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Original Article

Flexion deformity and laxity as a function of knee position at the time of tensioning of rigid anatomic hamstring ACL grafts

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A B S T R A C T

Background: Anatomic ACL grafts routinely display the anisometric length-tension behaviour seen in the native ligament with maximum length in full knee extension. Recent improvements in hamstring graft preparation and fixation have improved graft rigidity to the point where total graft lengthening after implantation may be less than 1 mm. Despite this it remains common practice to fix these grafts in a knee flexed position.

Methods: Nineteen participants underwent all-inside ACL reconstruction with optimally preconditioned 4 strand semitendinosus grafts using bi-cortical adjustable suspensory loop fixation. Using a computer navigation system, baseline measures of anisometricity, extension range, and tibial rotation were made. The graft was tensioned and provisionally fixed with the knee flexed 5° beyond its anisometric point and extension range recorded. The graft was then definitively fixed with the knee fully extended and extension range and tibial rotation recorded again. Anterior laxity measurements were made pre-operatively and postoperatively using a manual arthrometer and compared to those from the contra-lateral limb.

Results: Fixing the graft with the knee flexed produced a mean FD of 10.9° ($p < 0.0001$) and fixing in extension restored full extension ($p = 0.661$). Fixing in extension restored anterior laxity at 30° ($p = 0.224$) and at 90° ($p = 0.668$). There were very strong correlations between post-operative and control extension range ($r = 0.931$, $p < 0.0001$) and anterior laxity and 30° ($r = 0.830$, $p < 0.0001$) measures. Constraint of tibial internal rotation increased by 2.9° during the pivot-shift ($p < 0.001$) and increased with pivot shift grade ($r = 0.474$, $p = 0.040$).

Conclusion: Fixing rigid anatomic hamstring grafts in a knee flexed position routinely produces a flexion deformity. Tensioning and fixing grafts with the knee fully extended restores full extension and anterior laxity at 30° and 90°. Rotational constraint is significantly improved and correlates with the pivot-shift grade.

Clinical relevance: Rigid anatomic grafts should be tensioned and fixed with the knee fully extended.

What is known about the subject

Optimally preconditioned and fixed 4 strand hamstring grafts are rigid constructs with total initial and cyclic elongations potentially less than 1 mm (similar to BTB). Anatomic ACL grafts are anisometric as is the native ligament and are longer with the knee fully extended. It remains common practice to fix these rigid grafts in a knee flexed position for fear fixing in extension will leave the knee too lax in flexion.

What this study adds to existing knowledge

This is the first in-vivo study used optimally preconditioned and fixed 4-strand semitendinosus autografts to examine the subject.

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We used FD rather than tension or length change as the primary measure so that the consequences of over-constraint are very clear. Anterior laxity is restored and the correlated powerfully with control values at the clinically critical 30° angle. It is also the first in-vivo study to show that rotational constraint increases with the pivot shift grade. The reader should be confident that fixing a rigid anatomic graft with the knee fully extended avoids over-constraint without compromising stability.

Introduction

The primary goal of anatomic anterior cruciate ligament reconstruction is to restore native restraint to anterior tibial translation by placing a graft entirely within the native femoral and tibial footprints. The native ligament is anisometric with greatest tension and length in full extension.[1–4] Anatomic reconstructions mimic this anisometric behaviour[5–11] although the degree of anisometry varies depending on socket placement within the footprint, particularly on the femoral side.[5,9,10,12] Fixing an anatomic graft in a knee flexed position therefore, may over-constrain the joint as it extends into its anisometric range and result in high graft forces and a flexion deformity.[1,9,13,14] Graft behaviour under static and cyclic load varies depending on graft source,[15,16] preparation and fixation.[16] Hamstring autografts are traditionally less rigid than patellar tendon autografts[15] and require higher initial graft tension to minimize elongation due to creep/stress relaxation under static and cyclic load.[17] In addition, compared to bone-tendon-bone (BTB) aperture fixation, hamstring graft fixation is generally less rigid and if suspensory rather than aperture effectively lengthens the graft and commensurately, the potential for elongation under load.[18] These issues, combined with the concern that tensioning and fixing an anatomic hamstring graft with the knee extended, could result in excessive laxity in flexion,[13] have perpetuated the common practice of fixing grafts in a knee flexed position.[19] Recent technical adaptations to hamstring graft preparation and fixation include larger quadrupled Semitendinosus grafts (4ST), improved graft pre-conditioning and adjustable suspensory loop devices (ASLD) that allow tensioning and re-tensioning in situ and knotting of the tensioning sutures over the button. When combined, these adaptations can result in a powerful construct with total lengthening under cyclic load of less than 1 mm.[20,21] Given that anatomic graft anisometry is anywhere from 3 to 10 mm depending on socket placement within the footprints[12] there is a real concern than tensioning such a graft with the knee flexed may result in a flexion deformity, high graft forces and high compressive loads on articular cartilage. The obvious solution is to fix the graft with the knee fully extended but the concern is then that the joint will be too lax as the knee flexes.[13]

