Tension in a double loop tendon anterior cruciate graft during a simulated open chain knee extension exercise

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Abstract

Concerns exist regarding the tension developed in a reconstructed anterior cruciate ligament (ACL) during open chain knee extension exercises used to rehabilitate the knee. Therefore, the primary objective was to measure tension in an ACL graft during a simulated open chain knee extension exercise as a function of ankle weight. A secondary objective was to determine whether the graft tension was reduced with relatively high stiffness fixation. The open chain exercise was simulated in seven cadaveric specimens in which the ACL had been reconstructed with double loop tendon grafts. Graft tension was measured at 15° of flexion as the effective ankle weight was increased from 22.5 to 67.5 and then to 112.5 N for three different fixation stiffnesses (25, 125, and 225 N/mm). The initial tension was set to restore the 225 N anterior limit of motion to that of the intact knee at 30° of flexion. Increasing the ankle weight caused the graft tension to increase significantly ($p < 0.0001$), but the increase with the highest ankle weight was only 62 N on average. Increasing the fixation stiffness caused the graft tension to decrease significantly ($p < 0.0001$) because the initial tension decreased by 107 N as the fixation stiffness increased. Because the graft tension with the highest ankle weight was limited to 112 N on average, high stiffness fixation methods, which are also resistant to lengthening in the region of the fixation, may reduce the risk of graft construct lengthening during open chain knee extension exercises.
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Keywords: Graft; Rehabilitation; Knee; Quadriceps; Open chain; Force

Introduction

Postoperative rehabilitation determines the success of an anterior cruciate ligament (ACL) reconstruction [23]. Conservative rehabilitation, which restricts motion and passively exercises the knee, causes muscle atrophy and delayed return to sport [6]. Aggressive rehabilitation, which does not restrict motion and actively exercises the knee, minimizes muscle atrophy and quickly returns the patient to sport [36]. Because muscles in the quadriceps group are particularly prone to atrophy [15,22], identification of aggressive rehabilitation exercises that preferentially strengthen this muscle group is important.

Such exercises include closed chain leg squats and open chain knee extension exercises [8,27,32]. Patients who used both increased quadriceps strength significantly and returned to sport 2 months earlier than patients who used closed chain exercises alone [27]. This improved clinical outcome may be because open chain exercises near knee extension are particularly effective in building quadriceps strength [12].

Some authors recommend against using open chain knee extension exercises, particularly during the early phase (first 6 weeks) because these exercises could develop high tensile loads in the graft [6,8,32]. In part, these concerns stem from reports that strain in the intact ACL increases as the knee is extended under a quadriceps load [1,3,5]. Other studies have shown that anterior

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tibial displacement is greater in open versus closed chain exercises [41]. Finally, mathematical models predicted ACL ligament tension as large as 500 N in open chain knee extension exercises [30,45].

Other studies contradict these results. For example, anterior tibial translation for an open chain knee extension exercise under maximum quadriceps contraction was the same as that developed by the application of an 89 N anterior drawer force in the range of 15–45° of flexion [18], suggesting that such open chain exercises do not develop high ligament tension because the tension approximates the externally applied anterior force [34]. Also, in vivo ACL strains were not different between closed chain squatting exercises and open chain knee extension exercises [7]. Maximum graft tension during a simulated closed chain squatting exercise was less than 100 N [28], so that the combined results from these two studies imply that graft tension in an open chain knee extension exercise is relatively low.

