Original Article With Video Illustration

Predicting Quadrupled Graft Length and Diameter Using Single-Strand Tendon Dimensions in All-Inside Anterior Cruciate Ligament Reconstruction

Daniel B. Haber, M.D., Emily M. Brook, B.A., Kaitlyn Whitlock, P.A.-C., and Elizabeth G. Matzkin, M.D.

Purpose: To determine whether single-strand semitendinosus autograft or allograft dimensions can reliably predict quadrupled graft diameter and length. **Methods:** Intraoperative semitendinosus graft measurements were recorded for consecutive all-inside anterior cruciate ligament (ACL) reconstructions from 2013 to 2016 and retrospectively reviewed. Intraoperative single-strand tendon length and width and the corresponding quadrupled graft length and diameter were recorded. Pearson correlation coefficients were used to assess the linear association between single-strand width and quadrupled diameter, as well as between single-strand length and quadrupled length. Linear regression models were used to predict quadrupled values. To test the accuracy of the predicted quadrupled values, dimensions from an additional series of 30 all-inside ACL reconstructions were reviewed. **Results:** Seventy-three ACL reconstruction procedures were reviewed. We excluded 12 grafts because gracilis and semitendinosus constructs were used. Thus 61 semitendinosus quadrupled grafts (30 autografts and 31 allografts) were included. Single-strand width was associated with quadrupled diameter ($P = .012$), and single-strand length was associated with quadrupled graft length ($P < .001$). **Conclusions:** Quadrupled hamstring graft length and diameter may be accurately predicted based on length and width of the semitendinosus tendon used for all-inside, single-bundle ACL reconstruction. The ability to predict quadrupled graft dimensions can guide the surgeon in intraoperative decision making and ensure the desired ACL graft dimensions are achieved, thereby minimizing the risk of ACL reconstruction failure. **Level of Evidence:** Level III, retrospective comparative study.

Approximately 130,000 anterior cruciate ligament (ACL) reconstructions are performed annually in the United States.[1,2] The most common autograft types used to perform ACL reconstruction include bone–patellar tendon–bone, quadriceps tendon, and semitendinosus and/or gracilis tendon.[3-6] Recent attention has been directed toward the association between graft dimensions and outcomes. Previous efforts have correlated the cross-sectional area of ACL grafts with biomechanical properties and have suggested that diminutive grafts regardless of graft type are at increased risk of failure.[5,7-15] Specifically, studies have found that ACL grafts less than 8 mm in diameter are at increased risk of failure.[11,15] Spragg et al.[16] found that grafts ranging from 7 to 9 mm in diameter have a 0.82 times lower likelihood of requiring revision surgery with every 0.5-mm incremental increase in diameter. Therefore, ACL graft diameter has become an increasingly important consideration in optimizing patient outcomes.

The quadruple-strand semitendinosus hamstring graft is growing in popularity because of its larger diameter and superior biomechanical strength when compared with double-strand gracilis or semitendinosus hamstring grafts.[17] A quadruple-strand semitendinosus graft can be incorporated into an all-inside, single-bundle ACL reconstruction technique.[18,19] When this technique is used, it is essential that the quadrupled

From the Department of Orthopaedic Surgery, Brigham and Women's Hospital (D.B.H., E.M.B., K.W., E.G.M.); Harvard Combined Orthopaedic Residency Program (D.B.H.); and Department of Orthopaedic Surgery, Harvard Medical School (E.G.M.), Boston, Massachusetts, U.S.A.

The authors report that they have no conflicts of interest in the authorship and publication of this article. Full ICMJE author disclosure forms are available for this article online, as supplementary material.

Paper previously presented at: Arthroscopy Association of North America Annual Meeting, May 18-20, 2017, Denver, Colorado.

Received March 31, 2017; accepted August 11, 2017.

Address correspondence to Elizabeth G. Matzkin, M.D., Department of Orthopaedic Surgery, Brigham and Women's Hospital, 75 Francis St, Boston, MA 02115, U.S.A. E-mail: ematzkin@bwh.harvard.edu

0749-8063/17504/$36.00
http://dx.doi.org/10.1016/j.arthro.2017.08.257

graft length be less than the sum of the femoral and tibial socket lengths plus the intra-articular graft distance to prevent the graft from bottoming out in the sockets during final tensioning.[18,19] These considerations highlight the importance of accurate estimations of quadrupled graft length and diameter during graft preparation.