Anatomic centre-to-centre reconstruction (CTCR) has been shown to approximate the tension-flexion curve of the native ACL[1,5–12] and when tensioned with the knee in 20°-30° flexion, to better match the laxities of the intact knee than other anatomic constructs.[22,23] Much of the work on the biomechanics and isometricity of CTCRs has employed simulations or cadaveric models using 4-strand Gracilis-Semitendinosis (GST) grafts fixed with femoral closed loop devices (CLD) and tibial interference screw fixation. No in-vivo study of CTCR has examined the interaction of knee position at the time of graft fixation on extension range and anterior laxity using rigid optimally preconditioned, tensioned and re-tensioned 4ST grafts using knotted ASLDs. This in-vivo attempts to address these deficiencies.

The affirmative hypotheses of this study were:

1. That fixing rigid anatomic CTC grafts in a knee flexed position would routinely create a flexion deformity.
2. That fixing the same graft with the knee fully extended would allow full extension.
3. That anterior laxity at 30° and 90° of flexion would mimic that of the contralateral knee when the graft is tfixed with the knee fully extended.
4. That tibial internal rotation would be reduced when the graft is fixed with the knee in full extension.

Methods

This study was performed at a single centre by two orthopaedic (fellowship trained) knee surgeons. Prior ethics approval for this study was obtained from the health region ethics committee. All participants provided informed consent. Nineteen patients with unilateral ACL rupture undergoing reconstruction were included in the study between December 2014 and December 2015. The diagnosis of ACL rupture was made using both clinical and radiographic (MRI) assessment. Patients were excluded if they had received prior ACL surgery on either limb, had other associated ligamentous pathology, or had a pre-injury loss of range of motion (ROM) compared to the contralateral knee.

Preoperative and post-operative measurements were made under anaesthesia. Pre-operative extension and flexion range of both knees and post-operative extension of the operative knee were assessed using a digital inclinometer placed on the anterior surface of the thigh 10 cm proximal to the superior pole of the patella and 10 cm distal to the tibial tuberosity. Preoperative anterior tibial translation of both knees and post-operative translation of the operative knee were measured at 30° and 90° with a Rolimeter (http://www.drstorm.dk/Instruks_for_laeger/knae/Manual.pdf) by the senior surgeons (PM and MW) who were blinded to the result. On the operative limb, a graded pivot shift test was performed and graded according to Jakob et al.[24] Immediate postoperative measurements of the operative limb were made in an identical fashion.

ACL reconstruction

Reconstruction was performed using an all-inside technique with bi-cortical ASLDs (Tightrope RT®, Arthrex, Naples, Florida, USA) using an ipsilateral, loop and pulley 4ST graft,[25] pre-conditioned at 80 N. A two medial portal technique was used[26] to ensure optimal visualisation of the femoral footprint. A validated anatomic centre-to-centre single bundle technique was used for socket placement.[26,27]

Intraoperative measurements were made with a knee navigation system (Precision® CAS eNact Knee Navigation System v4.0 software, Stryker Leibinger, Freiburg, Germany) with standard tracker placement and each array mounted on two 3 mm Schanz pins. Registration was performed using standard landmarks with arthroscopic access. Navigation equipment was attached after the graft had been inserted but not tensioned or fixed.

