Prevention of graft-tunnel mismatch during anatomical anterior cruciate ligament reconstruction using a bone-patellar tendon-bone graft

Graft-tunnel mismatch of the bone-patellar tendon-bone (BPTB) graft is a major concern during anatomical anterior cruciate ligament (ACL) reconstruction if the femoral tunnel is positioned using a far medial portal technique, as the femoral tunnel tends to be shorter compared with that positioned using a transtibial portal technique. This study describes an accurate method of calculating the ideal length of bone plugs of a BPTB graft required to avoid graft–tunnel mismatch during anatomical ACL reconstruction using a far medial portal technique of femoral tunnel positioning.

Based on data obtained intra-operatively from 60 anatomical ACL reconstruction procedures, we calculated the length of bone plugs required in the BPTB graft to avoid graft–tunnel mismatch. When this was prevented in all the 60 cases, we found that the mean length of femoral bone plug that remained in contact with the interference screw within the femoral tunnel was 14 mm (12 to 22) and the mean length of tibial bone plug that remained in contact with the interference screw within the tibial tunnel was 23 mm (18 to 28). These results were used to validate theoretical formulae developed to predict the required length of bone plugs in BPTB graft during anatomical ACL reconstruction using a far medial portal technique.

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Anatomical single bundle anterior cruciate ligament (ACL) reconstruction using a bone-patellar tendon–bone (BPTB) autograft is a proven method of treating ACL deficiency, especially in high-performance athletes. The method of positioning the femoral tunnel has evolved from the conventional transtibial technique to the far medial (anteromedial) portal technique. This reflects the reasoning that the far medial portal technique of femoral tunnel placement replicates the normal femoral attachment of the ACL more accurately, and thereby can potentially provide better rotational stability. However, a clear difference between the functional results of these two techniques is yet to be identified.

Although technically more challenging, the far medial portal technique is better than the transtibial technique in achieving consistent anatomical siting of the femoral tunnel. Graft–tunnel mismatch with BPTB grafts occurs because the patellar tendon is usually longer than the ACL. This mismatch becomes more obvious when the femoral tunnel is created using the far medial technique because it is shorter compared with the femoral tunnel that is created using the transtibial portal technique.

Arthroscopic data are available for the dimensions of the lateral femoral condyle and the reconstructed tibial tunnel and the reconstructed ACL, but surprisingly little information is available about the length of the bone plugs that remain in contact with interference screws in the femoral and tibial tunnels at the end of the ACL reconstruction, when it is performed using the far medial portal technique of femoral tunnel placement. There are currently no described methods in the literature on how to predict the length of bone plugs of a BPTB graft accurately to prevent graft–tunnel mismatch while performing anatomical ACL reconstruction using the far medial portal technique. The aim of this study was to generate theoretical formulae that can predict the required length of bone plugs in a BPTB graft in order to prevent graft–tunnel mismatch and to test the validity of these formulae.

Patients and Methods

This study included 83 patients who underwent arthroscopic ACL reconstruction at various hospitals in Mangalore (Karnataka, India) between September 2011 and December 2013 (Fig. 1). Four women were excluded from the study for two reasons: they constituted < 5%...
of the patients we treated and their femoral and tibial dimensions differ from those of men. Patients whose height was < 160 cm (n = 2) or who weighed < 60 kg (n = 4) or > 100 kg (n = 2) were also excluded because of anticipated differences in the dimensions of their bones. Patients with an associated posterior cruciate ligament (n = 4) or multiligament injury (n = 5) were also excluded as these might affect the accuracy of the measured length of reconstructed ACL, because of posterior subluxation of the tibia and the absence of a posterior cruciate ligament as a critical landmark for locating the tibial insertion site of the ACL. Two patients who met more than one of the above exclusion criteria were also excluded. The remaining 60 patients formed the study group.

**Positioning for surgery.** The limb was held in a thigh holder, with the hip in neutral and the knee and foot unsupported. The degree of flexion of the knee was the same in all cases (80°) when the measurements were taken, as this affects the distance between the centre of the intra-articular openings of the femoral and tibial tunnels.

**BPTB graft harvesting.** The length of the patellar tendon was recorded and standard bone plugs were harvested: the patellar plug measured 25 mm × 10 mm × 10 mm and the proximal tibial plug 30 mm × 10 mm × 10 mm. The width of the patellar tendon therefore, was 10 mm. After passing the graft through the tunnels (see below) but before fixation with the interference screws, we shortened the bone plug on the femoral end of the BPTB graft as necessary to prevent graft–tunnel mismatch at the tibial tunnel.

**Preparation of the femoral tunnel.** A far medial portal was created, and a Steinmann pin used to mark the entry point for the guide wire in the posterosuperior quadrant in a position that leaves 1.5 mm of posterior cortex intact; a 10 mm diameter tunnel was then created. A guide wire was introduced through the far medial portal and drilled from the entry point to emerge on the superolateral aspect of the knee. A 4.5 mm cannulated reamer was used to ream the entire femoral condyle around the guide wire. The guide wire and 4.5 mm cannulated reamer were removed and the total length of the femoral condyle measured with a depth gauge. The guide wire was re-introduced and the condyle reamed to 9 mm less than the total measured length of the lateral femoral condyle using a 10 mm diameter acorn reamer.