The ability to consistently create a quadrupled semitendinosus graft that meets the required dimensions can be challenging. Such difficulty has fueled attempts to predict hamstring tendon autograft size before harvest using diagnostic imaging and anthropometrics.[11,20-23] Previous studies have used patient height and thigh circumference to predict quadrupled graft diameter, with varying success. Others have measured the cross-sectional area of hamstring tendons on magnetic resonance imaging to predict quadrupled graft diameter.[24,25] However, there is a paucity of literature that has sought to predict quadrupled graft length and diameter intraoperatively from single-strand tendons.

The ability to predict graft diameter and length allows the surgeon to predetermine the allograft or autograft size needed to prepare a quadrupled graft of adequate dimensions, individualized for patient size and primary or revision reconstruction. The purpose of this study was to determine whether single-strand semitendinosus autograft and allograft dimensions can predict quadrupled graft diameter and length. Our hypothesis was that single-strand tendon width and length would be able to predict quadrupled graft diameter and length, respectively.

Methods

Sample and Procedure

Intraoperative measurements of ACL graft dimensions were prospectively collected in a consecutive series of 73 all-inside ACL reconstructions from 2013 to 2016 and retrospectively reviewed for the purpose of this study. The inclusion criteria consisted of quadrupled grafts prepared from a single-strand semitendinosus tendon and used in all-inside, single-bundle ACL reconstruction. Twelve grafts were excluded because of the combined use of semitendinosus and gracilis tendons. In the 12 excluded grafts, gracilis augmentation was used to achieve a greater graft diameter. Single-strand tendon width (measured at the center of the tendon) and length were measured in millimeters with a surgical hand ruler. The tendon was not placed under tension for single-strand measurements. Final quadrupled graft length and diameter were measured after the graft had been placed under 10 to 15 lb of tension for a minimum of 5 minutes. Quadrupled graft diameter was measured by use of standard graft-sizing blocks (0.5-mm increments). The quadrupled graft diameter was determined when the entire quadrupled graft fit easily through the sizing block and would not fit through the 0.5-mm smaller size. All measurements were performed by 2 of the authors (E.G.M. and K.W.) involved in graft preparation and were mutually agreed on before the measured values were recorded. After statistical analysis of the included semitendinosus grafts, intraoperative graft dimensions were prospectively collected and retrospectively reviewed from an additional 30 consecutive ACL reconstructions performed in 2016 by 2 fellowship-trained sports medicine surgeons (including E.M.) to characterize the accuracy of predicted values. The same graft preparation and measurement techniques were used for these additional 30 cases. This study was reviewed and approved by the authors' institutional review board.

Graft Preparation Technique

This study used a previously described quadrupled technique for soft-tissue graft preparation (semitendinosus autograft or allograft) with adjustable buttons.[19] The technique described in this section and shown in Video 1 (available at www.arthroscopyjournal.org) was used for graft preparation after a semitendinosus autograft was harvested or a semitendinosus allograft was defrosted.

Two cortical suspensory buttons are placed on the graft preparation board with the button slots and suture loops facing each other. The length of the single-strand semitendinosus tendon is measured with a ruler. The width is measured at the center of the tendon with a hand ruler (Fig 1A). One end of the graft is placed through the first suture loop so that the graft is doubled and the tail ends are equal in length (Fig 1B). One free tail is taken and loaded through the bottom of the second suture loop and the other through the top of the same suture loop to form a quadrupled construct (Fig 1C).

For autograft preparation, 1 tail of the tendon was previously whipstitched with a suture during graft harvest with the needle still attached to the loop. A second suture is used to whipstitch the free tail 2 cm from the end of the tail (Fig 2A). For allograft preparation, the 2 tails are whipstitched together 2 cm from the tail ends (Fig 2B). The whipstitch needle can then be passed through the graft on the side of the first loop to tuck in the tails (Fig 2C). A sizing block is used to measure the quadrupled graft diameter (Fig 2D).