Using the navigation system, knee extension range and relative tibiofemoral axial rotation in full extension were measured. A pivot shift manoeuvre was performed and the pivot angle (PSA), defined as the point where the tibia was maximally internally rotated relative to the femur, was recorded.[28] The anisometric angle (AA) was defined as the degree of knee flexion recorded on the navigation screen at which the graft began to exhibit anisometric behaviour. This was accomplished by applying manual tension to the tibial side Tightrope sutures with the knee fully flexed and then extending the knee until suture retraction was detected at the tibial tunnel (Fig. 1a and b). The knee was then flexed 5° beyond its identified AA. The tibial end graft sutures were once again placed

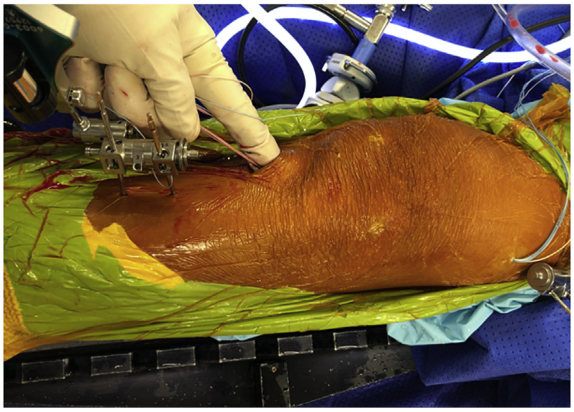

Fig. 1a. Tibial Tightrope sutures are manually tensioned and the index finger is placed over the tibial tunnel.

Fig. 1b. Determining the AA. The knee is extended from deep flexion. Knee flexion angle is recorded from the navigation screen once suture retraction into the tibial tunnel is detected.

Fig. 2. Simulating graft fixation in knee-flexed position. The knee is flexed 5° beyond the AA and the tibial Tightrope sutures are manually tensioned, passed around the tibial array mounting pins and clamped back to themselves.

under manual tension and then wrapped around the tibial navigation array pins and clamped with a needle holder so that no tibial suture retraction was possible (Fig. 2). The foot was then held and

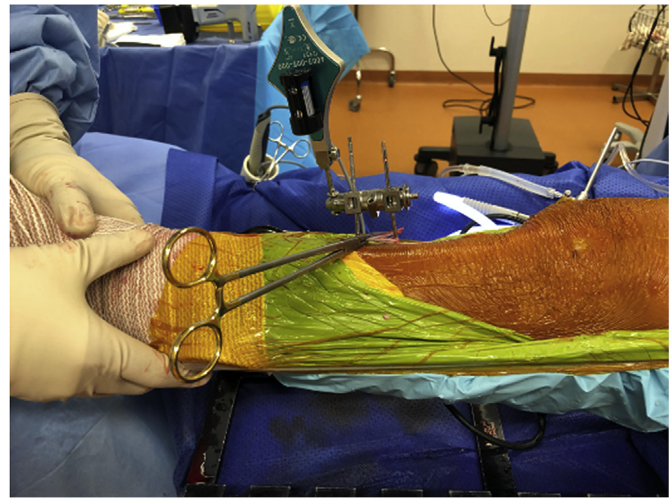

Fig. 3. Determining the flexion deformity caused by fixing the graft in a knee flexed position. The foot is held and the knee extends passively under its own weight. The knee flexion angle is recorded from the navigation screen.

the knee allowed to passively extend under its own weight. The resultant flexion angle was recorded from the navigation screen (Fig. 3).

The tibial end of the graft was then released from the tibial array pins. The knee was fully extended with tibia manually reduced under the femur. The graft was then tensioned with manual maximum tension on the ASLD tensioning sutures, first on the tibial and then on the femoral side. The knee was then ranged through 20 cycles and then re-tensioned with the joint once.

Again in its fully extended position. The tensioning sutures were knotted over both ASLDs to complete definitive fixation Final measurements of knee extension range and relative tibiofemoral axial rotation with the knee in full extension and at the PSA were recorded.

