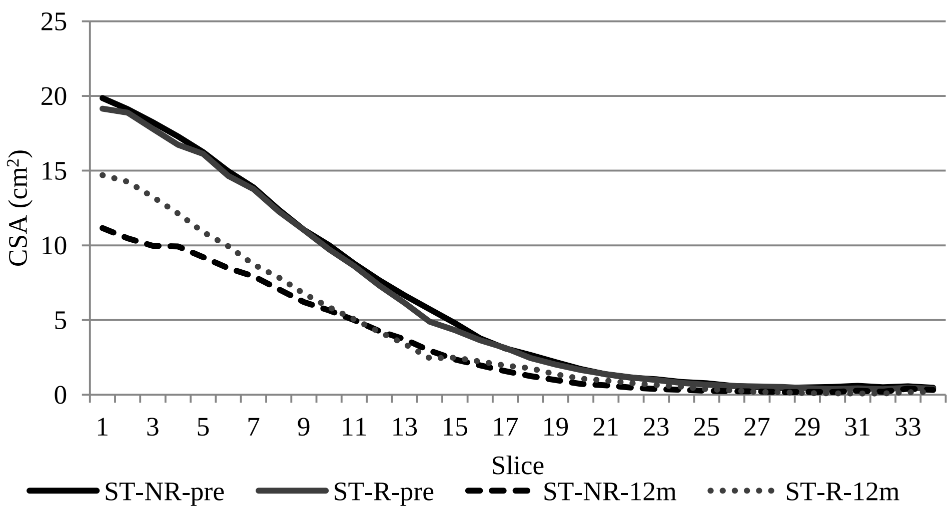


Figure 16. ST CSA pre- and 12-months post-surgery for R and NR limbs. Slice 1 is the most proximal image (ischial tuberosity) and Slice 33 is the most distal image (knee joint line).

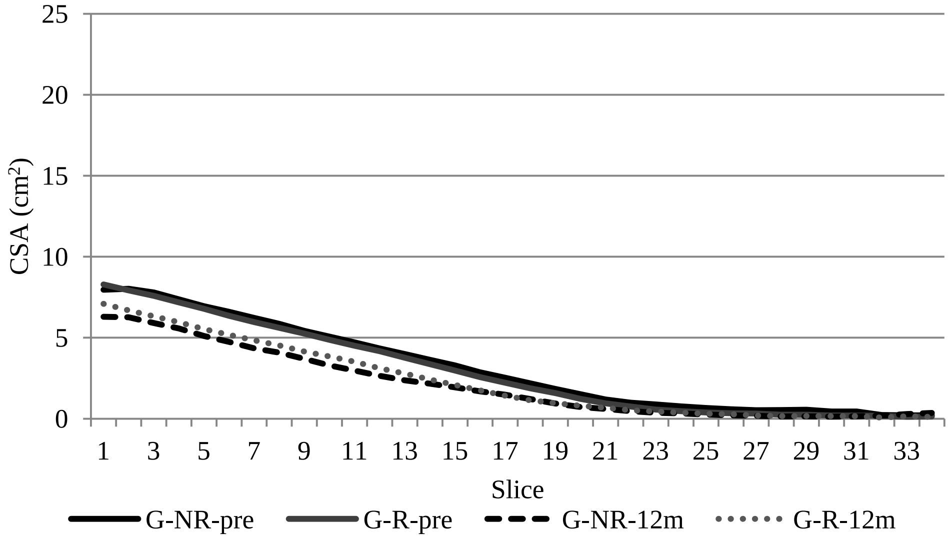


Figure 17. G CSA pre- and 12-months post-surgery for R and NR limbs. Slice 1 is the most proximal image (ischial tuberosity) and Slice 33 is the most distal image (knee joint line).

Slope

No differences in slope were found from pre- to 12-months post-surgery in ND or D for either ST or G (Table 10). No differences were found between limbs at pre-surgery or at 12-months post-surgery for either muscle. A similar pattern was found when comparing NR and R and the four limb conditions.

Table 10. Slope by muscle by ND/D limb for pre- and 12-months post-surgery.

Muscle	Limb	Pre-surgery slope (cm^2/slice)	12-months post-surgery slope (cm^2/slice)	p-value
ST	ND	1.22 (0.30)	1.22 (0.37)	0.886
	D	1.18 (0.33)	0.85 (0.89)	0.123
Between limbs comparison		p = 0.295	p = 0.168	
G	ND	0.37 (0.10)	0.38 (0.10)	0.695
	D	0.39 (0.12)	0.38 (0.14)	0.569
Between limbs comparison		p = 0.140	p = 0.917	

Volume

There was a significant decrease in muscle volume from pre- to 12-months post-surgery for ST and G in the D limbs ($p<0.001$ for both muscles) (Table 11). At 12-months, ST volume was 86.7% of pre-surgery on the ND limb and 27.4% on the D limb. G was 86.2% of pre-surgery on the ND limb and 51.9% on the D limb.

There were no significant differences in ST volume between ND and D at pre-surgery; but ST volume in D was significantly less than ND at 12-months post-surgery ($p=0.005$). G volume was significantly greater in D than ND at pre-surgery ($p=0.019$), and then volumes were not significantly different at 12-months post-surgery. However, when examining the change from pre- to 12-months post-surgery, the reduction in volume in D was significantly more pronounced than in the ND limb condition ($p=0.004$).

No pre-injury volumes were available so pre-surgery volume on the ACL intact side was used as a proxy and compared to the volume of the ND and D limbs at 12-months post-surgery. ST at pre-surgery on the ACL intact side was significantly greater than both ND ($p=0.016$) and D ($p<0.001$). Similarly, the volume of G on the ACL intact side at pre-surgery was also greater than both ND ($p=0.007$) or D ($p<0.001$).

Table 11. ST and G volume (cm^3) from the ischial tuberosity to the distal attachment at pre-surgery and 12-months post-surgery for ND and D limbs.

Muscle	Limb	Pre-surgery	12-months post	Mean difference	Pre-post p-value
ST	ND	134.3 (54.2)	115.5 (77.7)	35.2 (56.2)	0.183
	D	131.2 (55.8)	45.8 (60.8)	69.0 (58.5)	<0.001
Between limb p-values		0.492	0.005		
	ACL intact		135.1 (56.7)[a]		
G	ND	62.3 (17.9)	54.7 (30.2)		0.136
	D	70.1 (25.4)	39.3 (28.6)		<0.001
Between limb p-values		0.019	0.050[c]		
	ACL intact		68.6 (25.1)[b]		

[a]ST volume for both ND and D at 12-months post-surgery significantly lower than pre-surgery volume of ACL intact limb;
[b]ST volume for both ND and D at 12-months post-surgery significantly lower than pre-surgery volume of ACL intact limb;
[b]Change from pre- to 12-months post-surgery was significantly different between ND and D, with the decrease in G volume being significantly greater in D than ND ($p=0.004$).

Associations between muscle morphological parameters

ST CSA, volume, proximal shift and slope in the non-donor limbs at 12-months post-surgery were not significantly correlated with one another. In the donor limbs, ST CSA and volume were significantly correlated (r^2=0.635; p<0.001), and ST CSA and proximal shift were significantly correlated (r^2=0.330; p=-0.023).

Muscle Atrophy

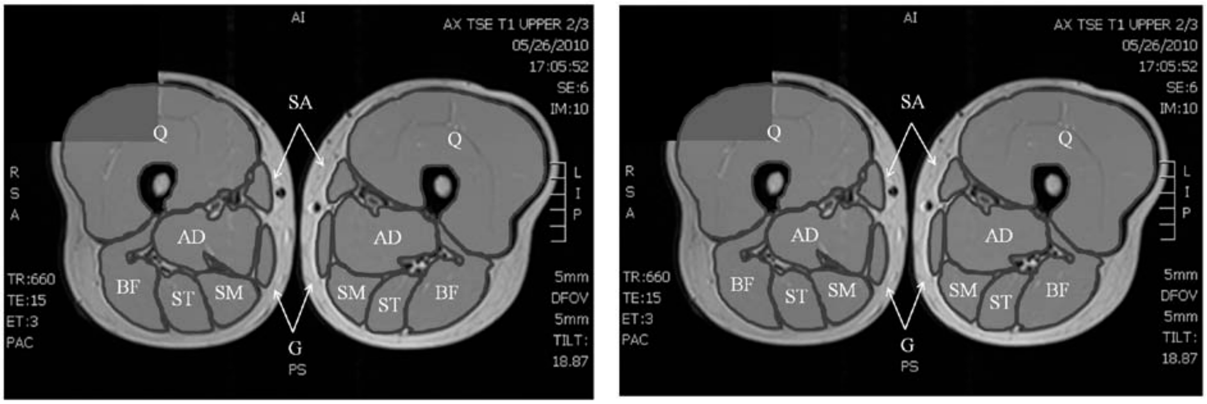
Participants were categorized based on percent reduction in muscle volume from pre-surgery for ST and G: less than 5% reduction, 5 to 20%, 20 to 80 percent, and more than 80% reduction. There was a significant difference in the distribution of participants across these categories for both ST (p<0.001) and G (p<0.001; Table 12).

Table 12. Number of participants based on percent reduction of ST and G CSA at 12-months post-surgery relative to pre-surgery.

Muscle	Condition	<5%	5-20%	20-80%	>80%
ST	Non-donor	8	5	4	0
	Donor	0	1	7	9
G	Non-donor	12	2	3	0
	Donor	2	1	13	1

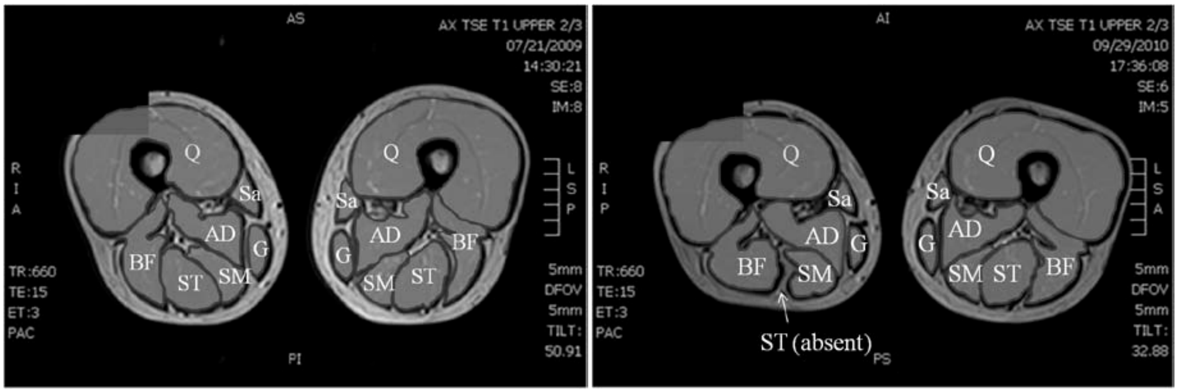
For the ST that did not undergo tendon harvest, eight participants maintained muscle volume to within 5% of pre-surgery levels, and six between 5 and 20%. The remaining 4 had a 20 to 80% reduction in size. For the donor-side ST, no participants maintained muscle volume within 5% of pre-surgery levels, and only one was within 5 to 20%. Seven experienced between 20 and 80%, while nine had greater than 80% reduction in muscle volume. With respect to G in the ND limb, twelve participants maintained muscle volume within 5% of pre-surgery, with two between 5 and 20% and three between 20 and 80%. As with ST, no participants experienced greater than 80% reduction in muscle volume. For G in the donor limb, there were two cases of participants maintaining volume of G within 5% of pre-surgery, and one with between a 5 and 20% reduction. Thirteen experienced between 20 and 80% reduction in volume and only one experienced extreme loss greater than 80%.

Figures 18 and 19 present example MRI images at pre- and 12-months post-surgery of a patient that experienced little to no atrophy and a patient that experienced complete atrophy.