The quadrupled graft is then sutured to incorporate all 4 limbs using a No. 2 suture. Two throws are made 20 mm from the ends of the quadrupled graft, and 2 throws are made 10 mm from the ends of the quadrupled graft, for a total of 4 throws (Fig 3 A and B; Video 1 [available at www.arthroscopyjournal.org]). The quadrupled graft length and diameter are measured with a hand ruler and sizing block,

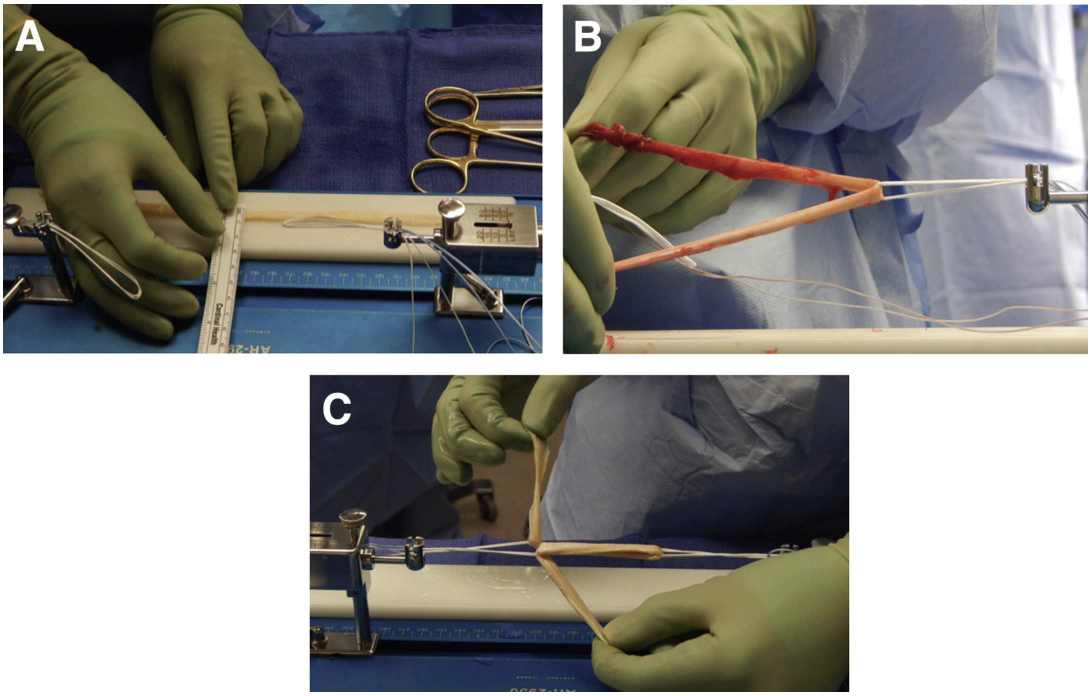

Fig 1. (A) The single-strand semitendinosus tendon is measured. The width is measured at the center of the graft by use of a surgical hand ruler, and the length is measured on the graft board ruler. The tendon is placed into the first loop to form a doubled construct (B) and then loaded through the top of the second loop, followed by the bottom of the second loop, to form a quadrupled construct (C).