Because the tension developed in an ACL graft during an open chain knee extension exercise remains unknown and because this knowledge can resolve the contradiction evident in the literature, our first objective was to directly measure the tension in a double loop ACL graft during a simulated open chain knee extension exercise and to investigate the effects of increasing ankle weight. In addition to ankle weight, fixation stiffness may also be an important factor affecting ACL graft tension during an open chain knee extension exercise. ACL graft tension in this type of exercise is a combination of the tension applied to the graft during fixation (i.e. initial tension) and the active tension created by the action of the quadriceps muscles. The fixation stiffness should influence the amount of initial tension required to restore the normal anterior laxity with high fixation stiffness requiring less initial tension than low fixation stiffness. ACL graft tension should, therefore, also be inversely related to fixation stiffness, provided that the interaction between the ankle weight and fixation stiffness is unimportant. Because the magnitude of the effect of the fixation stiffness on the graft tension during an open chain knee extension exercise is unknown, our second objective was to determine whether ACL graft tension is reduced with high fixation stiffness. If a reduction did occur, then it was also of interest to determine which contribution (weight or stiffness) was primarily responsible.

Methods and materials

Seven fresh-frozen cadaveric knee specimens obtained from tissue banks were tested in this study (average age = 67 years, range = 60–75 years). The knee joints were evaluated radiographically and visually at the time of ACL reconstruction. Specimens with evidence of degenerative arthritis were excluded. The skin and all tissue 50 mm from the joint line were removed. The bone was scraped to remove the periost-

eum. The fibula was anchored to the tibia with a screw and then sawn off 70 mm below the joint line. The canals of the tibia and femur were reamed, and intramedullary steel rods (10–12 cm diam) were inserted with PMMA. The knee remained in saline-soaked gauze throughout testing.

The load application system [2] is a six degrees of freedom apparatus that can apply loads in all degrees of freedom and measure the corresponding displacements according to a joint coordinate system [14]. Flexion/extension is adjustable over the full physiologic range, and unconstrained motion is allowed in the remaining degrees of freedom. Loads can also be applied to simulate the actions of the quadriceps, hamstrings, and gastrocnemius. For this study, AP force and quadriceps force were applied, and AP displacement was measured (resolution ±0.1 mm). Each specimen was secured to the system so that the natural axes of joint motion were aligned with those of the system [2]. The tibial and femoral shafts were then potted in aluminum tubes using PMMA, which were then clamped to the load application system.

The intact knee was preconditioned with a 250 N load applied to the tibia in 50 N increments in the anterior and posterior directions for five cycles at 0° and 90° of flexion. Zero degrees was the position of the knee with a 2.5 Nm extension moment [29]. The 225 N anterior limit of motion was measured at 30° [11]. The tibial load was increased from 0 to 45 N of anterior force, decreased to 0 N, increased from 0 to 45 N of posterior force, decreased to 0 N, and increased from 0 to 225 N of anterior force. Using the transducer measuring the AP tibial displacement with respect to the femur, the anterior limit was defined as the position at 225 N of anterior force.

A double-loop graft was constructed from bovine extensor tendons (DLBT) using the same technique as for preparing a double-loop semitendinosus and gracilis hamstring (DLSTG) graft. A DLBT graft has similar structural properties and is longer in length than a DLSTG graft [16]. The added length insured firm fixation in a freeze clamp. The tendons were harvested and trimmed so that when folded in half side-by side they fit snugly inside a 9 mm diameter sizing cylinder (Sizing Sleeves, Arthrotek, Inc., Warsaw, IN). The free ends of each tendon were trimmed and sewn with 1-0 suture using a criss-cross stitch to facilitate passage of the graft in the knee [21,40].

The joint was exposed using medial and lateral parapatellar incisions. The patella and patellar tendon were reflected distally, the joint was inspected for arthritis, and the ACL was excised. The ACL was reconstructed by drilling the femoral tunnel through the tibial tunnel using an over-the-top femoral aimer. A 2.4 mm diameter K-wire was placed using a tibial drill guide (Howell Tibial Guide, Arthrotek, Warsaw, IN) so that it formed a 70° angle in the coronal plane relative to the medial tibial plateau and entered the intercondylar notch between the medial and tibial eminences. The tibial drill guide customized the K-wire placement in the sagittal plane by accounting for variations in knee extension and slope of the intercondylar roof, which prevented the graft from impinging against the roof in full extension [19,20]. The tibial tunnel was drilled over the K-wire using a 9 mm diameter cannulated reamer.