	Pre-surgery		12-months post-surgery	
Muscle	ND (cm^2)	D (cm^2)	ND (cm^2)	D (cm^2)
AD	100.3	96.4	100.8	99.2
BF	93.6	94.3	83.6	93.9
G	14.1	17.4	17.1	12.7
Q	396.1	409.6	377.3	380.4
SA	13.6	15.3	17.0	17.9
SM	42.8	49.8	48.9	53.6
ST	45.5	52.7	47.0	45.4

Figure 18. MRI images and data from a single participant with nearly full recovery at 12-months post-surgery.



	Pre-surgery		12-months post-surgery	
Muscle	D (cm^2)	ND (cm^2)	D (cm^2)	ND (cm^2)
AD	64.9	68.7	63.5	64.3
BF	62.6	57.1	77.9	63.4
G	18.1	19.6	13.7	21.6
Q	274.6	288.8	267.7	269.3
SA	13.7	12.2	12.3	15.4
SM	26.0	25.5	35.1	26.2
ST	61.5	58.4	0.0	55.8

Figure 19. MRI images and data from a single participant with 25% atrophy of G and full atrophy of ST at 12-months post-surgery.

Strength

Compliance

Compliance with strength testing at each of the three study time points was very high (95%) with all examinations complete except for one participant who exited after the 6-month time point due to a traumatic injury unrelated to the surgery and one participant at 12-months who was lost to follow-up.

Knee extensors

Pre-surgery: There was a main effect of velocity for knee extensor strength overall, for R versus NR, D versus ND, and comparing all four conditions. Knee extensor torque lessened from -270 to 270 deg/s. There was no interaction effect based on limb. There was a pre-surgery side-to-side main effect between R and NR ($p=0.002$) with mean peak torque for NR being 27.2 (8.7) Nm greater than R. There was no side-to-side difference between D and ND pre-surgery ($p=0.590$; Figure 20). There was a main effect between limbs pre-surgery ($p=0.010$) which, based on post-hoc pairwise comparisons was attributable to differences between R and NR.

Twelve month post-surgery: Consistent with pre-surgery, there was a main velocity effect on knee extensor strength overall ($p<0.001$), and when comparing D and ND, R and NR, and all conditions. There was an ongoing difference in knee extensor strength between R and NR (0.040) at 12-months post-surgery with NR having 21.6 (10.4) Nm greater torque than the R side (Figure 20). When 12-month strength was controlled for pre-surgery strength, the relationship was no longer significant ($p=0.358$). There was no main effect of donor limb on knee extensor strength ($p=0.955$).

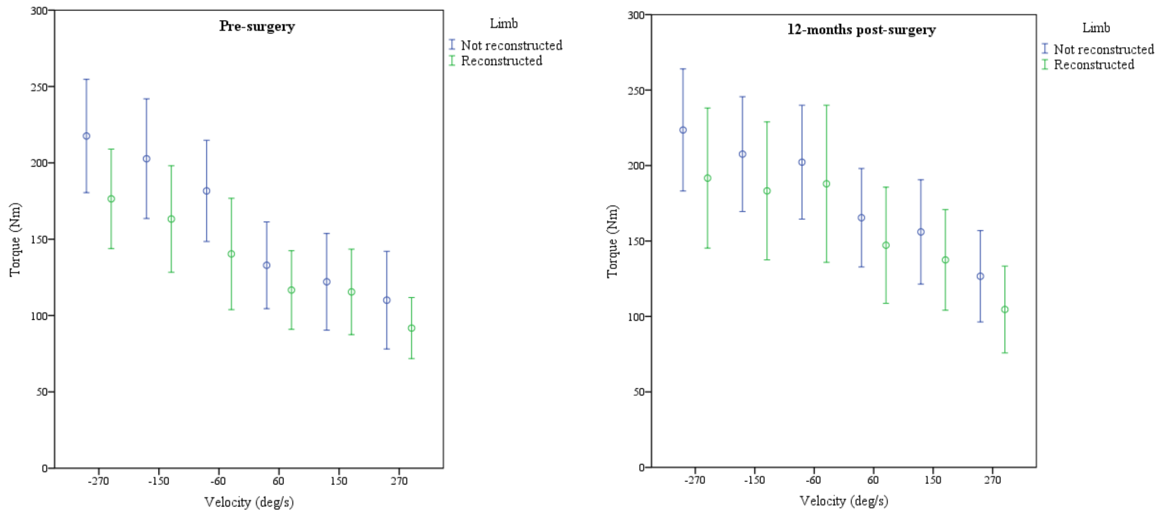


Figure 20. Mean (95% CI) knee extensor peak torque at pre-surgery (left panel) and 12-months (right panel) post-surgery comparing NR (blue) and R (green) limbs. Negative velocities represent eccentric contraction and positive velocities represent concentric contraction.

Knee flexors

Donor and Non-Donor: For peak knee flexor torque in the seated position (85° hip flexion) at pre-surgery, there was a significant effect from velocity (p=0.013) and no effect of donor limb (p=0.471; Figure 21). At 12-months post-surgery, there were no differences in strength based on velocity (p=0.379) or between ND and D (p=0.870) nor was there an interaction effect between the two (0.993). In addition, when examining the change in knee flexor torque from pre- to 12-months post-surgery, the effect of velocity, donor, and the interaction effects remained not significant (p=0.679, 0.744, 0917, respectively).

Reconstruction and Non-reconstruction: At pre-surgery, there was a significant difference between NR and R across velocities (p=0.001) with NR being greater by a mean difference of 19.4 Nm (Figure 22). There was no interaction between reconstructed limb and velocity (p=0.973). Similarly at 12-months post-surgery, there was a significant effect based on NR and R with NR being significantly greater (p=0.020) with a mean difference of 18.0

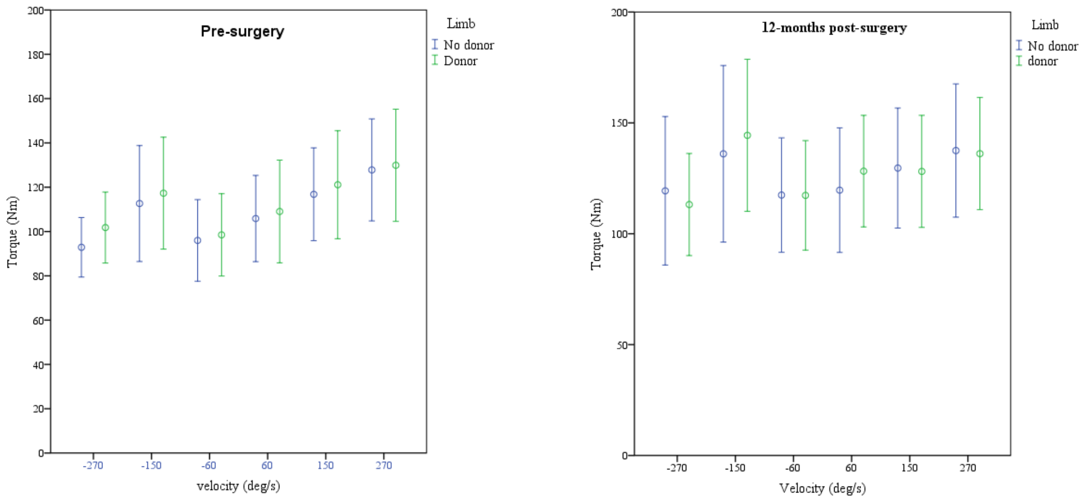


Figure 21. Mean knee flexor peak torque in seated position across velocities at pre- (left) and 12-months (right) post-surgery for ND (blue) and D (green) limbs. Negative and positive velocities represent eccentric and concentric contractions, respectively.

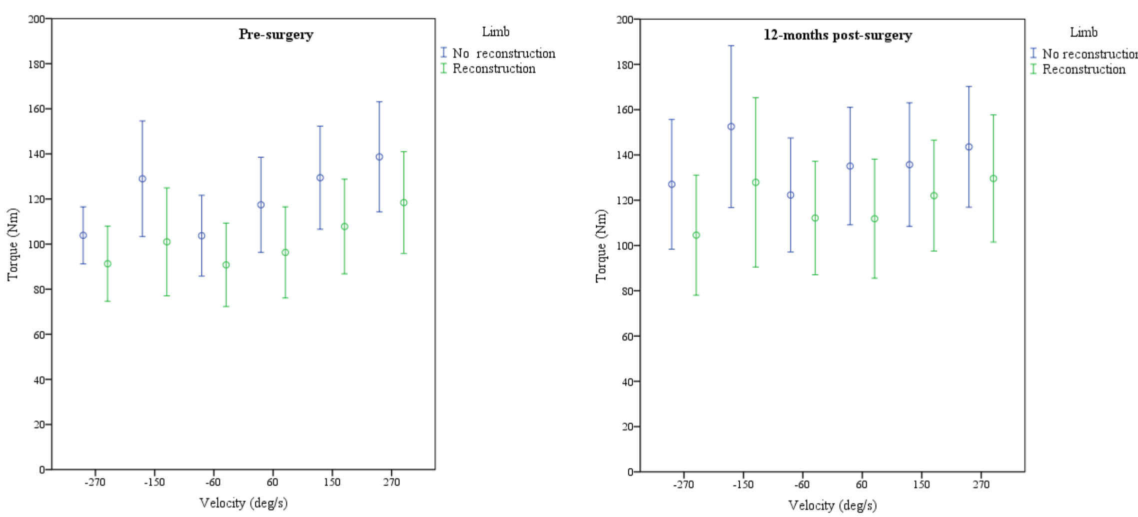


Figure 22. Mean knee flexor peak torque in seated position across velocities at pre- (left) and 12-months (right) post-surgery for NR (blue) and R (green) limbs. Negative and positive velocities represent eccentric and concentric contraction, respectively.

Nm. This held true across velocities (p=0.991). No main velocity effect was seen (p=0.347), so there was no reduction in torque from eccentric to concentric contraction type. When comparing NR and R in the change in knee flexor strength from pre- to 12-months post-surgery, the difference between limbs was not significant (p=0.614).

Effect of position: At pre-surgery, there was no significant difference between peak knee flexor torque based on donor limb in the seated (85° hip flexion; $p=0.471$) or supine position (5° hip flexion; $p=0.195$). At 12-months post-surgery, there was still no difference between limbs in the seated position ($p=0.870$); however, there was a significant difference based on donor limb in the hip-neutral position ($p=0.005$) with a mean difference between ND and D of 16.1 Nm. This relationship also holds true when examining change from pre- to 12-months post-surgery (Figure 23). This significant interaction effect between position and

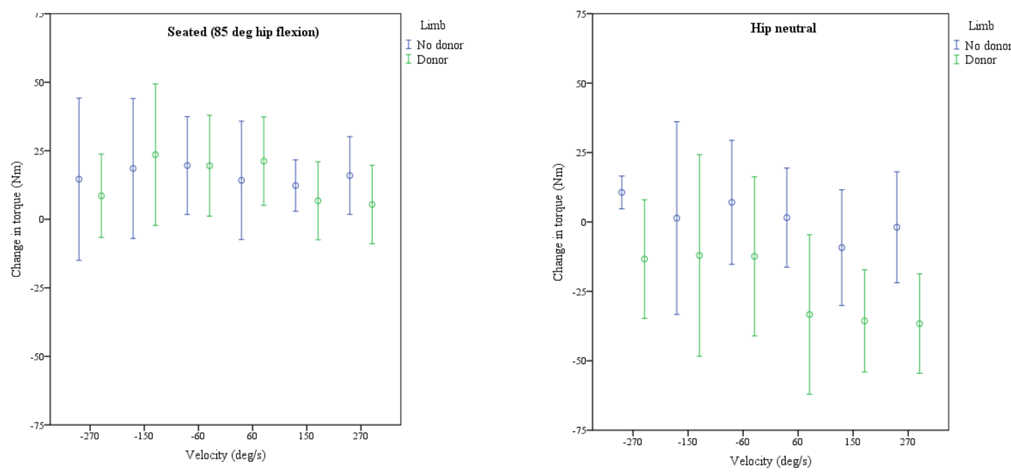


Figure 23. Mean changes in knee flexor peak torque from pre- and 12-months post-surgery across velocities for ND (blue) and D (green) limbs in seated (left) and hip-neutral (right) position. Negative and positive velocities represent eccentric and concentric contractions, respectively.

limb did not exist when comparing reconstruction and non-reconstructed sides at 12-months post-surgery.