Funding

Institutional research support was received from industry but there was no direct industry input or support for this study.

Data analysis

Statistical analysis was performed using Graphpad Prism 7.0d for MacOSX GraphPad Software, La Jolla California USA. Statistical comparison of means was performed using the Students t-test (paired and unpaired as appropriate). Correlations were examined using Pearson correlation coefficients. Statistical significance was set at $P < 0.05$. Data is represented as mean ± standard deviation (SD) with minimum and maximum values.

Results

Participants

The mean participant age was 29 years. Ten participants were male and 9 female. The right knee was reconstructed in 12 and the left in 7.

Non-isometric angle and pivot-shift angle

All knees demonstrated a point where the reconstructed ACL ceased to move isometrically as the knee was ranged from flexion to extension. The mean AA was 24.0 (Table 1).

Maximal extension

Fixing the graft in a knee flexed position 5° beyond the AA produced a mean flexion deformity of 10.9° (measured with navigation, paired Students *t*-test, −1.8° v 9.1°, $p < 0.0001$). Tensioning in extension resulted in the same extension range as the contralateral limb (measured with goniometer, unpaired Students *t*-test, −5.2° v −5.9°, p = 0.661) (Table 1). There was a very strong and highly significant correlation between the extension ranges of the contralateral and reconstructed knees (Pearson correlation coefficient, r = 0.931, $p < 0.0001$) (Fig. 4).

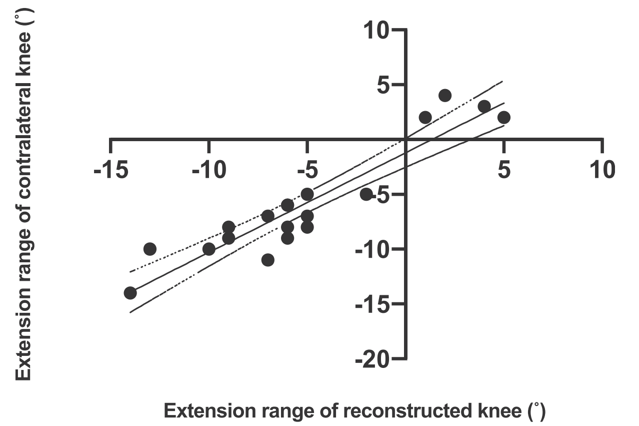

Fig. 4. Pearson correlation of contralateral and reconstructed extension range (goniometer) with linear regression curve and 95% confidence interval bands.

Anterior translation

Reconstruction of the ACL significantly reduced anterior translation at 30° (paired Students *t*-test, $p < 0.0001$) and 90° (paired Students *t*-test, $p < 0.0001$). Compared to the contralateral knee, ACL reconstruction resulted in similar mean anterior translation at 30° (unpaired Students *t*-test, p = 0.224). There was a very strong and highly significant correlation between the 30° anterior laxity measurements of reconstructed and contralateral knees (Pearson correlation coefficient, r = 0.830, $p < 0.0001$) (Fig. 5). Compared to the contralateral knee, ACL reconstruction resulted in similar mean anterior translation at 90° (unpaired Students *t*-test, p = 0.668) (Table 2). There was a moderately strong but non-significant correlation between the 90° anterior laxity measurements of reconstructed and contralateral knees (Pearson correlation coefficient (r = 0.403, p = 0.088) (Fig. 6).

Thirteen of 19 knees were constitutionally hyper-extensile by intra-operative navigation measurement. Full extension was restored after reconstruction in this subgroup (−4.5° v −4.0°, paired Student's *t*-test, p = 0.586). Anterior laxity at 30° (4.3 mm v 5.0 mm, unpaired Student's *t*-test, p = 0.346) and 90° (5.7 mm v 5.6 mm, unpaired Student's *t*-test, p = 0.866) was also restored compared to the controls.