The femoral tunnel was placed by inserting a 9 mm diameter endoscopic femoral aimer (Size-Specific Femoral Aimer, Arthrotek, Inc.) into the intercondylar notch through the tibial tunnel. The knee was flexed until the hook of the aimer locked into place in the over-the-top position, and a 2.4 mm diameter K-wire was drilled into the femur. A 30 mm closed-end femoral tunnel was drilled using a 9 mm diameter cannulated end reamer.

The femoral fixation used in the specimen had to be much stiffer than the stiffest spring (275 N/mm) to simulate the combined stiffness of a femoral and tibial fixation method. A special procedure was developed to create an ultra-high stiffness femoral fixation [24]. Briefly, a 4 mm diameter steel rod, acting as a cross pin intersecting the femoral tunnel 25 mm deep, was supported in a PMMA mantle. The stiffness of the steel rod-cement-bone construct was conservatively estimated as 13,500 N/mm, and the corresponding deflection under a 225 N anterior force was a negligible 0.02 mm. Following reconstruction, a 2.54 cm wide and 30-cm long nylon strap was sewn to the quadriceps tendon with a 5-0 suture using a criss-cross stitch. A loop was sewn into the free end of the strap with a 5-0 suture.

Three springs (25, 125, and 225 N/mm) were selected to represent stiffnesses of 18 different combinations of femoral and tibial fixation methods. The overall stiffness was calculated using a springs-in-series

Table 1
Fixation stiffness for 18 combinations of femoral and tibial fixation methods

Stiffness of femoral fixation	Stiffness of tibial fixation					
	#5 Sutures tied to post 70 N/mm[a]	Double staples 174 N/mm[a]	One 20 mm washer 192 N/mm[a]	Two tandem washers 318 N/mm[b]	Metal interference screw 340 N/mm[b]	WasherLoc 506 N/mm[b]
Endo button 24 N/mm[b]	18 N/mm	21 N/mm	21 N/mm	22 N/mm	22 N/mm	23 N/mm
Mitek anchor 26 N/mm[b]	19 N/mm	23 N/mm	23 N/mm	24 N/mm	24 N/mm	25 N/mm
Bone mulch screw with bone compaction 575 N/mm[b]	62 N/mm	134 N/mm	144 N/mm	205 N/mm	214 N/mm	269 N/mm

The fixation stiffnesses were calculated using values from two studies [25,38]. The fixation stiffness of these combinations ranged from 18 to 269 N/mm and provided the basis for the springs in our study that simulated the fixation stiffness (25, 125, and 225 N/mm).

[a] Stiffness of fixation determined using porcine tibia [25].

[b] Stiffness of fixation determined using either human tibia [25] or femur [38] from donors with an average age 35 years.

analysis [38] with available values for the stiffness of each femoral [38] and tibial [25] fixation method. The overall stiffness ranged from 18 to 269 N/mm (Table 1).

A custom fixture added to the tibial unit measured graft tension and allowed both initial graft tension and effective stiffness to be varied (Fig. 1). The four limbs of the graft were gripped with a freeze clamp [35]. A load cell (Futek Advanced Sensor Technology, Inc., Irvine, CA) measured both the initial tension and the graft tension. To adjust initial tension, a threaded shaft and knurled end cap were attached to the load cell. The shaft passed through a spherical alignment bearing in a steel plate bolted to the tibial unit. A coil spring was sandwiched between the plate and the end cap that threaded onto the shaft so that the spring was compressed when the graft was in tension. Turning the knurled end cap adjusted the initial tension. When the end cap was removed from the shaft, a coil spring of a different stiffness could be installed. Because the tibia was clamped to the steel plate, which was bolted to the system that allowed unconstrained motion in five degrees of freedom, the initial tension created a compressive load between the tibia and the femur and posterior translation of the tibia.