Physical Activity

Compliance

The rate of compliance of participants wearing an accelerometer for a minimum of 8 hours a day was 77.7%. The minimum criteria to be considered ‘eligible’ for inclusion in statistical analyses of at least 4 of 7 days wear time of 8 or more hours per day was met by thirteen participants at pre-surgery, 16 at 2-weeks, 16 at 6-months and 15 at 12-months.

PA monitoring parameters are presented in Table 13 based on eligible data points. The mean (SD) eligible number of days the accelerometer was worn per participant per time point ranged from 5.88 (1.025) to 6.54 (0.660). Mean wear times per day were similar across time points from 13.43 (1.453) to 13.78 (1.647) hours from pre- to 12-months post-surgery. There were no significant differences between the Standard and Contra groups on these variables.

Pre to 12-months post

Table 14 presents pre- and 12-months post-surgery mean PA parameters as measured in daily steps and EE as well as mean differences (SD) within participants between these time points. There were no significant differences between Standard and Contra groups at any time point on any of the step or EE parameters; therefore, data were collapsed and analyzed as one group.

Table 13. Mean days per week and hours per day accelerometer wear time based on eligible data points.

		Overall		Standard		Contra		
	Time	Mean	SD	Mean	SD	Mean	SD	p-value
Days/wk	Pre	6.54	0.660	6.71	0.756	6.33	0.516	0.320
	2 wk	6.06	1.063	6.13	1.126	6.00	1.069	0.823
	6 m	5.88	1.025	6.00	0.756	5.75	1.282	6.642
	12 m	5.93	1.280	6.57	0.787	5.38	1.408	0.068
Hours/day	Pre	13.43	1.453	13.29	1.423	13.59	1.61	0.727
	2 wk	13.51	1.649	13.15	0.837	13.86	2.200	0.408
	6 m	13.70	1.476	13.71	1.622	13.70	1.438	0.990
	12 m	13.78	1.647	14.17	1.460	13.44	1.819	0.411

In answering the fundamental question, does PA change from pre-surgery to 12 months post-surgery, a paired t-test was conducted on daily steps across all participants and was not significant (p=0.199). The mean difference in daily steps between pre-surgery and 12-months post-surgery was an increase of 1,557.4 (3,756.31) which is not considered a clinically relevant difference based on the previously defined threshold of 2,000 steps.[115–118]

Table 14. Pre- and 12-months post-surgery mean PA parameters, and mean differences within participants between these time points.

Parameter	Pre-surgery		12-months				
	Mean	SD	Mean	SD	Mean diff	SD	p
Daily steps (count)	7491.8	2480.27	9349.2	3211.6	1557.4	3756.31	0.149
Time stepping (hrs)[a]	2.4	0.81	2.8	1.05	0.3	1.11	0.396
Cadence (steps/min)	50.9	5.62	55.7	7.62	4.4	4.42	0.009
EE (kcal/day)	969.9	267.9	1168.2	454.0	198.3	494.9	0.213
Time active (hrs)[b]	5.1	1.57	5.6	1.76	2.8	1.73	0.601
Bouts of MVPA[c]	638.7	195.34	671.7	236.42	21.2	293.79	0.816
Mins of MVPA[d]	31.9	9.76	33.6	11.82	1.1	14.69	0.816
MVPA bouts >30s[e]	107.0	25.11	114.7	33.17	3.2	42.03	0.803
Proportion of days > 10,000 steps	0.23	0.273	0.40	0.303	0.15	0.377	0.219
Proportion of days > 12,500 steps	0.098	0.167	0.288	0.284	0.19	0.268	0.058

[a]The total time in a 24-hour period in which a step was detected;

[b]The total time in a 24-hour period in which activity counts were greater than zero. Thus, hours active was always less than wear time;

[c]Number of epochs in which resultant activity count exceeds threshold for the energy expenditure equivalent of 3 METS;

[d]Total number of minutes in which activity counts in an epoch exceeded the MVPA threshold;

[e]A bout was counted if activity counts in sequential epochs were maintained above the MPVA threshold for 30 seconds or more;

Even though cadence was significantly higher by 12-months reflecting a possible increase in exercise intensity, this did not translate into a significant increase in exercise expenditure from pre- to 12-months post-surgery (p=0.213). Furthermore, no significant differences were found between hours active, number of bouts of MVPA per day, or number of bouts of MPVA greater than 30 seconds.

PA Trajectory

Mean (95% CI) daily steps for each time point overall and for each study group are presented in Figure 24. Differences between groups were not significant across time points. For participants overall, the mean reduction in daily steps of 12% pre- to 2-weeks post-surgery was not statistically significant. Daily steps significantly recovered between 2-weeks and 6-months to within 1% of pre-surgery values (p=0.044). A further increase was seen between 6- and 12-months (p=0.002). Cadence increased across time points from 2-weeks to 6-months (p=0.023), and then from 6- to 12-months (p=0.022).

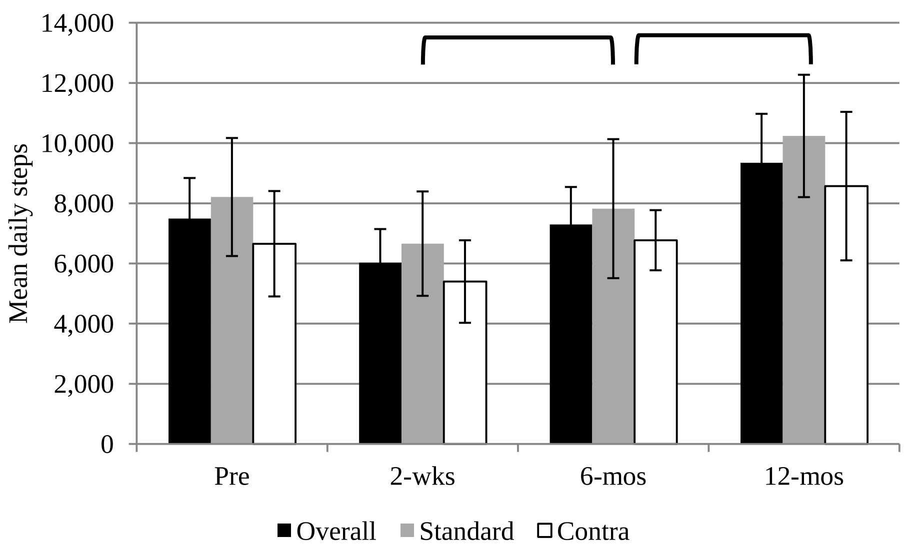


Figure 24. Mean (95% CI) daily steps overall and for Standard and Contra groups across all time points. Brackets indicate significant differences.

EE increased significantly from 6- to 12-months (p=0.022) post-surgery. The number of bouts of MVPA increased significantly from 2-weeks to 6-months (p=0.041) post-surgery. The number of bouts of contiguous MVPA greater than 30 seconds followed a similar pattern (p=0.016).

Comparisons to normative and other population data

Male participants had significantly lower daily steps pre-surgery, 6995 steps per day, compared to the national average, 9926 steps per day (p=0.003). Daily steps recovered to approximate the national average for men by 12-months post-surgery (p=0.884). There was no significant difference between daily steps of female participants compared to the Canadian national average for women age 20 to 39 (mean steps per day = 8875) at either pre-surgery (7907 steps per day; p=0.882) or 12-months post-surgery (7147 steps per day; p=0.399).

The commonly touted value of 10,000 steps per day, representing a minimal threshold for healthy lifestyle, was met on 23% of all eligible days pre-surgery. This proportion increased to 40% by 12-months post-surgery, but was not a statistically significant change (p=0.219). Fifty-four percent (7 of the 13 participants with eligible days of data) met the threshold at least one day of the 7-day study period pre-surgery while 80% (12 of 15) met it at 12-months post-surgery (Figure 25). Twelve thousand, five-hundred steps per day is the threshold recommended for an active lifestyle.[111] This was achieved by 31% (4 of 13) of participants at least one of the 7-day study period pre-surgery, and 67% (10 of 15) at 12-months post-surgery. Ten percent of all eligible days across all participants were greater than

12,500 steps pre-surgery and 29% at 12-months which was not a significant change (p=0.058).

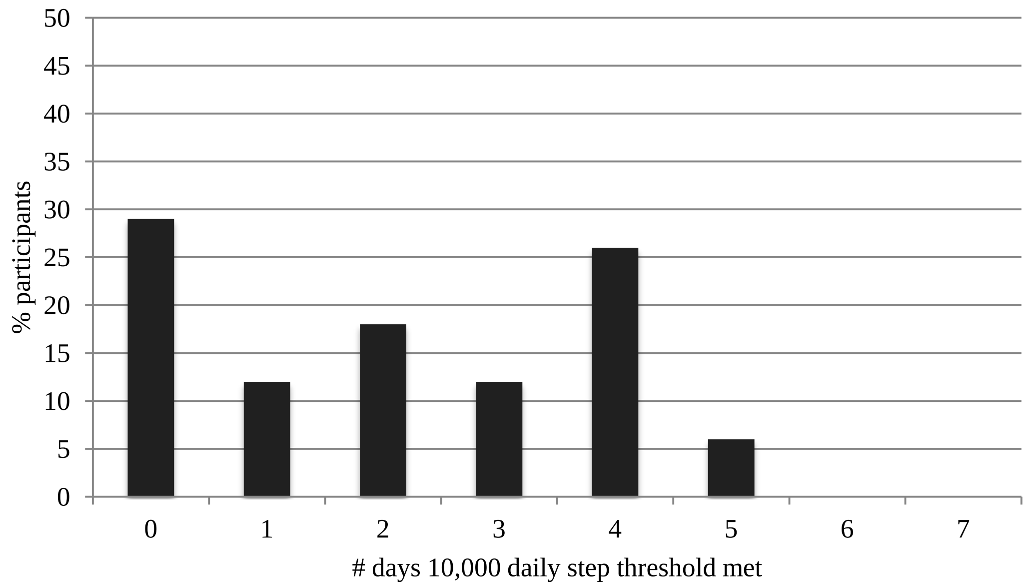


Figure 25. Number of days out of 7-day evaluation with accelerometer that participants met 10,000 steps threshold at 12-month post-surgery.

Muscle morphology as a predictor

Statistical models based on muscle morphometry parameters as potential predictors of subjective, functional, strength, and PA parameters are presented in Table 15. Values at 12-months for D and ND were used in all comparisons. Each of the variables that were entered into the regression analyses (i.e., CSA of Q, ST, G, Hams less STG, and volume, proximal shift and slope of ST and of G) were selected as a predictor for at least one outcome.

Subjective

CSA of all hamstrings on the non-donor side was found to be predictive of Tegner score (r^2=0.624; p = 0.005) while the same measure on the donor side was predictive of IKDC subjective score (r^2=0.348; p=0.033. No variables were predictive of Lysholm score.

Hop tests

No muscle morphometry parameters were predictive of any of the functional hop tests on the ND leg; and only the single-hop test had a significant predictive model, that is, CSA of quadriceps (r^2=0.446; p=0.015) which was true for both limbs. Timed hop and cross-over hop tests were not predicted by any of the morphometry measures. Triple hop was not evaluated as it was found to be very highly correlated with single-hop score (r^2=0.894; p<0.001). It is important to note that there was no change in the hop tests over time (See Figure 12). Despite the lack of change, regression was performed on the possibility that individual differences may be predicted by muscle parameters

Physical Activity

Predictive models based on muscle morphometry were found for PA, EE, cadence, number of bouts of MVPA, and minutes in MVPA, but the variables in each model differed. For PA, quadriceps CSA on the non-donor side in addition to slope of ST, hamstring CSA, and STG CSA on the donor side were significantly predictive (r^2=0.610; p=0.042). Adding slope of ST from the non-donor side increased the predictive capacity (r^2=0.805; p=0.014). For EE, slope and CSA of ST on the donor side was significantly predictive (r^2=0.613; p=0.009), and adding CSA of the same side increased this capability (r^2=0.847; p=0.001). Cadence was found to be significantly predicted by volume of G and the pre- to post-surgery muscle shift of ST on the non-donor side (r^2=0.507; p=0.035). Number of MVPA was predicted using the volume of G on the non-donor side (r^2=.494; p=.013) and minutes of activity was predicted also predicted by volume of G (r^2=.499; p=.013). This latter relationship was found to be even more predictive by adding the slope of ST on the donor limb (r^2=0.624; p=0.015).