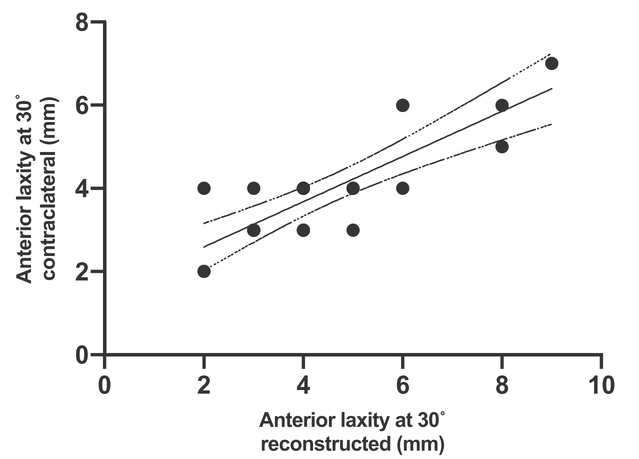

Fig. 5. Pearson correlation of contralateral and reconstructed anterior laxity at 30° with linear regression curve and 95% confidence interval bands.

Rotational constraint in reconstructed knee v ACL deficient knee

Overall, reconstruction of the ACL significantly reduced maximum tibial internal rotation of the tibia relative to the femur in full extension by a mean of 2.6° (paired Students *t*-test, $p < 0.001$) and at the PSA by a mean of 2.9° (paired Students *t*-test, $p < 0.001$), (Table 3). There was a moderately strong and significant correlation between reduction in tibial internal rotation at the PSA and the pivot-shift grade (r = 0.474, p = 0.040) (Fig. 7) as well as significantly different mean tibial internal rotation reduction values across the pivot grades (unpaired Students *t*-test, 2.2° for grade 2 and 4.0° for grade 3, p = 0.037) (Table 3).

Table 2
Pre-operative and post-operative anterior tibial translation (rolimeter).

Knee and Position	Mean ± SD (mm)	Min (mm)	Max (mm)
Pre op 30°	9.0 ± 1.8	6	11
Pre op 90°	8.1 ± 1.5	6	11
Post op 30°	3.9 ± 1.3	2	7
Post op 90°	5.6 ± 0.9	4	7
Contra 30°	4.6 ± 2.0	2	9
Contra 90°	5.8 ± 1.3	3	8

Discussion

The most important findings of this study were that: a) Fixing rigid ACTC grafts in a knee flexed position resulted in a mean 11°

Table 1
Extension, pivot-shift and anisometric angles.

Angle	Mean ± SD (⁰)	Min (⁰)	Max (⁰)
Intraoperative extension (graft fixed in knee flexed position-nav)	9.1 ± 4.3	0	18.0
Intra-operative extension (graft fixed in knee extended position-nav)	−1.8 ± 4.9	−11.0	5.5
Post-operative extension (reconstructed knee-goniometer)	−5.2 ± 5.2	−14.0	5.0
Extension (contralateral knee-goniometer)	−5.9 ± 5.2	−14.0	4.0
Pivot-Shift Angle (nav)	25.4 ± 4.8	20.0	35.0
Anisometric Angle (nav)	24.0 ± 7.3	5.5	38.0

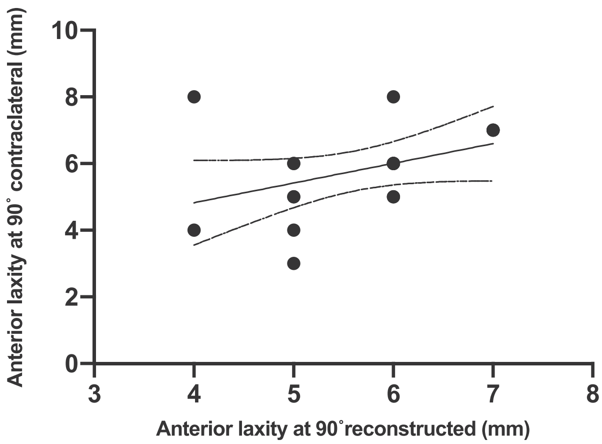

Fig. 6. Pearson correlation of contralateral and reconstructed anterior laxity at 90° with linear regression curve and 95% confidence interval bands.