Once the graft was frozen in the freeze clamp, an arbitrary initial tension greater than 250 N was applied with the knee at 0° and with the stiffest spring (225 N/mm) installed. The knee was subjected to the same preconditioning protocol that was used for the intact knee. The initial tension was then set to 100 N at 0°, and the knee was pas-
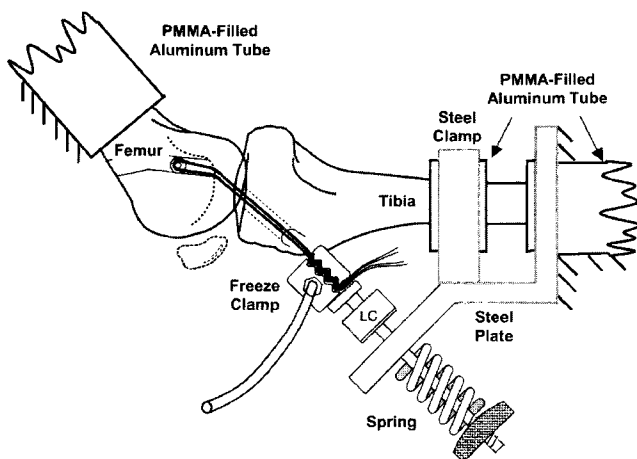

Fig. 1. Diagram of the mechanism used to connect the free ends of the graft to the tibial unit, allowing interchange of springs that represented the overall stiffness of different combinations of femoral and tibial fixation methods. The method of setting initial tension created a corresponding reaction load on the tibia, which caused compression between the tibia and femur and posterior translation of the tibia. The steel rods that were cemented into canals of the tibia and femur and large gussets that reinforced the steel plate are not illustrated for clarity.

sively flexed to 120° while the graft tension was recorded. This check ensured that the tension did not rise prematurely at an early flexion angle. A premature tension rise is an indication that the graft has been impinged by the intercondylar roof as a result of the femoral tunnel being too anterior [13].

The knee was subjected to the same anterior/posterior/anterior load cycle used for the intact knee. Once one of springs was randomly selected, the initial tension was varied at 0° of flexion through a trial-and-error procedure until the 225 N anterior limit of the reconstructed knee at 30° matched that of the intact knee at 30° within a tolerance of 0.0 to 0.5 mm. The initial tension was varied at full extension rather than at 30° because the graft tension at full extension is considerably greater, thus allowing greater control in adjusting initial tension. When the proper tension was determined, the knee was returned to 0°, and the process was repeated for the remaining springs until the proper initial tension was determined for all springs.

An open chain knee extension exercise was simulated. Because the weight of the shank/foot for each specimen was unknown, the weight of the shank/foot was set at 43 N, which corresponded to the weight of the 50th percentile male [10]. Ankle weights were set at 22.5, 67.5, and 112.5 N. Based on our experience and reports by others [5,31], these weights encompassed the practical range that might be used in rehabilitative exercises particularly during the early healing phase when the graft construct is most susceptible to lengthening. A 15° flexion angle was chosen because previous studies observed peak strain [1,6] and maximum tibial displacement [17,18] at this angle.

A manual test was performed to determine the quadriceps load necessary to equilibrate the shank/foot weight and the ankle weights at the flexion angle tested. With the knee at 15° and removed from the system, the quadriceps tendon strap was pulled with a hook fixed to a load cell (Futek Advanced Sensor Technology, Inc., Irvine, CA). Force was applied until the tibial rod was just pulled off the table on which it was resting. This was performed five times to obtain the average quadriceps load necessary to equilibrate the specimen's tare weight. Next, the 22.5 N ankle weight was fixed 40 cm from the joint center [17,30,45], and the pull test repeated another five times. Finally, the shank/foot weight was added at the center of mass of the shank/foot (26.2 cm from the tibial plateau for the 50th percentile male [10,44]), and the pull test repeated another five times.