Strength

Significant predictive models for strength were found for both eccentric and concentric contraction. Quadriceps CSA was predictive of both eccentric and concentric knee extensor strength in both D and N-D limbs. All Hamstring CSA was predictive of eccentric and concentric strength in sitting and supine positions for the N-D limb. For eccentric flexor in sitting and concentric flexor in supine, the addition of slope of G to the model significantly increased the predictive value. For the D limb, All Hamstring CSA was once again predictive of eccentric and concentric knee flexor strength with the exception of eccentric flexor in the supine position. ST slope, G slope, G volume, and ST and G shift increased the predictive value of these models.

Table 15. Predictive models of muscle morphology based on 12-month post-surgery outcomes.

Category	Dependent	Model	r^2	p
Subjective	Tegner	ND- All Hams CSA	0.624	0.005
	Lysholm			NS
	IKDC	D-All Hams CSA	0.348	0.033
Hop tests	ND-Single hop	ND-Quads CSA	0.428	0.024
	D-Single hop	D-Quads CSA	0.446	0.015
	ND-Timed hop			NS
	D-Timed hop			NS
	ND-Cross-over hop			NS
	D-Cross –over hop			NS
Physical Activity	Daily steps	ND-Quads CSA + ND-ST Slope+ D-ST Slope + D-All Hams CSA + D-STG CSA	0.805	.014
	EE	D-ST slope + D- ST CSA + D-G CSA + D-ST CSA	0.847	0.001
	Cadence	ND- G volume + ND-ST shift	0.507	0.035
	Bouts of mod-vig activity	ND-G volume	0.494	0.013
	Time in mod-vig activity	ND-G volume	0.499	0.013
		+ D-ST slope	0.624	0.014
Strength	ND-Ecc Ext	Quads CSA	0.395	0.004
	ND-Con-Ext	Quads CSA	0.420	0.004
Sitting:	ND-Ecc-Flex	All Hams CSA	0.717	<0.001
		+ G slope	0.756	<0.001
	ND-Con-Flex	All Hams CSA	0.612	<0.001
Supine:	ND-Ecc-Flex	All Hams CSA	0.430	0.006
	ND-Con-Flex	All Hams CSA	0.443	0.008
		+ G slope	0.593	0.004
	D-Ecc-Ext	Quads CSA	0.775	<0.001
	D-Con-Ext	Quads CSA	0.886	<0.001
Sitting:				
	D-Ecc-flex	All Hams CSA	0.667	0.001
		+ Slope ST	0.769	0.001
	D-Con-flex	All Hams CSA	0.608	0.003
		+ G shift	0.719	0.003
		+ G volume	0.790	0.003
Supine:				
	D-Ecc-flex	G slope	0.889	0.001
		+ G volume	0.978	<0.001
	D-Con-flex	All Hams CSA	0.494	0.031
		+ Shift ST	0.703	0.021
		+ Slope ST	0.871	0.010

Physical Parameters as Predictors

Statistical models based on PA parameters as potential predictors of subjective, functional, strength, and muscle morphology parameters are presented in Table 16. Values at 12-months for D and ND were used in all comparisons.

Subjective

Minutes in MVPA per day was predictive of Tegner scores (r^2=0.574; p=0.001), but there were no predictive models were found for Lysholm or IKDC scores.

Hop Tests

Daily EE was found to be predictive of triple hop on ND (r^2=0.291; p=0.042) and D (r^2=0.331; p=0.044), cross-over hop for ND (r^2=0.265; p=0.042), and also the timed hop for distance on D (r^2=0.331; 0.044). Models for the other hop tests were not significant.

Strength

No PA parameters were found to be predictive of strength on either leg.

Table 16. Predictive models of PA based on 12-month post-surgery outcomes.

Category	Dependent	Model	R^2	p
Subjective	Tegner	Mod-vig active mins	.574	0.001
	Lysholm		NS	
	IKDC		NS	
Function	ND-Single hop		NS	
	D-Single hop		NS	
	ND-Triple hop	EE	0.291	0.042
	D-Triple hop	EE	0.331	0.044
	ND-cross-over hop	EE	0.264	0.042
	D-cross-over hop		NS	
	ND-timed hop		NS	
	D-timed hop	EE	0.331	0.044
Strength	No significant models			
Muscle	ND-Slope of G	Daily steps + bouts of MVPA	0.395	0.019
	ND-Slope of ST	Daily steps	0.323	0.016
	CSA, Volume, proximal shift, slope of D		NS	

SUMMARY OF RESULTS

Subjective

- All subjective Tegner, Lysholm and IKDC scores significantly improved across time points from pre- to 6- and 12-months post-surgery;
- Mean Tegner score increased from 2.3 at 2 weeks pre-surgery (walking on uneven ground possible, but impossible to backpack or hike; light work) to 6.9 (recreational sports such as tennis, badminton, down-hill skiing and jogging at least 5 times per week);
    - Improvement was still significantly less than the mean pre-injury Tegner score of 7.9 (competitive sports such as tennis and running and recreational sports such as soccer, football, hockey and basketball), reflecting a self-identified deficit of 1.25 levels at 12 months;
- There was no significant correlation between the three subjective scores;
- There were no differences in subjective scores between Standard and Contra groups at any time point.

Hop tests

- There were no differences between legs in any of the hop tests at any time point regardless of reconstruction or STG tendon harvest;
- There were no differences in hop test outcomes between the un-injured leg pre-surgery and the reconstructed limbs at 12-months post-surgery;
- Single and triple hop tests were significantly and very highly correlated;
- Cross-over hop test and timed 6 m hop test were significantly and moderately correlated.

Cross-sectional area of muscle

For non-donor limbs:

- SM CSA was significantly greater at 12-months compared to pre-surgery;
- There were early significant reductions in Q, BF, SM, and SA CSA at 2-weeks post-surgery that were recovered by 6-months.

For donor limbs:

- By 12-months post-surgery, total CSA decreased to 89.2% of pre-injury;
- All muscles significantly decreased at 2-weeks post-surgery except AD, and all recovered by 6-months except ST and G CSA;
- ST and G CSA significantly declined across time to 41.5% and 65.5% of pre-surgery;
- A significant reduction in total hamstring CSA was attributable to ST and G, but when they were not included, there was a 4.5% increase in CSA attributable to non-significant increases in BF and SM.

Non-reconstructed limbs:

- ST and G were significantly less at 12-months while SM increased significantly.

For reconstructed limbs:

- Only G was reduced from pre-surgery to 87%.

Four limb conditions combined:

- No muscles significantly exceeded pre-surgery CSA at 12-months post-surgery;
- There were no impacts on CSA at 12-months post-surgery of any muscle in the non-donor limbs regardless of if reconstruction was conducted or not;

- ST and G were significantly less at 12-months post-surgery in both donor limb conditions, but a significant increase in BF was measured only in the donor limb that also underwent reconstruction;
- CSA of ST and G between the two donor limb conditions were not significantly different.

Morphology measures based on multiple images

- There was a 5.7 (2.9) cm proximal shift in ST and 4.2 (2.3) cm in G in the level at which muscle CSA could be detected in the D limbs, and no proximal shift detected in the ND limbs;
- Volume significantly decreased from pre- to 12-months post-surgery for ST in D and G in both ND and D;
- ST and G volumes in both ND and D limbs were significantly smaller at 12-months post-surgery than the volume in the ACL-intact limbs at pre-surgery;
- There were no differences in the slope of the ST and G taper lines for any comparisons between time points or between limbs;
- ST volume was within 20% of pre-surgery in 13 of 17 participants in the ND condition and in only 1 of 17 participants in the D condition;
- Nine of 17 participants had more than an 80% reduction in volume in the D condition compared to none in the ND condition;
- G volume was within 20% of pre-surgery in 14 of 17 participants in the ND condition compared to 3 in the D condition;
- No participants in the non-donor limb and only one participant in the donor limbs had greater than 80% reduction in muscle volume of G from pre- to 12-months post-surgery.

Strength

Knee extensor torque

- As expected, there was a significant velocity effect on knee extensor strength with peak torque decreasing from -270 to 270 deg/s at pre- and 12-months post-surgery for all limb conditions;
- When pre-surgery differences were controlled, there were no differences in knee extensor strength between limbs at 12-months post-surgery.

Knee flexor torque

- Pre-surgery, there was a velocity effect on peak knee flexor torque but not in the expected direction (torque increased from -270 to -150 and also increased across concentric velocities;
    - A 12-months post-surgery and in the difference between time points, no velocity effects were found when comparing ND versus D or NR versus R;
- There were no differences in peak knee flexion torque in the seated position at 12-months surgery or in the change from pre- to 12-months post-surgery between ND and D, NR and R or the four limb conditions;
- In the supine position, there was a significant difference between limbs in peak knee flexion torque with a mean difference of ND being 16.1 Nm greater than D. This did not hold true for NR and R;
- There were no differences in peak knee flexor torque between the donor limbs that underwent reconstruction and those that did not.

Physical activity

- Daily steps increased, but the change was not statistically or clinically significant, and this was true regardless of study group (Contra or Standard);
- Cadence significantly increased from pre- to 12-months post-surgery;
- Patients were found to have comparable activity levels to the general age-matched population, but this level was less than that necessary for a healthy life-style (10,000 steps).

Interactions

- Morphological parameters were predictive of Tegner, IKDC;
- Morphological parameters were predictive of single hop test (Quads CSA);
- Morphological parameters were highly predictive of daily steps (Quads CSA and slope of ST on the non-donor side plus slope of ST and CSA of STG and CSA of all hamstrings on the donor side;
- Morphological parameters were highly predictive of EE (slope and CSA of ST on the donor side, CSA of G on the donor side;
- Morphological parameters are moderately predictive of cadence (volume of G on the non-donor side plus proximal shift of G on the donor side);
- Morphological parameters are moderately predictive of number of MVPA (volume of G on the non-donor side) and the number of minutes in MVPA (volume of G on the non-donor side plus the slope of ST on the donor side);
- Morphological parameters were predictive of strength;
- Quads CSA was moderately predictive of knee extensor strength on the non-donor side and highly predictive of knee extensor strength on the donor-side;

- Eccentric supine knee flexor strength in the donor limbs was highly predicted by G slope and G volume;
- All Hams CSA in addition to one or more other factors were predictive of the other knee flexion strength test outcomes, that is, for concentric sitting strength, the addition of proximal shift and volume of G, concentric supine strength with the addition of proximal shift and slope of ST, and eccentric sitting strength with the addition of slope of ST;
- Minutes in MVPA per day was predictive of Tegner scores (r^2=0.574; p=0.001);
- Daily EE was predictive of triple hop on ND (r^2=0.291; p=0.042) and cross-over hop on the non-donor limb and of the triple hop and timed 6 m hop for the donor limb.

DISCUSSION

The primary finding of this study was that tendon graft harvest, as part of ACL reconstruction surgery, negatively impacted donor ST and G and that the changes in muscle morphology were related to PA, function, strength and self-reported measures. A comprehensive set of parameters related to ST and G muscles was derived, and it was revealed that one or more of each of these parameters on the donor side was related to decreases in knee flexor strength and ongoing post-operative deficiencies in objectively measured PA, hop test outcomes, and some subjective findings. PA was not significantly better than pre-surgery and was low for the expected level of performance return.