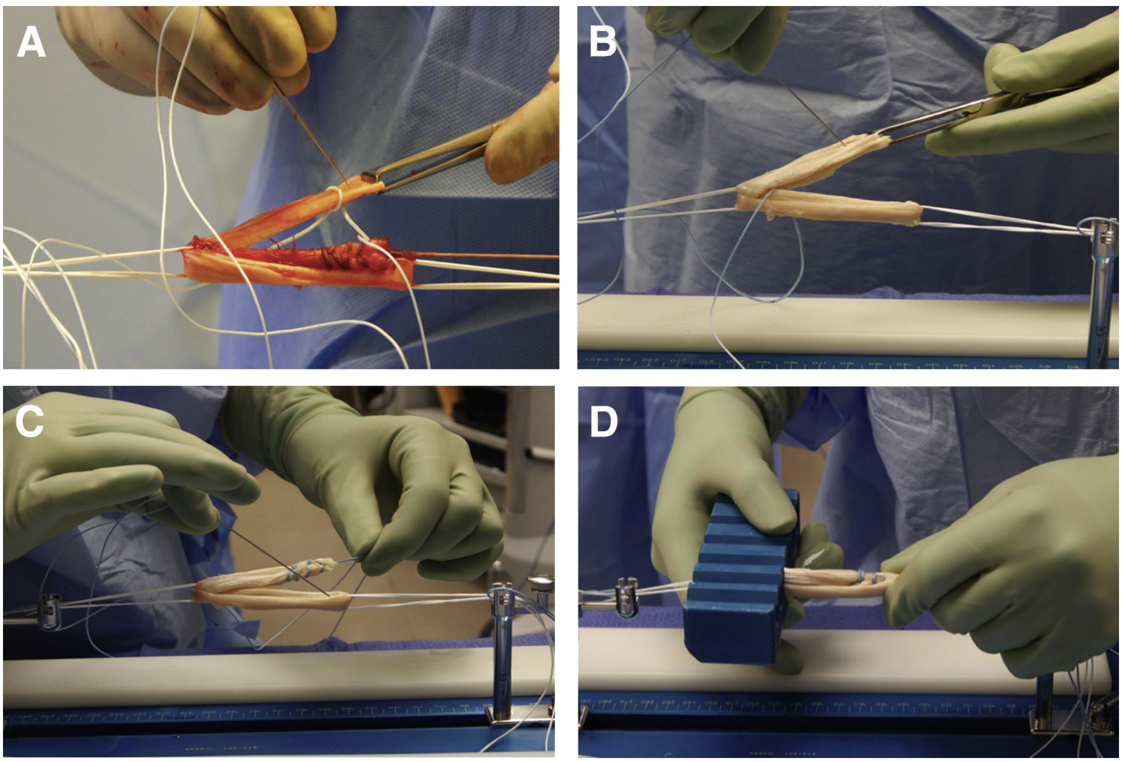

Fig 2. The second free tail of the semitendinosus autograft is whipstitched (A), and if the surgeon is preparing an allograft, the 2 free tails are whipstitched together (B). (C) The whipstitched ends are passed through the graft to tuck in the tails and form the quadrupled construct. (D) The approximate diameter is measured with a standard graft-sizing block.

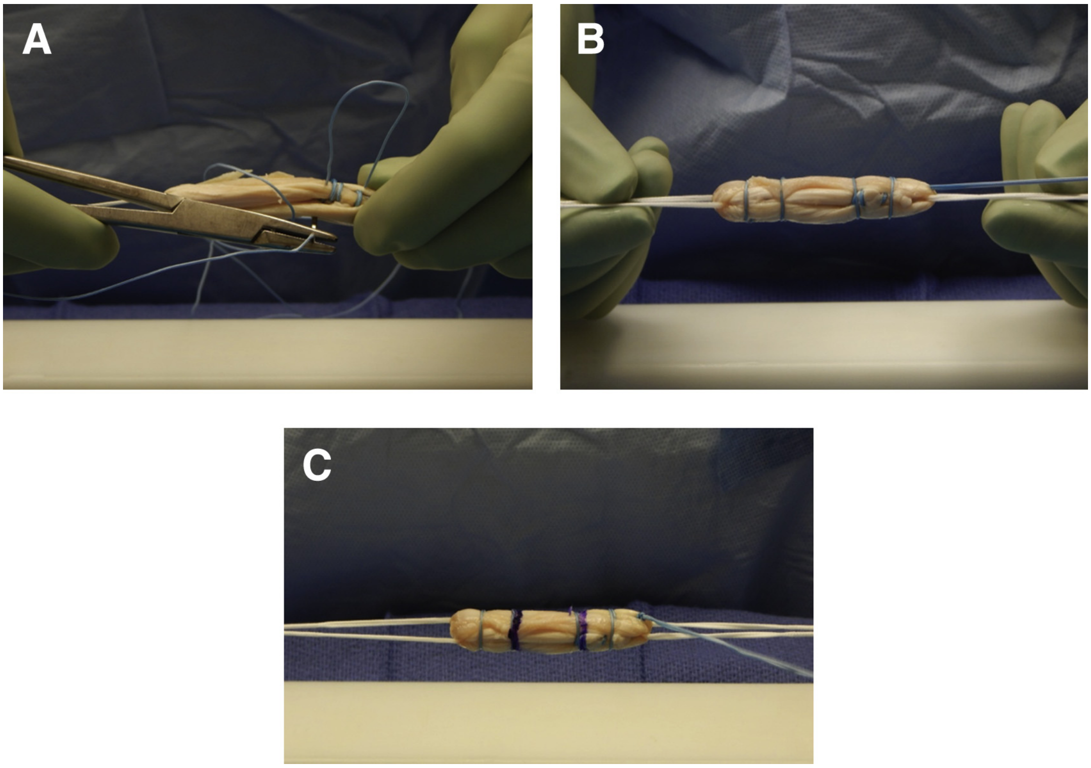

Fig 3. The quadrupled construct is sutured together with No. 2 suture (A) for a total of 4 throws (B). (C) The graft is marked with a marking pen 2 cm from each end to act as a visual aid for the amount of graft in the femoral and tibial tunnels during graft placement.