The quadriceps force to equilibrate the weight of the shank/foot alone was determined by subtracting the average quadriceps force for the 3rd test from the average for the 2nd test, and the quadriceps force to equilibrate the ankle weight alone was determined by subtracting the average force for the 2nd test from the average force for the 1st test. The quadriceps force used during the simulation of the open chain knee extension exercise was the sum of the quadriceps force to equilibrate the shank/foot alone plus the quadriceps force to equilibrate the ankle weight alone. The quadriceps forces for the 67.5 and 112.5 N ankle weights were calculated by multiplying the quadriceps force for the 22.5 N ankle weight alone by three and five, respectively. This calculation was necessary because the required pull for the 67.5 and 112.5 N ankle weights exceeded manual capability and was validated in a pilot study on two specimens by applying a 45 N ankle weight; the scaled quadriceps force was within 5 N of the measured quadriceps force.

Once the quadriceps forces were determined, the knee was placed back in the system with the quadriceps load frame attached [2]. The load frame consisted of an air driven piston attached to the load cell in turn attached to a hook. The hook was fixed to the strap attached to the quadriceps tendon. A spring was randomly selected, and the corresponding initial tension applied at full extension. The knee was flexed to 15°. A posterior force, chosen at random to represent the sum of one of the ankle weights plus the weight of the shank/foot, and corresponding quadriceps force were applied while the graft tension was recorded. The knee was then returned to full extension, the initial tension adjusted, after which another ankle weight was randomly selected. Once testing was completed for all the ankle weights, another spring was randomly selected, and the process repeated until testing was completed for all springs.

Statistical analysis

A two-factor repeated measures ANOVA analyzed the effects of the independent variables (ankle weight at three levels and fixation stiffness at three levels) on the dependent variable (graft tension).

Because the interaction between the main effects was not significant ($p = 0.8727$), a Tukey's multiple comparisons test followed for the significant main effect(s). The significance level was set at $p < 0.05$.

Results

As the ankle weight increased, the graft tension increased significantly ($p < 0.0001$ from ANOVA). For the highest fixation stiffness, the graft tension with the 22.5 N ankle weight was 85 N, which increased by only 27 N when the ankle weight was increased to 112.5 N (Table 2, Fig. 2). The average active tension was 35, 52, and 62 N for the 22.5, 67.5, and 112.5 N ankle weights, respectively. The graft tension for both the 67.5 and 112.5 N ankle weights was significantly greater than that at 22.5 N ($p < 0.05$ from Tukey's), but the

Table 2
Average total graft tension and active tension (i.e. tension due to ankle weight) in $N \pm 1$ standard deviation (in parentheses) for the various combinations of fixation stiffness and ankle weight

Spring stiffness (N/mm)	Ankle weight (N)			
	0[a]	22.5	67.5	112.5
25	152(73)	181(74)	188(77)	192(76)
		29(13)	**36(17)**	**40(16)**
125	67(52)	104(61)	122(71)	132(75)
		37(20)	**55(33)**	**65(39)**
225	45(41)	85(62)	105(74)	112(81)
		40(29)	**60(45)**	**66(52)**
Active tension averaged over three spring stiffnesses		**35(29)**	**52(45)**	**62(38)**