Muscle morphometry

The objective to evaluate impact of graft harvest on muscle morphometry of ST and G as the muscles recover from ACL reconstruction and graft harvesting was addressed longitudinally using several different measures, specifically CSA, volume, slope, proximal shift, and proportion of atrophy. As hypothesized, graft harvest had a significant negative impact on all of these measures, with the exception of slope, when comparing between pre- and 12-months. Donor-side ST CSA was dramatically reduced to 41.5% and G CSA was substantially reduced to 65.5% of pre-surgery value, while, as expected, muscle mass on the non-donor side was preserved to approximate pre-surgery size with CSA at 102% and 97.4%, for ST and G, respectively. Preservation of muscle has a dramatic influence on force generation and our findings suggest that the atrophy of ST and G was not solely a product of de-conditioning, but also a lack of specific rehabilitation exercise targeting early preservation and/or restoration of muscle (i.e., hypertrophy-based exercise strategies). That being said, the finding that non-donor muscle did not exceed pre-surgery CSA, likely in a de-conditioned state from pre-injury, indicates a shortfall of recovery to pre-injury status whether a donor limb or not.

In an exploratory process, ten of the muscle morphology parameters (CSA of ST, G, hamstrings less STG, and quadriceps, and ST and G volume, slope, and proximal shift – for donor and non-donor limb conditions) were selected as potential predictors of strength, subjective scores, PA, and hop test outcome. It is interesting to note that ST and G CSA for both donor and non-donor limbs and each of the multi-image parameters were included in at least one predictive model. This supports the notion that the impact of muscle morphological changes is multi-faceted, and these impacts cannot be understood based on any one measure. A much more detailed analysis of the clustering of these muscle parameters needs to be undertaken, as there was significant multi-co-linearity between them. The salient point is that muscle restoration may be an important parameter in relation to functional restoration of the patient. One participant in the study was able to restore ST muscle to within 20% of pre-surgery demonstrating increased recovery is possible. We need to conduct controlled trials examining post-surgery rehabilitation to evaluate improvement in function based on muscle-restoration specific exercises.

The vast majority of previous studies conducted on muscle morphology compared operated to non-operated limb conditions at a post-surgery time point. There is inherent bias in this approach because the non-operated and operated limbs differ, even prior to injury, with respect to ‘dominance,’ potentially reflected in different muscle morphology and in different neuromuscular control. In addition, the non-operated limb experiences some degree of de-conditioning due to inactivity during the wait for surgery and in post-surgery recovery that makes it far removed from representing a pre-injury ‘control’ limb. A longitudinal design including the pre-operative state allows for within-participant analyses increasing the power of the current study and allowing for evaluation of the trajectory of change over time. Comparing pre- to post-surgery does not account for the de-conditioning and other changes that take place in the non-injured limb following the time of initial injury of the opposite leg. If no difference between pre-surgery and post-surgery were found, this is not to say that pre-injury or an ‘unaffected’ state has been restored. Previous studies compared operated to non-operated side with a mean ST CSA across all studies of 63%.[52,59,64,71,72] To be able to directly compare to these other studies, we performed a side-to-side comparison within the standard group of operated (R-D) versus non-operated (NR-ND) limb conditions and found that ST CSA on the operated side was 72% of the non-operated side. In this comparison, ST CSA in both limbs concurrently declined over time, which is a sign of de-conditioning and inadequate exercise progression or lack of compliance with protocol. In contrast, using a longitudinal approach, the CSA of ST was 41.5% of pre-surgery in the donor limbs. Using the longitudinal approach reflected a much greater magnitude of change because we are comparing the current state to the state of the same limb prior to multiple impacts in the ACL management process (i.e., wait time for surgery, wait time for early recovery, etc.).

Recovery is often considered “successful” when the reconstructed limb achieves the same status as the non-reconstructed limb. However, pre-injury status does not equal pre-injury status. Exemplifying this concept, Hiemstra and colleagues found a strength deficit of the reconstructed leg at one-year post-surgery in 24 participants was still up to 50% less than of their age matched peers. [119]

Based on similar principals to Wolff’s Law with respect to bone reformation, it is well understood that the size, physiology, and neural control of a muscle are an adaptation in response to the types and magnitude of stimulation imposed upon it. In the current study, there was significant variability between participants in muscle morphology parameters in both ST and G. The technical aspects of the surgery were not considered to be the sole or even the primary determinant of this variability, because all ACL reconstructions and graft harvest procedures were conducted by a single, experienced orthopaedic surgeon. In ST in the non-donor limbs and G in the donor and non-donor limbs, pre-surgery muscle volume was highly associated with 12-month post-surgery muscle volume. This supports the idea that these muscle volumes may be dependent, at least in part, on post-operative rehabilitation more than the ACL and graft harvest procedure itself. With respect to ST in the donor limbs, pre-surgery volume was not significantly associated with 12-month post-surgery volume, which indicates that something specific in the surgical process or the post-operative environment for re-growth (e.g., proximity of other tissue to provide scaffolding) uniquely impacted ST as opposed to G. Once graft harvest took place, however, two-week post-surgery volume was highly associated with 12-month post-surgery volume, and this relationship was strengthened when controlled for early post-surgery PA, supporting the idea that post-operative stimuli also influence outcome of ST, even if it is more dramatically impacted by graft harvest.

The impact of graft harvest of ST on muscle volume was greater in the current study than previous literature. At 12-months post-surgery, ST volume was 35% of pre-surgery compared to 63 and 58.5% in the two other longitudinal studies identified.[70,71] The reasons for these differences are unclear. One of the previous studies examined participants 9 to 11 years post-surgery so there may have been some opportunity for volume recovery over time.[72] The mean age of participants was about 6 years younger than the current study which may have also had an impact on post-surgery activity level and recovery as they would have still been in a stage of life more likely to pursue athletic endeavors. Another element that sets the current study apart from previous research is that we used a threshold method to accept voxels with 50% or more muscle, thereby rejecting fatty elements. Other studies may have included areas of fatty infiltration in quantification of muscle, thus potentially over-estimating the actual magnitude of CSA, volume, etc. Data from the current study could be used for secondary analysis of the impact of including or not including fatty infiltration in measures of muscle size, but it is worth noting that may have been a contributor in differences between study outcomes.

For both ST and G, a greater impact of graft harvest was seen when measured in terms of volume as opposed to CSA. ST CSA was 41.5% and G CSA was 65.5% of pre-surgery compared volume of 35% for ST and 57.5% for G. So, although significant impacts on muscle are measurable using a one-slice MRI cross-section, there may be some benefit to using volume, as it may be a better representation of functional consequence. From volume, we are still not able to make any statements regarding line of action, force generation, changes in number of articulations, etc., but it may provide additional information that CSA does not. As one example, muscle volume of G in the non-donor limb was included as a significant predictor of moderate to vigorous PA and appeared in conjunction with hamstrings CSA as a significant predictor of two measures of knee flexor strength.

Proximal shift in the current study was also greater compared to another study examining this measure. Proximal shift based on our methodology was measured as the point, distally to proximally, at which muscle (not tendon) could be detected on MRI, unlike previous studies in which it was the point, proximally to distally, at which tendon was detected. We do not expect that this difference in approach is reason for the difference between study findings, 2.7 and 4.7 cm shift in ST and G, respectively in the study by Simonian et al, compared to 5.7 and 4.2 cm in the current study.[63] The populations in the two studies are of similar age and neither was categorized as elite athletes. The difference is likely not due to a simple variance issue between studies and may be a result of differences in graft harvest technique (although technique was not specified in the study by Simonian and colleagues), approach to rehabilitation or both. Certainly rehabilitation protocols to date are not explicit in exercise progressions specifically for hamstrings and do not consider muscle changes beyond atrophy (i.e., what exercise or stimuli would impact tendon regrowth, muscle orientation, connection of muscle to surrounding tissues after tenotomy, etc). In addition, there may be post-surgical stimuli that should be avoided to reduce risk of complete non-regeneration of muscle, as was seen with respect to ST in 9 of our study participants, or perhaps specific stimuli that could be provided to enhance re-growth.

To examine other possible approaches to describe changes in muscle morphology, slopes of the centre-line of ST and G were measured at 12-months post-surgery. This variable was established as another descriptor of the muscle, and was based on the rate of change of CSA over the length of the muscle, beginning from the distal point where muscle was detectable to the proximal insertion on the ischial tuberosity. There were no significant differences found in slope from pre- to post-surgery or between limbs at 12-months post-surgery. However, slope of both ST and G at 12-months post-surgery were captured in the predictive models of daily step count, energy expenditure and some aspects of strength suggesting some functional consequence of this parameter. It may be simply that greater rate of change in CSA by slice resulted in greater CSA in the muscle at the proximal insertion;

however, it may also reflect differences in the line of action of the muscle acting on the knee or hip, or it may reflect in some capacity a more functional point of re-attachment of the tenotomized region. It was not possible to know, as the muscle CSA increases proximally, in what direction or manner the increase CSA is distributed. For example, the marginal CSA may be evenly distributed around the muscle, or shifted to one side or another. Slope was not found to be correlated with any other muscle morphology parameter, but was selected in several predictive models (over other muscle morphology measures) including, daily step count, daily energy expenditure, time in MVPA, and several measures of knee flexion strength. Further study may add greater understanding of the relevance of this outcome, and if it is worth including as a future outcome measure in studies of this nature.

Another novel approach to describing change in muscle morphology was the categorization of the degree of atrophy of ST and G based on percentage reduction in volume at 12-months post-surgery relative to pre-surgery. This approach revealed that both donor and non-donor ST and G muscles were impacted by surgery and time to recovery, that donor muscles are impacted to a substantially greater degree than non-donor muscles, and that the impact on ST is substantially greater than on G. The number of participants who were measured as having no or almost no ST muscle remaining in this study was surprisingly high, with 9 participants of 17 having greater than 80% atrophy relative to pre-surgery, and this degree of atrophy would almost certainly have been even higher if based on a comparison to pre-injury state. This is a substantially higher rate of “failure” than previous studies based solely on tendon regeneration. This is reinforced by the fact that muscle morphology is a predictor of functional indices. Other studies were based on identifying the tendon as being present or absent relying on where it would ‘normally’ be, but there was no means to state the quality of the tendon, to what it was attached, the quality of that attachment, and what force generating capabilities of the muscle to the tendon might be. In the current study, we look beyond the presence or absence of tendon to see if there is actually any muscle that may potentially contribute to force production at the hip and/or knee.

The other limitation of tendon regeneration studies is there is no current method that can reliably track the path of the tendon from the point of insertion, and establish the functionality of this connection. The studies previously conducted that confirm tendon tissue regeneration is possible were a critical step in understanding the initial impact of tendon harvest; however, further examination of what force is generated through the tendon and the line of action of the forces is needed. Detailed high resolution MRI or 3D computer tomography studies may allow for models to be developed. Possibly cadaveric work can be performed to help understand functionality using modeling, as well as electrical stimulation of the involved muscle and examining tension through in-line optical force sensors in what is thought to be the involved tendon may be a useful next step.

The other interesting finding of the current study is that the degree of atrophy was substantially different between ST and G. Only one participant had greater than 80% atrophy in G while, while 9 of 17 experienced virtually complete atrophy of ST. The graft harvest of the two tendons was essentially the same, and yet some aspect of G protected it from the dramatic loss that ST experienced. For example, there may be some relationship between G and its proximity to other tissues that can serve as scaffolding upon which to attach and recover compared to ST that may not have that same support from other structures. Alternately, the type of loading placed on G early post-operatively as an adductor versus ST acting mostly in flexion may play a role. Three study participants reported experiencing a sensation of a “pop” or strain in the hamstring region early post-surgery (prior to the 6-month follow-up), and coincidentally, all of these participants were among those with no detectable ST. It is conceivable that the location of re-attachment or the type of loading on G differs and somehow provides some degree of protection from disruption in the early stages of re-attachment and re-growth. Anatomical study of the pathway of the two muscles and their surrounding structures may shed light on providing ST with adequate scaffolding upon which to re-grow.