respectively, after the graft is placed under 10 to 15 lb of tension for a minimum of 5 minutes. The length of graft to be placed into the femoral and tibial sockets is marked to serve as a visual reference when pulling the graft into the respective sockets (Fig 3C). All grafts in this study were marked 20 mm from each end to ensure that approximately 20 mm of graft was equally pulled into the femoral and tibial sockets.

Statistical Methods

We first described the overall graft characteristics by comparing single-strand length, single-strand width, quadrupled length, and quadrupled diameter overall and by graft type (allograft vs autograft). To evaluate the linear association between single-strand size and quadrupled size, we assessed Pearson correlation coefficients between single-strand length and quadrupled length, as well as between single-strand width and quadrupled diameter. We then used simple linear regression to predict quadrupled length and diameter from single-strand length and width, respectively, as well as graft type. Finally, we used multiple linear regressions to assess the association between quadrupled dimensions and single-strand dimensions, adjusting for graft type. We assessed collinearity for multiple regression models using the variation inflation factor score; a variation inflation factor score of greater than 10 is considered evidence of collinearity. The 30 intraoperative graft dimensions collected after statistical analysis were assessed for accuracy, which was defined as the predicted quadrupled construct value minus the intraoperative quadrupled construct value for both length and diameter.

Results

A total of 61 semitendinosus grafts (83.6%) met the inclusion criteria. Twelve grafts were excluded because of the combined use of semitendinosus and gracilis tendons. Of the grafts included in the final cohort, 31 (50.8%) were semitendinosus autografts and 30 (49.2%) were semitendinosus allografts. For the overall cohort ($n = 61$), the mean and range for single-strand width and length, in addition to quadrupled diameter and length, are presented in Table 1.

We observed a modest correlation between single-strand width and quadrupled diameter, with a Pearson correlation coefficient of 0.32 ($P = .012$). Bivariate analysis indicated that single-strand width was significantly associated with quadrupled diameter ($P = .012$). On average, an increase of 1 mm in single-strand graft width led to an increase of 0.366 mm in quadrupled graft diameter (Table 2). Multiple linear regression showed a significant association between single-strand width and quadrupled diameter ($P = .015$), with adjustment for length and type of graft. Type of graft

Table 1. Intraoperative Single-Strand and Quadrupled Graft Dimensions

	Width, mm	Diameter, mm	Length, mm
Single-strand tendon (n = 61)	6.4 ± 0.46 (6-8)	—	246.4 ± 10.7 (180-260)
Quadrupled construct (n = 61)	—	9.2 ± 0.53 (8-11)	62.0 ± 2.2 (51-65)

NOTE. Data are presented as mean ± standard deviation (range).

was not associated with final diameter ($P = .95$). There was no evidence of collinearity on multiple regression analysis.

We identified a correlation between single-strand length and quadrupled graft length, with a Pearson correlation coefficient of 0.68 ($P < .0001$). On bivariate analysis, single-strand length was associated with quadrupled length ($P < .0001$). On average, an increase of 1 mm in single-strand length was associated with an increase of 0.14 mm in quadrupled length (Table 2). With adjustment for single-strand length and type of graft, the association between single-strand length and quadrupled length remained significant ($P < .0001$). Type of graft was not found to be significantly associated with quadrupled graft length ($P = .93$). We did not find any evidence of collinearity on multiple regression analysis.

An additional 30 intraoperative graft measurements (13 autografts and 17 allografts) were retrospectively reviewed from a series of consecutive ACL reconstructions to determine the accuracy of predicted values (Table 3). Accuracy was defined as the difference between the predicted value for graft diameter or length and the actual value recorded intraoperatively. Of the quadrupled graft diameters, 26 (87%) were within 1 mm of the predicted diameter. Of the quadrupled graft lengths, 25 (83%) were within 3 mm of the predicted length.