Bold entries are the active tension.
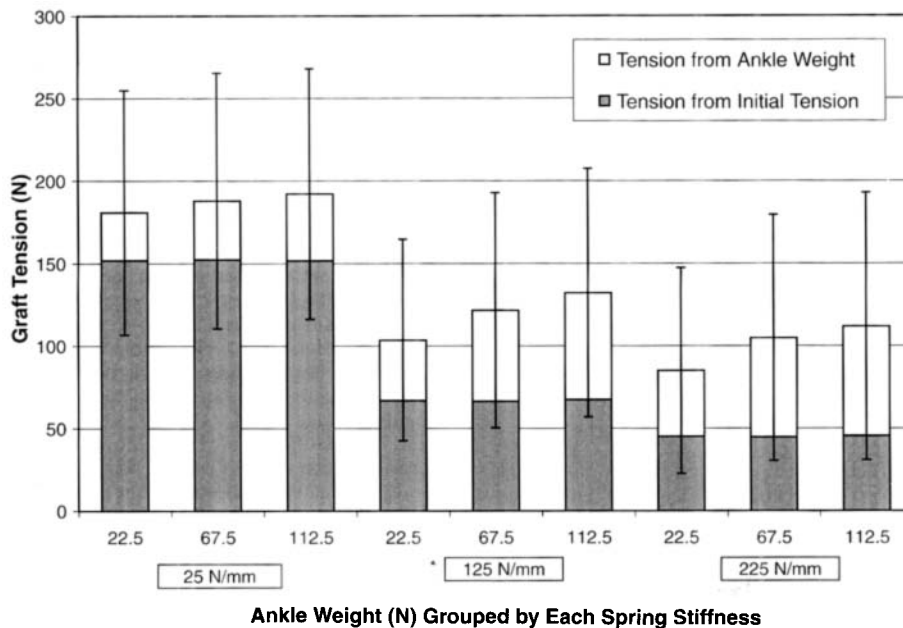[a] 0 N of ankle weight corresponds to the initial tension.

Fig. 2. Graft tension for each combination of ankle weight and fixation stiffness. The contributions of both initial tension and active tension (i.e., tension from the ankle weight) to the graft tension are also shown. Error bars indicate ±1 standard deviation.

graft tension for the 112.5 N ankle weight was not significantly greater than that for the 67.5 N ankle weight.

As fixation stiffness increased, the graft tension decreased significantly ($p < 0.0001$ from ANOVA). For the highest ankle weight of 112.5 N, the graft tension for the lowest fixation stiffness was 192 N, which decreased to 112 N for the highest fixation stiffness (Table 2, Fig. 2). The decrease in the graft tension was due to the decrease in the initial tension as the fixation stiffness increased. The lowest stiffness fixation (25 N/mm) required 152 N of initial tension, which was more than three times the 45 N of initial tension required by the highest stiffness fixation (225 N/mm). The graft tension for both the 125 N/mm and the 225 N/mm stiffnesses was significantly less than that at 25 N/mm ($p < 0.05$ from Tukey's), but the graft tension for the 125 N/mm stiffness was not significantly greater than that for the 225 N/mm stiffness.

Discussion

Exercises included in aggressive rehabilitation programs should be chosen so that they return the patient to normal activities as rapidly as possible while not subjecting the graft to excessive loads that could lead to increased anterior laxity. We directly measured the graft tension in a double-loop tendon graft during a simulated knee extension exercise. The key findings of our study were that the graft tension increased only 62 N for the largest ankle weight of 112.5 N and that increasing the stiffness of fixation caused a substantial decrease in graft tension because the initial tension decreased.

One methodological issue that must be considered is how the force system correctly simulated the knee extension exercise. The intersegmental loads transmitted by the knee in the simulation had to be the same as those transmitted by the knee during the exercise. With the shank/foot weight plus ankle weight, the intersegmental loads consist of a posterior force (tibia on the femur) and an accompanying flexion moment that must be equilibrated by an extension moment provided by the quadriceps muscles force. The load application system allowed the application of a posterior force to the tibia without an accompanying flexion moment. However, the extension moment was equilibrated by a flexion moment provided by the system itself because the knee flexion angle was fixed. Therefore, the intersegmental loads in the simulation were the same as those in the open chain knee extension exercise.

The maximum ankle weight was limited by the strength of the sewn connection between the strap and the quadriceps tendon. At the combination of the 43 N shank/foot weight and the 122.5 N ankle weight, the average required quadriceps force was 1273 N, corresponding to 20–25% of the maximum force that the muscle group can generate [4].