Subjective Scores

The improvement in subjective scores in the current study from pre- to post-surgery is consistent with other longitudinal studies.[58,71,75,85,120,121] Post-surgery Lysholm and IKDC scores ranged between 80 and 95% reflecting normal or nearly normal self-report of function and symptoms. One limitation of the Lysholm scale is the impact of a ceiling effect, measured in one recent study as 70%., based on the proportion of 47 post-ACL reconstruction participants scoring between 90 and 100%. [122] In our study, a comparable 64% of participants scored themselves at this level. The IKDC subjective score also has been shown to have a ceiling effect of 55% in a previous study of 35 participants.[123] The ceiling effect of the IKDC score in the current study was 41%. Both the Lysholm and IKDC scores are validated, and widely used with an ACL reconstructed population; however, they represent more of a “lack of disability” or improper functioning of the knee rather than a subjective measure of ability or proficiency in movements required for return to support. Tegner scores in the current study ranged between 5 and 8. Although impacted to some extent by the ceiling effect of Lysholm and IKDC scores, the lack of correlation between the three subjective scores suggest that high Lysholm and IKDC subjective scores do not necessarily translate into high Tegner activity scores. In other words, lack of symptoms (pain, instability) and self-reported ability to perform functions such as cutting and pivoting, without taking into account quality and intensity of these tasks, does not mean that an individual has returned to their pre-injury level of play or PA. A study by Peterson and colleagues reported mean pre-injury Tegner activity score as 7, pre-surgery as 3, one-year post-surgery as 5 and 4-years post-surgery as 6.[85] Another study by Volpi and colleagues reported mean pre-injury Tegner score as 8, and then post-surgery as 7.[124] The current study reported a significant drop of 1.25 levels from pre-injury to 12-month post-surgery demonstrating that current rehabilitation protocols are not restorative. This decrease represents a substantial negative impact on activity level, possibly shifting an individual from the level of elite to recreational athlete, from contact and/or impact sports to only non-impact sports, from moderate to light work duties, etc. The self-reported Tegner score was the only subjective measure that was highly significantly associated with objectively measured PA. Patients were asked at each study time point to recall their activity level at pre-injury, and interestingly, there was no difference in these Tegner scores between pre- and post-surgery time points. This suggests that participants remained aware of their earlier level of activity, and have somehow adapted to or rationalized their new post-operative limitations.

Strength

Significant knee flexor strength deficits were detected in the current study in a hip-neutral position with a mean difference of 16.1 Nm (approximately 10% less than the non-donor limb). The bi-articular hamstring muscles are in a shortened position when the hip is neutral and the knee is flexed, and so even in the unaffected knee, knee flexor strength is considerably lower in this position as a result of the force/length relationship. STG graft harvest seemingly exacerbated this, perhaps due to a shift from being bi- to “uni-articular” or minimally through a change in the line of action and overall length depending on the point and quality of reinsertion. In sitting, it is possible the mechanics of other muscles such as semimembranosus and the adductors allow for a certain degree of compensation for the limitations of ST and G while the ability of other muscles to compensation when the hip is in neutral are more limited. There would be less sarcomeres in series to begin with and the ST and G muscles must retrain in this new shortened position through learning to reintegrate muscle sensor signals as well as adapt sarcomere number to the new resting state. The golgi tendon organs and muscle spindles would have been disrupted as well, resulting in potentially decreased activation of the motor neurons activating the muscle cells.

Deficits in strength in this position have functional implications as the hip is in neutral or extending when one is running or jogging, stepping up stairs, stepping over something on the ground, and others. Of note in the current study is that knee flexor strength improved over time for both the ND and D limb conditions; however, strength actually declined over time for both limbs in a hip-neutral position, with the impact on the D limb being greater in magnitude than on the ND limb. Rehabilitation protocols must incorporate exercises that focus on knee flexion strength in a hip neutral or extended position, particularly with increased knee flexion where the hamstrings are at their shortest length. Transition to functional activities in standing are key, but special attention must be paid to limit compensatory motions in cases where the knee flexors are too weak to function. These can include hip circumduction or elevation and increased hip flexion while flexing the knee.

Some previous studies of knee flexor strength in a seated position described persistent deficits of 10 to almost 30% but these were based on cross-sectional data comparing side-to-side.[51,52,58,63,64,74,75] It could be that pre-operative de-conditioning reduced the strength of the operated limb more than the non-operated limb and that both limbs recovered equally but that those early deficits were still detectable, creating a side-to-side difference. Knee flexor strength deficits in the seated position were not detected in the current study nor in a previous study conducted by the same researchers on a similar population.[66]

Knee extensor strength in the current study followed the expected velocity-strength curve, but this was not true for knee flexor strength. Normally, eccentric strength is greater than concentric with concentric strength decreasing with increasing velocity.[119,125] In the comparison of donor versus non-donor limb conditions, concentric strength was greater than eccentric strength and concentric strength increased with increasing velocity. This was not only true post-surgery, but pre-surgery as well. Interestingly, in the comparison between reconstructed and non-reconstructed limbs, knee flexor strength in the non-reconstructed limb pre-surgery, in other words the 'unaffected' limb, reflected a more typical torque-velocity relationship. The unusual torque -velocity curve at pre-surgery in the ACL deficient limb may be a reflection of the disruption in neural regulation that still has not resolved by 12-months post-surgery, and is exacerbated in the conditions that included STG graft harvest. A lack of functional neuromuscular retraining may be one of the causes. Of concern is that an eccentric deficit would manifest in many circumstances that would be deleterious to performance in landing or even cutting maneuvers.

Quadriceps CSA in isolation was moderately predictive of knee extensor strength while hamstring CSA was moderately predictive of knee flexor strength. As well, each of the multi-image muscle parameters for ST and G, except ST volume, was included as an additional predictive variable in at least one of each of the models for knee flexor strength (eccentric, concentric, seated, hip-neutral). Given the difference in size of ST and G, and given their parallel roles as knee flexors, the predominance of parameters related to the morphology of G in predicting knee strength was unexpected. One plausible reason for this outcome is that G was impacted by graft harvest to a lesser extent than ST. The neural control of G may be more effective and/or the muscle may be in a better mechanical position to contribute and may cross the knee joint line more consistently than ST, and thus still act on the knee joint.

Hop tests

As a well-used measure of function following post-surgery in ACL surgical studies, a series of four hop tests were incorporated into the current study. Pre- to post-surgery comparisons could not be conducted, as patients did not perform hop tests in their ACL deficient limb prior to surgery. There were no side-to-side differences between limbs at 6 months or 12-months post surgery, and there were no differences between post-surgery donor, non-donor, reconstructed, or non-reconstructed limbs when compared to the pre-surgery ACL-intact limb as a proxy for pre-injury status. The pre-surgery ACL-intact limb likely experienced de-conditioning and change in performance from the time of injury, so to say that there was no difference between hop test outcomes for this limb and hop test outcomes for the four limb conditions at 12-months post-operative does not indicate a necessarily positive result, and in fact, could be interpreted as a negative impact. As there were no differences between limbs at 12-months post-surgery, there was no identified hindrance to function that could be attributed to the healing process of the ACL or of the graft donor site in this population. But, there was no betterment of hop test performance from the less than optimal “pre-injury proxy” despite whatever therapy was undertaken.

Participants should have exceeded this level, particularly by 12-months post-surgery, as they were already "cleared" to return to play. Reduced knee flexor strength in a hip neutral position may have played a role in the lack of improvement. Also, although plyometric training (e.g., box jumps, bounding) was listed in the rehabilitation protocol provided, no progression was recommended to the patient/therapist and compliance to the protocol is unknown. Interestingly, the only muscle morphology parameter found to be predictive of hop test outcome was Quads CSA and this only applied to the single hop test. The fact that such an association was only significant for the most basic hop test may be evidence of only limited confidence or ability to hop. The need for adequate agility and cutting training exists to prevent future injury and maximize return to play proficiency.

Daily energy expenditure was found to be significantly associated with triple hop and timed hop for distance outcomes in the donor limb and triple hop and cross-over hop outcomes in the non-donor limb conditions. As such, the performance of the high acceleration activities was predictive of higher energy expenditure per day which may be a result of greater confidence in higher level movement.

Physical Activity

Contrary to our hypothesis, PA did not improve statistically from pre-surgery level. Furthermore, PA was likely less than pre-injury even at 12-months post-surgery. This finding was reflected in the self-reported level of activity reported using the Tegner scale wherein activity level improved from pre-surgery to post-surgery, but did not recover to pre-injury levels. PA of our population did not differ from their age-matched peers. This is not to say that our participants were achieving a level of PA conducive to a healthy lifestyle. The majority of patients only met the recommended 10,000 step minimum for two days or less in the week PA was evaluated. This PA level was not what was expected given the moderately active designation reflected in patients self-reported activity level on the Tegner scale. A “clinically relevant” change in activity was previously defined as an increase in 2,000 daily steps and this threshold was not met in the current study.[115–118] Although this threshold is not based specifically on improvement following knee injury or ACL reconstruction, it should be noted that 2,000 steps is equivalent to approximately one mile of walking and even this modest improvement in PA from pre-surgery to 12-months post-surgery was not achieved.

Many outcome measures, subjective or functional, are oriented toward meeting return to play criteria, for example, the ability to cut, pivot, and accelerate rapidly. With the ACL reconstructed population, very little emphasis has been placed on return to a generally physically active lifestyle. As the current study shows, in the moderately active study population (based on Tegner scores, i.e., self-report), participants not only did not return to a physically active (12,500 steps per day) or healthy lifestyle (10,000 steps per day), and they did not return to their pre-injury activity level. One mile of walking is equivalent to approximately 2,000 steps and is considered a ‘clinically relevant’ improvement. The participants in this study, on average, fell short of adding the equivalent of one mile of walking per day to their activity levels after one year of rehabilitation. Patients could potentially be more reluctant to undergo surgery if they were given the understanding that they would make little gain in PA from their pre-surgery state. Health care providers need to have discussions with patients pre-operatively to make them articulate their expectations of surgery, and make them aware of possibly pitfalls of waiting for surgery, such as becoming less active, and then not putting in the time or effort to recover to their fullest capacity. This means both return-to-play and return to an active lifestyle. It may even be beneficial as part of their pre-surgery process to measure patients' daily step counts and use that as starting point that they should aim to surpass in the post-surgery period.

Standard versus Contralateral Graft Harvest

In the current study, participants were randomized to the standard approach to surgery with one limb undergoing both ACL reconstruction and tendon harvest and the other remaining surgically unaffected, or to undergo the less common approach in which ACL reconstruction takes place on one side, and tendon harvest is conducted on the other. All four limb conditions were compared, but the data was also collapsed to allow comparisons between limbs that underwent reconstruction or not, and to compare between limbs that underwent tendon harvest or not. This group collapse increased power (by doubling n size), and was performed only after the between group comparison illustrated that the differences were not statistically different. It was confirmed that impacts on muscle morphology and strength were detectable more on the basis of being in the graft donor condition than having undergone reconstruction of the ACL. When comparing the four limb conditions, the two conditions that involved graft harvest had similar outcomes regardless of whether reconstruction had taken place or not. Furthermore, there was little difference between the 'unaffected leg' and the leg that underwent reconstruction with no graft donation. One previous study examined tendon harvest ipsi- and contralateral to the ACL deficient knee with the aim of isolating the impacts of reconstruction from the impacts of graft harvest.[64] Similar to the current study, strength of knee extensors was unaffected by harvest of ST and G. Knee flexor strength, tested only in the seated position, decreased in the graft harvest limbs and then recovered by about 9 months post-surgery. Another more recent study comparing ipsi- and contralateral graft harvest found no difference in ACL-Quality of Life outcome scores at 2-years post-surgery, no differences in knee extensor strength, and decreased knee flexor strength that resolved by 3-months post-surgery across slow (60 deg/s) to rapid (240 deg/s) concentric velocities. Once again, knee strength testing was conducted only in a seated position. By introducing graft harvest from the limb contralateral to the ACL deficient leg, early and comprehensive rehabilitation of the harvested ST and G is possible, as patients are not restricted by post-surgery limited range of motion, and having to protect the newly reconstructed ligament. In comparisons in the current study between the Standard and Contra groups, no differences were found in PA, strength, hop tests, or subjective outcomes, that is, no drawbacks to contralateral graft harvest were identified. Although no clear benefits were identified with this approach either, the rehabilitation protocol utilized in the current study was not designed to take advantage of the possible benefits of early targeting of STG rehabilitation. Given the significant and wide-reaching impacts of changes in muscle morphology identified herein, further exploration into contralateral graft harvest with a properly designed rehabilitation protocol to take advantage of managing these impacts early and in isolation may be beneficial.