**Preparation of the tibial tunnel.** A standard 11 mm tibial tunnel was created with an alpha angle of 50° (standard deviation (SD) 10°) and a beta angle of 25° (SD 5°). The length of the tibial tunnel was measured from the centre of
the in-tra-articular opening to the centre of the extra-articular opening at the level where the cortical bone is circumferentialy present. The distance between the centres of the intra-articular openings of the femoral and tibial tunnels was measured with a depth gauge; this represents the reconstructed length of the ACL.

**Preparation of the graft.** The patellar bone plug of the BPTB graft was meant for femoral fixation and the tibial bone plug of the BPTB graft was meant for tibial fixation of the reconstructed ACL. One drill hole was made on the patellar bone plug of the BPTB graft and a no.5 polyester suture was passed through the drill hole. Similarly, on the tibial bone plug the end of the BPTB graft was prepared with two drill holes and two no.5 polyester sutures.

**Positioning and fixation of the graft.** Both ends of suture in the patellar bone plug of the BPTB graft was passed through the tibial tunnel and retrieved through the far medial portal. A 2.4 mm Beath pin (Smith and Nephew, Mumbai, Maharashtra) was passed through the far medial portal into the femoral tunnel and the proximal end was secured on the superolateral aspect of the knee external to the skin. The Beath pin was loaded with the both ends of the suture retrieved from the patellar end of the BPTB bone graft and the Beath pin was pulled out completely to retrieve the sutures from the superolateral aspect of the knee. The graft was pulled in to sit flush with the retained 9 mm outer cortex of the femoral tunnel and tensioned on both ends to see how much of the bone plug was inside the tibial tunnel. A minimum of 18 mm inside the tibial tunnel was considered adequate. In cases where there was between 14 mm and 18 mm of plug inside the tibial tunnel, the graft was rotated up to $540^\circ$ to allow at least 18 mm to be placed inside the tunnel. If $< 14$ mm of bone plug was inside the tibial tunnel, the graft was withdrawn and the femoral bone plug was shortened to allow at least 18 mm to reside within the tibial tunnel. Final fixation of the graft was achieved with titanium interference screws (Fig. 2).

**Theoretical formula for calculating the length of ‘FP’ and ‘TP’**. From Figure 2, the relationship between ‘A’ (length of the femoral tunnel), ‘B’ (intra-articular distance between the femoral and tibial tunnels), ‘C’ (length of the tibial tunnel) and ‘FP’ (length of the femoral plug), ‘PT’ (length of the patellar tendon) and ‘TP’ (length of the tibial plug) can be represented as follows:

**Formula 1**: $A + B + C = FP + PT + TP$

The relationship between ‘B’, ‘a’ and ‘PT’ can be represented as $PT = B + 2a$.

Rearranging this in terms of ‘a’ gives:

**Formula 2**: $a = (PT – B) / 2$

The relationship between ‘a’, ‘FP’ and ‘A’ can be represented as $A = FP + a$. Substituting the value of ‘a’ from formula 2 gives $A = FP + (PT – B) / 2$. Rewriting this in terms of ‘FP’ gives:

**Formula 3**: $FP = A – [(PT – B) / 2]$

The relationship between ‘a’, ‘TP’ and ‘C’ can be represented as $C = TP + a$. Substituting the value of ‘a’ from formula 2 gives $C = TP + (PT – B) / 2$. Rewriting it in terms of ‘FP’ gives:

**Formula 4**: $TP = C – [(PT – B) / 2]$

**Statistical analysis.** The mean of ‘A’, ‘B’, ‘C’, ‘FP’, ‘PT’ and ‘TP’ were calculated including their variance, $\sigma$, standard error and 95% confidence intervals (CI). The maximum sample size required to generalise each individual value of ‘A’, ‘B’, ‘C’, ‘FP’, ‘PT’ and ‘TP’ that we to the obtained normal population was calculated using the formula,

$$n = \frac{z^2 \cdot \sigma^2}{\varepsilon^2}$$

where ‘$n$’ is the required sample size of ‘A’ or ‘B’ or ‘C’ or ‘FP’ or ‘PT’ or ‘TP’, ‘$z$’ is the $z$-score for the 95% CI (1.96), ‘$\varepsilon$’ is the acceptable error (0.05), $\sigma$ is the standard deviation and ‘$x$’ is the mean of ‘A’ or ‘B’ or ‘C’ or ‘FP’ or ‘PT’ or ‘TP’.

The mean values of ‘A’, ‘B’, ‘C’, ‘FP’, ‘PT’ and ‘TP’ were substituted in Formula 1, the mean values of ‘A’, ‘B’, ‘FP’, ‘PT’ were substituted in formula 2, the mean values of ‘B’, ‘C’, ‘FP’, ‘PT’ were substituted in formula 3 and the mean values of ‘B’, ‘C’, ‘PT’, ‘TP’ were substituted in formula 4 to test the internal validity. An error of $< 5\%$ in the numerical value obtained after substitution of actual mean values on either side of formulae 1, 3 and 4 was considered acceptable in order to prove internal validity of the formulae.