The graft tension at the tibial fixation site was measured because this tension may be more predictive of the risk of graft construct lengthening (and concomitant increase in anterior knee laxity) during a knee extension exercise than the graft tension at the femoral fixation site. The tibial fixation method is arguably more prone to lengthening (e.g., slippage) in the region of fixation than the femoral fixation method because the commonly used cross-pin femoral fixation does not allow slippage whereas commonly used tibial fixation methods (e.g., cortical screw and washer) do [25]. Therefore, we measured the graft tension distal to the tibial tunnel at the site of tibial fixation where the graft construct is most vulnerable to lengthening.

Although the graft tension increased as the ankle weight increased, the increase was not proportional. Increasing ankle weight from 22.5 to 67.5 N increased graft tension by 17 N when averaged over the three springs, whereas increasing ankle weight from 67.5 to 112.5 N increased graft tension by only an insignificant 10 N. One explanation for this finding is that the resistance to anterior tibial translation increases as the knee joint is compressed [18,26]; another is that the anterior component of the quadriceps force diminishes as the tibia displaces anteriorly on the femur [18,42].

Our results indicate that tension developed in a double-loop graft during the knee extension exercise can depend to a large extent on the fixation methods used, provided that the initial tension is maintained postoperatively. For example, for a relatively high stiffness fixation, such as a metal fixation post in the femur and a multiple spiked washer and screw in the tibia, the initial tension can be reduced by an average of 107 N compared to that for less stiff fixation methods, such as sutures (e.g., endobutton or sutures tied to a post). Such a reduction caused a substantial 80 N average decrease in graft tension with a 112.5 N ankle weight. Lowering the graft tension lowers the risk of fixation failure and corresponding graft construct lengthening when performing this exercise for rehabilitation after an ACL reconstruction.

In showing that the graft tension increased with increasing ankle weights, our results indicate that the risks of graft construct lengthening and fixation failure associated with this exercise do increase if higher ankle weights are used. However the increases in graft tension are relatively modest compared to the decreases that can be achieved by increasing the fixation stiffness (Fig. 2).

The strength of fixation must also be considered in using high fixation stiffness to reduce the risk of fixation failure. Arguably the most meaningful measure of strength for this study is lengthening in the region of fixation, because the graft will experience repetitive loads with each repetition of the exercise. For the three high stiffness fixation combinations (Table 1), lengthening in the region of fixation can range from 0.15 to 1.80

mm up to 250 N of load [25]. Because of this wide variance, lengthening is an additional important consideration in the choice of a fixation method when reconstructing a knee that is to be rehabilitated using exercises that repeatedly load the graft.

One premise on which the preceding discussion is founded is that the initial tension is maintained postoperatively. For the tension differences between high and low stiffness fixation methods to be realized in vivo, the initial tension must be maintained during the early healing period [33,43], which may not always be the case [9,37,39]. If not, then the tension during an open chain knee extension exercise would decrease accordingly, remembering that the interaction between fixation stiffness and ankle weight was not significant. This implies that the initial tension (affected by the fixation stiffness) and the active tension (affected by the ankle weight) are additive. Of course, if the initial tension is not maintained and a low fixation stiffness is maintained, then the AP laxity will increase.

In summary, when averaged over three fixation stiffnesses, the active graft tension increased modestly by 62 N for the highest ankle weight of 112.5 N. The graft tension decreased substantially (107 N on average) by using tibial and femoral fixation methods with a high combined stiffness because a lower initial tension was required for the high stiffness combinations. Because the fixation stiffness and ankle weight did not interact significantly, the graft tension can be approximated by adding the active tension to the initial tension. For a high stiffness fixation of 225 N/mm that requires a low initial tension of 45 N, the graft tension for the highest ankle weight was 112 N on average. Thus high stiffness fixation methods, which are also resistant to lengthening in the region of the fixation, may reduce the risk of graft construct lengthening during open chain knee extension exercises.

Acknowledgement

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