Table 3
Reduction in maximum tibial internal rotation (nav) after definitive graft fixation.

	Mean ± SD (°)	Min (°)	Max (°)
Change in rotation in full extension	2.6 ± 1.5	−1	4
Change in rotation at the PSA			
Overall	2.9 ± 1.9	0	8
Grade 1 pivot-shift	2	2	2
Grade 2 pivot- shift	2.2 ± 1.4	0	4
Grade 3 pivot shift	4.0 ± 2.0	2	8

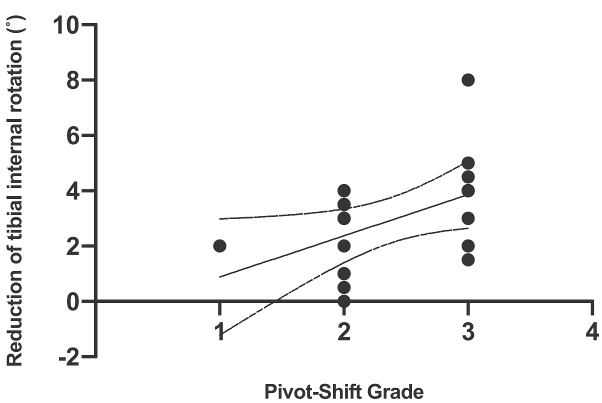

Fig. 7. Pearson correlation of reduction in tibial internal rotation (Nav) at the PSA and Pivot-shift grade.

flexion deformity. b) Full extension was reliably restored by fixing the graft with the knee fully extended. c) Doing so did not result in excessive laxity at 30° or 90°. d) Constraint to tibial internal rotation was modest but increased significantly with the grade of pivot.

The study has a number of strengths. The study was in-vivo and used autologous grafts, rather than sutures or allografts, with an evidence based best practice graft preparation and tensioning protocol as well as a validated, consistent socket placement technique. Both femoral and tibial socket positions affect ACL anisometry. For example, if the femoral socket is in the anatomic centre position, the more posterior the tibial socket is placed the more dramatic graft anisometry becomes. Similarly, if the tibial socket is in the anatomic centre position, the more the femoral socket is moved from anteromedial towards posterolateral bundle insertions the more dramatic graft anisometry becomes.[29] Quality assurance steps for femoral socket placement were the use of an accessory medial portal for viewing the femoral footprint and the use of a ruler to confirm position. For tibial socket placement the posterior margin of the anterior horn of the lateral meniscus was used as a reference point.[26] The use of the normal contralateral limb as a control for extension range and laxity was important in terms the post-reconstruction result validity. The use of resultant FD rather than changes in graft tension or length as a primary end point gives the reader a very clear real-world appreciation of the consequences of fixing a rigid anatomic graft in a knee flexed position. The statistical method employing Pearson correlations and not only comparison of central tendencies improves understanding of how well-matched results were on an individual basis.

The study also has a number of weaknesses. The surgery involved only a single centre and only 2 surgeons so external validity could be questioned. Socket position was not validated radiographically and variability of socket placement could explain some of the findings in terms of the non-isometric angle and resultant flexion deformity. Perhaps most importantly the preoperative and post-operative anterior laxity measurements were not independent with all measurements made by the senior surgeon in each case (PM and MW). The Rolimeter arthrometer utilized for laxity measurements has been well and truly validated[30,31] but is perhaps better in experienced hands[32] so the decision have the senior clinician execute all measurements was made to minimize variation in technique. There was no control for the tibial internal rotation measurements. Finally, the results are time zero so although relevant cannot be interpreted in terms of long-term clinical outcomes.