Limitations

One limitation of the current study was that the end point was 12-months post-surgery. With respect to changes in muscle, there is evidence from previous literature that tendon regeneration can continue to 24-months and beyond, and also that the trajectory of some outcomes may not have plateaued (e.g., strength, PA). But, patients are considered to have the ability to be fully functional (although not evaluated by proficiency tests) by 12-months post-surgery with standard protocols (including the on utilized in this study) supporting full return to play by 9 to 12 months. Longer-term follow-up would not have changed the findings and clinical implications of the current study, however, evaluations at 24-months and beyond would further add to our understanding of the trajectory of recovery. Pursuing further evaluations such as progression in muscle loss/gain, strength, and PA of our patient group are proposed.

The objective of this study was to establish that morphological changes are relevant to subjective and functional outcomes and now that the presence of such associations has been established, more work can be done to narrow down the identified predictive models, if possible, and create interventional studies to determine causality. At this point, we cannot assert that because one parameter was selected as part of a significant predictive model, that it should be the focus of an intervention with the goal of more positive functional outcomes. That being said, which specific factors are most important may not have great clinical relevance as many would change for the better with adherence to properly designed, comprehensive rehabilitation protocols.

The use of accelerometers, albeit a much more credible means of collecting PA than self-report or pedometry, has some limitations. Activity using some exercise modalities would not be captured by an accelerometer, for example, swimming and biking. This may have led to an underestimation of activity level, particularly at 6-months post-surgery when these modalities are incorporated in early rehabilitation of ACL reconstruction. However, our study population reported participation in land-based sports (i.e., hockey, basketball, dodgeball, ultimate), so the impact of this would be minimal.

Finally, several study outcomes may have been influenced by life events and/or changes other than the ACL surgery, for example, marriage, children, change in job.

Anecdotally, several participants commented on these as having impacted their rehabilitation and overall activity level; however, formal data collection related to this was not done. We did not ask participants to record their day-to-day rehabilitation activities or complete any form of compliance log; therefore, we are not able to examine the types and quantity of stimuli that resulted in their eventual level of recovery. It would not have changed the outcomes of the study; but it would have provided further insight into what type of guided input each individual sought, and the priority they placed on formal rehabilitation.

Generalizability

The population of the current study was moderately active ACL deficient individuals between 18 and 50 years old, with an average age of 29.2 years. The findings presented herein are not likely generalizable to a highly active and motivated population or populations that have greater access to guided rehabilitation, for example, elite athletes. Also, the current study findings are probably not generalizable to patients that undergo ACL reconstruction utilizing another graft type. This is because the majority of changes in muscle morphology were attributable to donor harvest as opposed to the reconstruction itself. That being said, it may be possible to extend the findings with respect to PA to those for whom another graft type was used because the same aspects of de-conditioning and other inadequacies of current rehabilitation approaches would apply.

All ACL reconstructions on patients included in analyses for this study were conducted by one experienced, fellowship trained orthopaedic surgeon. This may limit the generalizability of the current study findings to surgeons with less experience, or to those with different technical approaches; however, this also minimized variability imposed by between-surgeon differences.

CLINICAL IMPLICATIONS

Our moderately active population fell short of achieving optimal patient outcomes. This could have arisen due to any combination of factors including inadequate post-operative protocol design, lack of patient compliance, insufficient patient education, lack of adequate guidance, and re-prioritization of PA and level of return-to-play by the patient. There are many reasons to undergo ACL reconstruction surgery including reestablishing knee stability, minimizing risk of injury to other structures in the knee (e.g., menisci), and reducing post-operative risk of osteoarthritis. But we must ensure that patients understand that undergoing surgery alone will not return pre-injury neuromuscular performance and daily PA, and that long term dedication to a thorough post-operative rehabilitation program is necessary to optimize outcomes. The milestones typically outlined in rehabilitation protocols for ACL reconstruction take into account pain, swelling, range of motion, proprioception, strength, agility, and return to sport. With potentially months from the time of injury to surgery to recovery, changes not only in these factors, but also in overall PA may be affected. Patients may not be aware that their level of activity has drifted to become more sedentary and goal setting around returning patients to pre-injury status, and beyond pre-surgery status must be a priority. There is a need for focused neuromuscular retraining (e.g., agility, cutting) based upon our hop test findings as well as targeted muscle hypertrophy exercises based on the degree of muscle loss found in our muscle parameters. The application of adequate stimuli should provide an optimal environment in which both the reconstructed ligament can heal and the other significantly impacted structures can be restored and even enhanced.

Our study population represents what some may consider a ’typical’ ACL reconstruction patient who is interested in returning to activity, but whose motivation may be not as high as say, an athlete representing their university or one competing at a national level. Furthermore, this ‘typical’ ACL patient likely has only limited access to physiotherapy, with most being restricted by the threshold of third-party payer insurance companies that typically allow for approximately 10 treatments within a calendar year. Interestingly, in a survey study of Canadian surgeons conducted in 2009, almost 40% indicated that the recommended duration of physiotherapy was between 6 and 12 weeks with another 40% recommending between 12 and 24 weeks. At 24 weeks post-surgery, the muscle adaption process in response to surgery and graft harvest is still ongoing and a majority of patients would have only been given permission to begin participation in return-to-play activities. It is key to discuss patient expectations regarding the outcome of surgery, and provide early education regarding compliance to properly designed and executed rehabilitation protocols and emphasize overall activity beyond pre-surgery status. It may be beneficial to evaluate the impact of physiotherapy guidance over a longer duration of the rehabilitation phase, but keeping within the allotted treatments available to a patient. Barring any post-surgical complications, time in physiotherapy-guided treatment during early recovery to regain range of motion and reduce swelling may be better spent in the later stages where specific return to sport training can potentially reduce, enhance performance, and help individuals regain confidence.

A mainstay of post-operative clinical evaluation is knee extensor and flexor strength using dynamometry or based on manual muscle testing, but most often evaluated in a hip flexed position. From the current study, health care practitioners must be aware that strength deficits may not be notable until knee flexor strength is tested in a hip-neutral position. Ongoing deficiencies in knee flexor strength when the hip is in neutral or in extension can have significant functional implications. Fundamental motions can be impacted as a result, such as ascending and descending stairs, stepping over objects, even walking and running involve knee flexion in a hip-neutral or extended position. Deficient knee flexor strength at the level measured in this study should be addressed in aspects of the rehabilitation process in order to reduce strength or, at least, maximize function. One of the more concerning findings of this study was that beyond the identified deficit in knee flexor strength at 6-months post-surgery, knee flexor strength in hip-neutral position actually declined even though knee flexor strength in the sitting position continued to increase. This may reflect a shift from targeted rehabilitation early post-surgery with a guided protocol versus the ‘return to play’ stage in which basic post-operative exercises such as knee curls may no longer be a priority. There are innumerable exercises and functional activities that can be undertaken from early post-surgery to months after that maximize knee strength and other facets of recovery that need to be a part of a comprehensive, long-term rehabilitation plan.

FUTURE DIRECTIONS

It would be valuable to pursue conducting the same study as above, but on an elite athlete population. It would allow us to extend our understanding of the relationships between muscle change and outcomes that were described herein. One might expect that these same relationships would be found as the majority of changes were resulting from a stimulus-response. However, given the participants were only moderately active, examining the elite athlete population would allow us to extend our understanding to the level of response to higher degree of stimuli and if other barriers exist and/or if the relationships between muscle morphology and strength, function, and subjective measures are maintained. This would not only be relevant to the elite population, but would confirm that the response to stimuli in a moderately active population would lead to more positive outcomes if the stimuli were of greater magnitude and more comprehensive.

Another proposed future study would be to evaluate PA patterns of those that are highly motivated and that begin in a more highly active state pre-injury. Examining the time course of recovery would provide elite athletes with information and possibly re-assurance in what to expect in the early post-operative period. From this stand point, other studies in the area of sports medicine orthopaedics that incorporate objective PA measurement would provide valuable information to health care providers, for example, surgery to repair or remove a torn meniscus.

As one aspect of improving post-ACL recovery, an intervention study utilizing pedometry or accelerometry to monitor and set milestones for PA in a moderately active population would also be worthwhile. The cost of these measurement tools has become very reasonable and there are several examples of intervention studies in which PA has been enhanced through daily tracking, goal setting, etc.[116,117]

Return to play is a clear aim of ACL reconstruction surgery, but the fundamental goal to maintain or improve on a healthy lifestyle through PA can and should also be a priority in this population. As a next step in the development of improved rehabilitation protocols, conducting a survey of practicing physiotherapists regarding their approaches, priorities, and preferences would be useful. It would provide information regarding what post-operative restrictions are placed on patient activities, what and how milestones are set and achieved, and what tools to maximize compliance are used. Another information-gathering study that would be useful is to compile and synthesize ACL rehabilitation protocols from practicing surgeons. Improving rehabilitation protocols would be more efficient if looking at what approaches are currently considered ‘standard of care’ and building upon them.

In the longer term, there is a great need to conduct an intervention study comparing current approaches to rehabilitation to a well-designed, comprehensive, physiotherapy-led protocol; however, the resources needed and the logistics to perform such a study may be prohibitive. The current findings indicate that the impacts of ACL reconstruction using ST and G tendon autograft are largely due to the graft harvest. However, our findings also support that recovery is limited, at least in part, by lack of adequate stimuli. It remains unknown why ST completely atrophies in some patients, and not in others. It was also demonstrated in our findings that the presence of ST does not ensure positive outcomes nor does the absence of ST ensure negative ones. As part of this intervention study, it would be worthwhile to include a group of participants that undergo contralateral graft harvest to see if early, isolated rehabilitation of the ST and G muscles enhances patient outcomes.

CONCLUSIONS

Changes in muscle morphology following tendon harvest of ST and G in ACL reconstruction were found to be related to measured decreases in knee flexor strength, and ongoing post-operative deficiencies in objectively measured PA, hop test outcomes, and subjective findings at 12-months post-surgery. This study was prospective and longitudinal in nature, and examined interactions between several elements of post-surgery recovery more extensively than previously undertaken. The components of muscle morphology described were CSA of all thigh muscles, ST and G volume, proximal shift of the point at which muscle was detectable in the thigh, and each of these elements was shown to be predictive of other outcomes. This is also the first-ever study of objectively measured PA in an ACL deficient/reconstructed population. PA was shown to not significantly or clinically increase from pre- to 12-months post-surgery in the moderately active population studied.

Milestones typically outlined in rehabilitation protocols for ACL reconstruction take into account pain, swelling, range of motion, proprioception, agility, strength, and return to sport. With potentially months from the time of injury to surgery to recovery, the muscles in the ACL deficient limb, and in particular, the muscles that act as graft donors, must adapt to a series of critical impacts. Furthermore, patients may not be aware that their level of activity has drifted to become more sedentary. It is key to discuss patient expectations regarding the outcome of surgery, and provide early education regarding compliance to properly designed and executed rehabilitation protocols and emphasize overall activity beyond pre-surgery status.