Discussion

The main finding of this study is that quadrupled hamstring graft length and diameter may be accurately predicted from single-strand semitendinosus graft length and width, respectively, in all-inside, single-bundle ACL reconstruction. These findings hold true for both allografts and autografts. The data presented in this study add to the growing body of literature on ACL surgical planning and provide an intraoperative reference for surgeons using the all-inside, quadrupled ACL reconstruction technique to help ensure desired graft dimensions are met.

Inadequate ACL graft size has been implicated as a cause of ACL reconstruction failure, contributing to the reported ACL reconstruction failure rate of 1.8% to 10.4%.[26] Some failures have been attributed to insufficient graft diameter, with several studies providing convincing evidence that a diameter of at least 8 mm is needed. Park et al.[15] performed a retrospective analysis of 296 patients who underwent hamstring autograft ACL reconstruction, and no failures were observed in patients with a graft diameter of 8 mm or more. Among patients with a graft size of less than 8 mm, Park et al. noted a revision risk of 5.2%. Magnussen et al.[27] conducted a retrospective study of 256 patients who had undergone ACL reconstruction; they found that 16 of 18 revision ACL reconstructions occurred in patients with hamstring autografts 8 mm in diameter or less. In a MOON (Multicenter Orthopaedic Outcomes Network) group study authored by Mariscalco et al.,[14] increased graft diameter was noted to correlate with improved patient-reported outcome scores. Revision was required in 0 of 64 patients with grafts greater than 8 mm in diameter and 14 of 199 patients (7.0%) with grafts 8 mm in diameter or smaller ($P = .037$). Last, Spragg et al.[16] found that grafts ranging from 7 to 9 mm in diameter have a 0.82 times lower likelihood of requiring revision surgery with every 0.5-mm incremental increase in diameter.

Complications in ACL reconstruction may also be associated with inadequate graft length. Highlighting this, Qi et al.[28] published a series of 40 adult canines that underwent ACL reconstruction with Achilles tendon grafts with varying graft lengths in the tibial bone tunnels. They found that the histologic maturity and biomechanical strength of the bone-tendon junction after ACL reconstruction were delayed at an early stage if the intratunnel graft length was less than

Table 2. Results of Linear Regression Models Predicting Quadrupled Diameter and Length From Common Single-Strand Tendon Dimensions

	Predicted Quadrupled Diameter, mm	Predicted Quadrupled Length, mm
Single-strand tendon width, mm		
4.5-5.5	8.5-8.9	—
6-6.5	9.0-9.3	—
7-7.5	9.5-9.7	—
Single-strand tendon length, mm		
230-240	—	59.7-61.2
241-250	—	61.3-62.6
251-260	—	62.7-64.0
261-270	—	64.1-65.4
271-280	—	65.5-66.8

NOTE. The linear regression equations used were as follows: (1) Final diameter (mm) = 6.9 + 0.366 × Starting width (mm). (2) Final length (mm) = 26.83 + 0.143 × Starting length (mm).

Table 3. Accuracy of Quadrupled Diameter and Length Based on Predicted Values From 30 Grafts Prepared by 2 Surgeons

	Grafts (n = 30), n
Accuracy of predicted quadrupled graft diameter	
<0.5 mm	11 (37%)
0.5-1.0 mm	15 (50%)
>1.0 mm	4 (13%)
Accuracy of predicted quadrupled graft length	
<2.0 mm	16 (53%)
2.0-3.0 mm	9 (30%)
>3.0 mm	5 (17%)

NOTE. Accuracy is defined as the difference between the predicted value and intraoperative quadrupled graft value.

15 mm. They suggested that 15 mm is the minimum acceptable amount of intratunnel graft to allow satisfactory early tendon-bone healing. Mariscalco et al.[29] evaluated patient-reported outcome scores based on varying graft lengths in human femoral tunnels. They concluded that as little as 15 mm of intratunnel length in the femur can be used without adverse consequences.

Although additional studies are needed to identify the ideal intratunnel graft length, many surgeons aim to place at least 15 mm of graft within bone tunnels in an attempt to optimize bone-to-graft healing. To do so, surgeons must also account for the intra-articular distance to ensure the graft will be of sufficient length. At the same time, the surgeons must ensure that the graft is not too long, exceeding the sum of the intra-articular distance and the length of the tibial and femoral sockets when using an all-inside technique. If this were to occur, the graft would bottom out in the sockets and prevent in situ graft tensioning, leading to instability and failure.