**Results**

The mean, range, variance and 95% CIs of ‘A’, ‘B’, ‘C’, ‘FP’, ‘PT’ and ‘TP’ are shown in Table I. The maximum sample size required to generalise the results of ‘A’, ‘B’, ‘C’, ‘FP’, ‘PT’ and ‘TP’ to a normal population was found to be $< 60$. 

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**Fig. 2**

A bone–patellar tendon–bone graft placed in the femoral and tibial tunnels, with perfect graft/tunnel matching. ‘A’ is the distance between the centres of the intra- and extra-articular openings of the femoral tunnel, which excludes the 9 mm outer cortex (*) that is not prepared with a 10 mm reamer; ‘B’ is the distance between the centres of the intra-articular openings of the femoral and tibial tunnels (i.e. the length of the reconstructed ACL); ‘C’ is the distance between the centres of the intra- and extra-articular openings of the tibial tunnel; ‘FP’ is the final length of the femoral bone plug that has contact with the interference screw within the tunnel; ‘PT’ is the length of the patellar tendon; ‘TP’ is the final length of the tibial bone plug that has contact with the interference screw within the tunnel; ‘$a$’ is half of the length of the patellar tendon that is in excess of the required length of the reconstructed ACL.
the surgeon believes that a femoral bone plug of 12 mm is required length of these bone plugs of a BPTB graft, the minimum accepted length of a tibial plug. This is based on their finding that the medial and lateral femoral condylar depths are the same, we calculated the mean width of the lateral femoral condyle using the formula:

\[
\text{Mean femoral condylar width} = (\text{mean bicondylar width} - \text{mean intercondylar width}) / 2.
\]

This method will allow the surgeon to introduce a femoral plug of at least 21 mm (12 mm + 9 mm) in length in cases where the patellar tendon is 52 mm.

It is also important to decide which of the two bone plugs should be longer in order to achieve the best possible fixation. The minimum length of femoral plug that we considered acceptable was 12 mm, which is 6 mm less than the minimum accepted length of a tibial plug. This is based on the fact that, unlike the tibial tunnel, which will be in line with the reconstructed ACL, the femoral tunnel is oriented at a divergent angle to the reconstructed ACL when the femoral tunnel is placed anatomically through a far medial portal. This divergence between the femoral tunnel and the reconstructed ACL by itself improves the pull-out strength of the femoral bone plug.

There are several important limitations to this study. The results require external validation to be applicable to races other than the studied population. The dimensions of the femoral condyle and tunnel had been measured in the Caucasian and Chinese populations. Terzidis et al. reported on femoral condylar morphology in Caucasians using 360 dried femora. They found that the mean values of the bicondylar and intercondylar widths in male Caucasians were 8.86 cm (SD 0.42) and 2.20 cm (SD 0.18), respectively. Assuming that the width of each femoral condyle is the same, based on their finding that the medial and lateral femoral condylar depths are the same, we calculated the mean width of the lateral femoral condyle using the formula:

\[
\text{Mean femoral condylar width} = (\text{mean bicondylar width} - \text{mean intercondylar width}) / 2.
\]

By this method, the mean lateral condylar width was estimated to be 33.3 mm, which is 0.4 mm greater than the result we obtained (23.9 mm of inner femoral cortex = 32.9 mm). This difference is clinically negligible, hence, we suggest that the results of our study are also applicable to male Caucasians.

Another limitation is the applicability of the results of our study to the female population. Again, reviewing the study of Terzidis et al., we found that the mean bicondylar and intercondylar widths in Caucasian women were 7.85 cm (SD 0.30) and 1.87 cm (SD 0.10), respectively, which is approximately 10% less than the values obtained for Caucasian men. Our figures were similar to that, though we only treated five female patients. If the intention is to use
these formulae for predicting the required length of bone plugs in BPTB graft for women, we recommend the use of constants which are 10% less, i.e., 34 and 42 instead of 38 and 46 in formulae 5 and 6, respectively, when calculating the length of the bone plugs for female patients.

The results may not be applicable to patients < 160 cm tall and who weigh < 60 kg or > 100 kg. We do not recommend using our formulae in these patients. Currently, we prepare the femoral and tibial tunnels, measure the intra-articular distance between the two, and decide to harvest the BPTB graft or use an alternative graft. The results are also not applicable to children.19

In spite of these limitations, we conclude that this method of calculating the required length of bone plugs in BPTB grafts was applicable to > 85% of the clinical situations we encountered in our practice.

Author contributions
C. K. Boddu: Performing surgeries; Writing the paper.
S. K. Arif: Writing the paper.
S. Sankaranarayanan: Writing the paper.
M. M. Hussain: Data collection.
P. R. Sujir: Writing the paper.

No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.

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References