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APPENDIX 1: ACL REHABILITATION PROTOCOL

Post-Op ACL Reconstruction Protocol
Week 1

General Observation	Weight bearing with 2 crutches when:	
	- Postoperative pain is controlled	
	- Hemarthrosis is controlled	
	- Voluntary quadriceps contraction	
Evaluation	- Pain	Controlled
	- Hemarthrosis	Mild
	- Patella mobility	Good
	- ROM / minimum	10 - 90°
	- Quadriceps contraction & muscle spasm / patella migration	1 cm
	- Soft tissue contraction	Normal
Treatment	- Patella mobilization	
	- Active quadriceps isometrics	
	o ROM	Full extension
	o Sets x reps	1 x 10
	o Hold	10 seconds
	- Balance training	
	o Wt. Shift - side/side	
	o Wt. Shift - forward/back	
	o Lateral step ups / 2 to 4 inches	
	- Straight leg raise (weight above knee)	
	o Flexion	5 x 10
	o Extension	5 x 10
	o Abduction	3 x 10
	o Adduction	3 x 10
	- Heel raise / toe raise	3 x 10
	- Knee extensions (active assisted)	
	o ROM	90 - 30°
	o Sets x reps	3 x 10
	- Hamstring stretches	
	o Sets x reps	1 x 10
	o Hold	10 - 30 seconds
	- Gastroc-Soleus stretches	
	o Sets x reps	1 x 10
	o Hold	10 – 30 seconds
	- Ankle pumps	5 minutes
	- Ankle work with theraband	5 minutes
Goals	- Muscle stimulation if unable to do quads set	15 minutes
	- ROM 0 - 90°	Utilization
	- Adequate quadriceps contraction to control ROM	2 – 3 visits
	- Control inflammation & effusion (home modality)	
	- 25 – 50% full weight bearing (must control abnormal mechanics)	

Post-Op ACL Reconstruction Protocol
Weeks 2-3

General Observation	Weight bearing with cane when: - Pain is controlled without narcotics - Effusion is controlled - ROM 10 - 100° - Muscle control throughout ROM	
Evaluation	- Pain	Mild
	- Effusion	Minimal
	- Patella mobility	Good
	- ROM	0 - 125°
	- Muscle control	3/5
	- Active extension	Excellent
	- Inflammatory response	None
	- Assess need to perform joint mobilization	
Treatment	- Patella mobilization	5 minutes
	- Belt isometrics*	
	o Mode	90, 60 and 30°
	o Speed	None
	o Sets x reps	2 x 10
	- Balance training	
	o Wt. Shift - side/side	5 sets x 10 reps
	o Wt. Shift - forward/back	5 x 10
	o Balance board 2 legged	3 – 5 minutes
	o Lateral step ups / 2 to 4 inches	5 x 10
	- Straight leg raise (weight above knee)	
	o Flexion (sets x reps)	5 x 10
	o Extension	5 x 10
	o Abduction	5 x 10
	o Adduction	5 x 10
	- Heel raise / toe raise	5 x 10
	- Knee extensions (no resistance)	
	o ROM	90 - 40°
	o Sets x reps	5 x 10
	- Hamstring stretches	
	o Sets x reps	1 x 10
	o Hold	10 – 30 seconds
	- Ankle pumps	5 minutes
	- Mini-Squats	
	o ROM	0 – 30 °
	o Sets x reps	3 x 10
	- Hamstring curls	3 x 10
	- Wall slides	
	- Bike (for ROM)	10 minutes
Goals	- ROM 0 - 125°	Utilization
	- Muscle control (available ROM)	4 - 6 visits
	- Control inflammation & effusion to prevent scarring	
	- 50 - 75% full weight bearing	
*Belt Isometrics – with knee bent to appropriate position, patient pushes into extension against resistance of belt / strap (no movement)		

Post-Op ACL Reconstruction Protocol
Weeks 4-5

General Observation	Independent ambulation when:	
	- Pain is controlled	
	- Effusion is controlled	
	- ROM 5 - 115°	
	- Muscle control throughout ROM	
	- Joint arthrometer results within 2 mm	
Evaluation	- Pain	No RSD
	- Effusion	Minimal
	- Patella mobility	Good
	- ROM	0 - 125°
	- Muscle control	4/5
	- Extension	Complete
	- Inflammatory response	None
	- Gait	Symmetrical
Treatment	- Patella mobilization	5 minutes
	- Belt isometrics	
	o ROM	90, 60 and 30°
	o Repetitions	3 x 10
	- Standing hip isotonics with tubing	
	o Flexion	3 x 30
	o Extension	3 x 30
	o Abduction	3 x 30
	o Adduction	3 x 30
	- Balance training	
	o Two –legged balance board	3 sets x 6 minutes
	o Lateral step-ups – 4 inch	5 x 10
	- Straight leg raise (weight above knee)	
	o Flexion	3 x 20
	o Extension	3 x 20
	o Abduction	3 x 20
	o Adduction	3 x 20
	- Mini squats	
	o ROM	0 - 30°
	o Sets x reps	3 x 10
	- Eccentrics (Step downs)	3 x 30
	- Knee extensions	
	o ROM	90 - 30°
	o Sets x reps	5 x 15
	- Hamstring curls	5 x 15
	- Leg press 10 - 45°	5 x 15
	- Gastroc-Soleus stretches	
	o Sets x reps	1 x 10
	o Hold	10 – 30 seconds
	- One legged calf raise	
	o Flat	3 x 45
	o Progress to step	
	- Hamstring stretches	1 x 10
	o Sets x reps	10 – 30 seconds
	o Hold	300 feet / 20 minutes
	- Tube walking	300 feet / 20 minutes
	- Water walking	15 minutes
	- Bike	
Goals	- ROM 0 – 135°	
	- Maintain ROM	
	- Muscle endurance	
	- Control inflammation & effusion to prevent scarring	
	- 100% full weight bearing with a normal gait	
	- Early recognition of complications (motion loss, RSD, laxity)	

Post-Op ACL Reconstruction Protocol
Weeks 6-12

General Observation	- No effusion: Painless ROM: Joint stability - Performs activities of daily living & can walk 20 minutes without pain - Range of knee motions, 0 - 125° - Full weight bearing	
Evaluation	- MMT	
	o Hamstrings	
	o Quadriceps	
	o Hip abductors	
	o Hip adductors	
	o Hip flexors	
	o Hip extensors	
	- Biodex isometric test (mean avg. torque / % deficit)	
	o Quadriceps (agonist)	30° - knee ext - conc
	o Hamstring (antagonist)	quads
	- Swelling	30° - knee ext - ecc
	- Patellar mobility	hams
	- Crepitus	None, slight, good
Treatment	- Standing hip isotonics with tubing	
	o Flexion	3 x 30
	o Extension	3 x 30
	o Abduction	3 x 30
	o Adduction	3 x 30
	- Leg press 10 - 45°	3 x 10
	- Balance training	
	o Two –legged balance board	5 – 10 minutes
	o One – legged balance board	5 – 10 minutes
	- Straight leg raise (progress weight distally)	
	o Flexion	3 x 30
	o Extension	3 x 30
	o Abduction	3 x 30
	o Adduction	3 x 30
	- Mini squats	
	o ROM	0 – 40°
	o Sets x reps	3 x 15
	- Eccentrics (Step downs)(increase height)	5 x 10
	- Knee extensions	
	o ROM	90 - 30°
	o Sets x reps	5 x 15
	- Hamstring curls	5 x 15
	- Gastroc-Soleus stretches	
	o Sets x reps	
	o Hold	1 x 10
	- One legged calf raise	10 – 30 seconds
	o Flat	
	o Progress to step	3 x 45
	- Hamstring stretches	
	o Sets x reps	1 x 10
	o Hold	10 – 30 seconds
	- Aerobic conditioning	
	o Stepping / elliptical trainer	10 minutes
	o Cross country ski device	20
	o Water running	20
	o Walking	20
	o Bike	15 – 20
	o Fitter	5 minutes
	o Mini tramp	5 minutes
	• hopping	
	• 2 foot	
	• alternate	
	• 1 foot	
	• stick loading	
Goals	- Increase strength and endurance so there is no fatigue with ADL	

Post-Op ACL Reconstruction Protocol
Weeks 13-24

General Observation	- No effusion: Painless ROM: Joint stability - Performs activities of daily living & can walk 45 minutes without pain - Range of knee motions, 0 - 125° (should be full) - Full weight bearing	
Evaluation	- Biodex isokinetic test (peak torque, % difference) o Quadriceps o Hamstring - Swelling - Patellar mobility - Crepitus	 20 – 25 20 – 25 None Good None/slight
Treatment	- Leg press - Standing hip isotonics with tubing o Flexion o Extension o Abduction o Adduction - Straight leg raise (progress weight distally) o Flexion o Extension o Abduction o Adduction - Mini squats o ROM o Sets x reps - Knee extensions o ROM o Sets x reps - Eccentrics – step downs (increase height) - Hamstring curls - Gastroc-Soleus stretches o Sets x reps o Hold - One-legged calf raise o Flat o Progress to step - Hamstring stretches o Sets x reps o Hold - Aerobic conditioning o Stepping / elliptical trainer o Cross country ski device o Water running/walking o Walking o Bike - Running program o Jog o Walk o Backward walk - Plyometric training o Box jumps / 4 inch platform o Single or double leg bounding o Rope skipping - Fitter - Mini tramp o hopping o 2 foot o alternate o 1 foot o stick loading	3 x 10 3 x 30 3 x 30 3 x 30 3 x 30 3 x 30 3 x 30 3 x 30 3 x 30 0 - 40° 5 x 10 90 - 30° 5 x 15 3 x 20 5 x 15 1 x 10 10 – 30 seconds 3 x 45 3 x 20 1 x 10 10 – 30 seconds 20 minutes 20 – 30 20 – 30 20 – 30 15 – 20 begin week 20 – 24 1/4 mile 1/8 mile 20 yards 3 x 15 – 20 10 – 30 yards 3 x 10 5 minutes 5 minutes
Goals	- Increase strength and endurance of lower extremity for limited activity	

Post-Op ACL Reconstruction Protocol

Weeks 25-52

General Observation	- No effusion: Painless ROM: Joint stability	
	- Performs activities of daily living & can walk 60 minutes without pain	
	- Range of knee motions, full	
	- Full weight bearing	
Evaluation	- Biodex isokinetic test (peak torque, % difference)	
	o Quadriceps	15
	o Hamstring	15
	- Swelling	None
	- Patellar mobility	Good
	- Crepitus	None / Slight
	- Function tests	
	o One-legged distance hop (% involved/uninvolved)	90% of distance of uninvolved one-legged hop
	o One-legged timed hop	
Treatment	- Leg press	
	o Mode	Isokinetic
	o Repetitions	3 x 10
	- Standing hip isotonics with tubing	
	o Flexion	3 x 30
	o Extension	3 x 30
	o Abduction	3 x 30
	o Adduction	3 x 30
	- Straight leg raise (weight at ankle)	
	o Flexion	3 x 30
	o Extension	3 x 30
	o Abduction	3 x 30
	o Adduction	3 x 30
	- Mini squats	
	o ROM	0 - 40°
	o Sets x reps	5 x 10
	- Eccentrics – step downs	3 x 30
	- Knee extensions	
	o ROM	90 - 30°
	o Sets x reps	3 x 15
	- Hamstring curls	3 x 15
	- Gastroc-Soleus stretches	
	o Sets x reps	1 x 10
	o Hold	10 – 30 seconds
	- One-legged calf raise	3 x 20
	- PNF	
	o Flexion	3 x 10
	o Extension	3 x 10
	o Abduction	3 x 10
	o Adduction	3 x 10
	- Hamstring stretches	
	o Sets x reps	1 x 10
	o Hold	10 – 30 seconds
	- Aerobic conditioning	
	o Stepping / elliptical trainer	20 minutes
	o Cross country ski device	20 – 30
	o Water running/walking	20 – 30
	o Water	20 – 30
	o Bike	20 – 30
	- Running program	begin week 25-31
	o Jog	1 mile
	o Backward jog	20 yards
	o Twisting and curling	20 yards
	- Plyometric training	
	o Box jumps / 4 inch platform	3 x 15 – 20
	o Single or double leg bounding	10 – 30 yards
	o Rope skipping	3 x 10
	- Fitter	15 minutes
	- Mini tramp	5 minutes
	o hopping	
	o 2 foot	
	o alternate	
	o 1 foot	
	o stick loading	
Goals	- Increase function	
	- Maintain strength and endurance	
	- Return to previous activity level	

APPENDIX II: UNIVERSITY OF MANITOBA ETHICS APPROVAL

APPENDIX III: CONSENT FORM