Recognizing the importance of preparing ACL grafts of specific dimensions, several studies have attempted to predict hamstring tendon autograft size before graft harvest as a way to plan for ACL reconstruction.[11,22,23] Asif et al.[24] found, in their sample of 46 patients, that 4-strand semitendinosus and gracilis hamstring graft diameter was directly associated with patient height and thigh circumference. They concluded that the following equation can be used: Graft diameter (mm) = 0.079 height (cm) + 0.068 thigh circumference (cm) − 9.031. Grawe et al.[25] used the preoperative magnetic resonance imaging cross-sectional area of the hamstring tendons in 84 patients undergoing ACL reconstruction to predict the quadrupled 4-strand semitendinosus-plus-gracilis graft diameter. They found that a combined (semitendinosus plus gracilis) total cross-sectional area of greater than 22 mm^2 can reliably provide a graft diameter of greater than 8 mm at the time of surgery. They also identified young age, short stature, and female sex as risk factors for producing an at-risk graft size smaller than 8 mm in diameter.

Although these techniques have proved useful in some respects, none have focused on predicting the diameter and length of the quadrupled graft used in all-inside, single-bundle ACL reconstruction. As the use of the all-inside, quadruple-strand semitendinosus graft technique grows in popularity, it is important that surgeons be able to meet specific graft size parameters to provide each patient a graft that minimizes the risk of failure.

The ability to predict quadrupled graft dimensions intraoperatively from single-strand allograft or autograft may help determine when graft augmentation is necessary. For instance, if a harvested single-strand semitendinosus tendon is less than 6 mm in width, the predicted quadrupled diameter will likely be less than 9 mm (Table 2). In this scenario, we would recommend augmentation with the gracilis tendon to achieve a quadrupled graft diameter greater than 8 mm, thereby reducing the risk of graft failure.[11,15] We use the predicted graft diameter of 9 mm as our cutoff for single-strand use, given that the data presented in Table 3 indicate that 87% of predicted grafts will be within 1 mm of the predicted value, and the MOON group data suggest a graft greater than 8 mm in diameter is needed to decrease the risk of failure.[14] When using allograft tendon, the surgeon should choose an allograft of appropriate dimensions to yield a predicted quadrupled graft size greater than 9 mm.

With respect to quadrupled ACL graft length, using the values presented in Table 2, a surgeon may choose to trim the single-strand length to achieve a length that corresponds to the desired quadrupled length. For example, a surgeon may want to prepare a shorter total graft length for a patient with a smaller knee. As noted earlier, regardless of patient size, the surgeon should plan for at least 15 mm of graft to be placed into each bone socket to optimize bone-to-tendon healing.

Limitations

One limitation of this study is that our data have not been formally validated. However, in an effort to provide pilot data to preliminarily show the reproducibility and accuracy of our results, the intraoperative measurements of 30 additional semitendinosus grafts (prepared by 2 independent surgeons) for all-inside ACL reconstruction were recorded. These results show that the predicted values for diameter are within 1 mm of the prepared quadrupled graft 87% of the time and the values for length are within 3 mm 83% of the time (Table 3).

Additional limitations of this retrospective study include a limited sample size of 61 semitendinosus grafts used in ACL reconstruction cases. Standard surgical measuring methods with a simple surgical hand ruler and standard graft-sizing block were used for all measurements rather than digital calipers with micrometer increments; therefore, the measurements are subject to some variability. Furthermore, the predicted quadrupled graft dimensions are dependent on the graft preparation techniques used by the surgeon. The results are also limited to only surgeons preparing a quadrupled semitendinosus graft for all-inside, single-bundle ACL reconstruction and are not applicable to surgeons using other types of grafts or techniques.

Conclusions

Quadrupled hamstring graft length and diameter may be accurately predicted based on length and width of the semitendinosus tendon used for all-inside, single-bundle ACL reconstruction. The ability to predict quadrupled graft dimensions can guide the surgeon in intraoperative decision making and ensure the desired ACL graft dimensions are achieved, thereby minimizing the risk of ACL reconstruction failure.

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