The results of this study cannot necessarily be extrapolated to all graft constructs. What is clear is the importance of preconditioning, tensioning, re-tensioning and knotting tensioning sutures over buttons to minimize graft elongation.[33] The configuration of the 4ST construct can affect elongation but there is consistent evidence that elongation is between 1 and 2.5 mm[16,33,34] which is well below reported graft length changes when using anatomic centre socket positions.[7,29] As such the principle of fixing optimally prepared, conditioned and fixed 4ST grafts with the knee fully extended can probably be applied in a broader sense. This principle may be especially important when using a BTB autograft as the habit of fixing these rigid grafts in a knee flexed position may explain the reduced extension range and higher incidence of osteoarthritic changes after BTB ACL reconstruction.[35,36]

The importance of rapidly achieving full knee extension following ACLR is unquestioned as a primary rehabilitation objective and tensioning the graft with the knee fully extended unequivocally ensures the patient can begin rehabilitation without an FFD. Thirteen of the 19 participants had constitutional hyperextension in both the control and operative limb. The fact that this was restored without negatively affecting anterior laxity relieves the surgeon and physiotherapist of any anxiety in terms of return of constitutional hyperextension range damaging the graft.

The Pearson correlation coefficients for anterior laxity between the control and reconstructed knees were greater at 30° than at 90° although mean laxity values were not significantly different from controls at either angle. Nevertheless, this would indicate that with ACTC grafts, laxity at 90° is less predictable in any one individual than it is at 30°. Given that laxity at 30° is very strongly correlated between reconstructed and control knees the moderate correlation at 90° is probably a reasonable tradeoff to avoid a post-operative flexion deformity.

We identified a mean PSA of 25° so the very strong correlation between 30° anterior laxity measurements of reconstructed and control knees is of particular relevance on terms of functional stability. We also demonstrated not only a significant reduction in tibial internal rotation in full extension and during a pivot-shift manouvre. Furthermore, the magnitude of rotational constraint correlated with the pivot-shift grade which, to the best our knowledge, has not previously been demonstrated with ACTC grafts. Previous work has shown greater reduction of tibial IR when an ACTC graft is tensioned in flexion[37] but given the results of this study, this rotational constraint comes at the expense of extension range. Determining how much rotational constraint is required depending on the pivot-shift grade is additionally complicated by the anisometric behaviour of anatomic grafts in the internal/external rotation plane as well as the flexion-extension plane.[38] During a simulated pivot-shift manouvre in a robotic simulator study using cadaveric specimens and BTB grafts, section of the ACL was shown to produce mean increases in tibial internal rotation of only 1.1° and 1.3 in specimens with intact and lax secondary restraints respectively. This was corrected in both groups with a single bundle anatomic graft.[39] Our mean reduction in tibial IR during a pivot-shift of 3° may therefore be consistent with at least physiologic restraint. The role of a lateral extra-articular tenodesis to add rotational constraint requires ongoing examination.

Cadaveric studies on the ACTC technique have demonstrated mean graft elongation of 6.7 mm between 90° and 0° of flexion and significant changes in length for every 15° increment of flexion between 0° and 90°.[7] Increased graft failure rates have been reported with CTCR compared to an anatomic anteromedial femoral socket technique[40] but the position of the knee at the time of final graft fixation was not specified. The higher failure rate could be attributed to high graft forces at low flexion angles when tensioned in flexion[9] or, when tensioned in full extension, loss of graft tension in flexion, particularly at around 30° of flexion where the pivot-shift of ACL deficient knee occurs.[28,37]

In recent years research on ACL anatomy has shifted emphasis from bundle anatomy to ribbon anatomy with direct and indirect fibres.[41–43] The IDEAL femoral socket location[44] reflects these changes and differs from the anatomic centre location. The IDEAL socket location exhibits less anisometry but nonetheless is not isometric, does result in a graft that lengthens as the knee extends and does have individual variation in terms of anisometry.[12] It therefore follows that a rigid graft, placed in the IDEAL location and fixed in a knee flexed position could also result in over-constraint. The findings of this study should give the surgeon confidence that fixing such a graft with the knee fully extended will not leave the joint under-constrained in terms of anterior laxity.

Conclusions

Fixing rigid ACTC grafts in a knee flexed position resulted in a mean 11° flexion deformity that was reliably prevented by fixing the graft with the knee fully extended. Doing so did not result in excessive laxity at 30° or 90°. Constraint to tibial internal rotation is modest but increases significantly with the grade of pivot. Rigid anatomic grafts should be fixed with the knee fully extended.

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