Article

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Effect of the positional relationship between the interference screw and the tendon graft in the bone tunnel in ligament reconstruction

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Abstract

Purpose: To reveal the effects of the positional and length relationships between the interference screws (ISs) and the tendon graft in the bone tunnel on the fixation strength in ligament reconstruction. **Methods:** We compared three IS positions on the anterior (the Anterior group) or posterior (the Posterior group) or side (the Side group) of the tendon graft in relation to the pullout direction. The tendon graft was pulled at 0°, 30°, 60°, and 90° to the bone tunnel, and the maximum pullout load at each angle was compared among the groups. We also investigated the relationship between the length of the tendon graft and the length of the IS in the bone tunnel. The direction of the pullout force was the same as that of the Anterior group, and the maximum load was compared between groups in which the tendon graft was longer or shorter than the IS. **Results:** The maximum loads of the Anterior group were significantly greater than those of the Posterior and Side groups at the traction angles of 30° and 60°, respectively. An IS shorter than the tendon graft was found to provide significantly superior fixation strength compared to an *IS* longer than the tendon graft. **Conclusions:** Better fixation strength was achieved when the IS was placed on the side of the anchorage tunnel on which the tendon graft was loaded and the IS was shorter than the tendon graft.

Keywords

biomechanics, interference screw, ligament reconstruction, screw position

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Introduction

The reconstruction of ligaments using interference screws (ISs) and soft-tissue grafts is considered a standard clinical technique. Examples of this IS/graft technique are medial patellofemoral ligament (MPFL) reconstruction[1] and anterior talofibular ligament (ATFL) reconstruction.[2] The primary fixation strength of the tendon graft is recognized as an important factor in enabling the early rehabilitation of patients who have undergone ligament reconstruction.[3,4] Several authors have reported research pertaining to the primary fixation strength of the tendon grafts.[5–7] It was reported that the initial fixation strength of the tendon graft depended on the contact area of the IS and the tendon graft and the diameter of IS.[8–11] Stalder et al.[4] showed that the pullout force was increased with a short IS, because better graft fixation was achieved when the tip of the IS did not extend past the end of the tendon graft. However, to the best of our knowledge, there have been no reports focusing on the positional relationship between the IS and the tendon graft and the effect of the pullout direction of the tendon graft.

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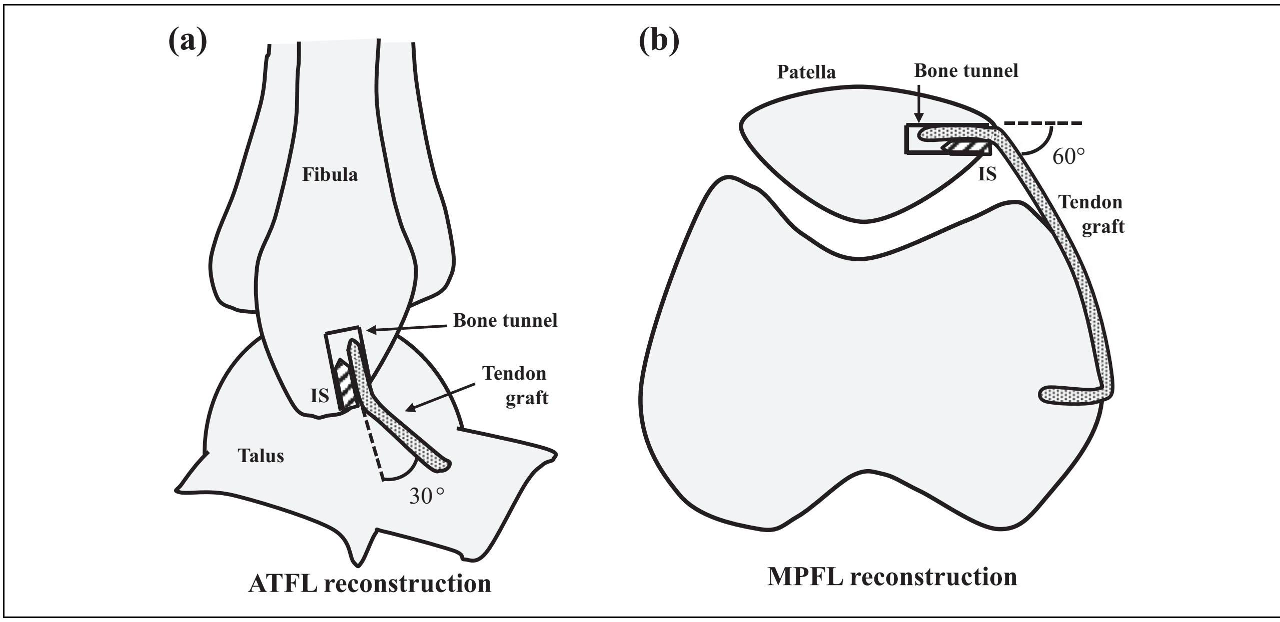

Figure 1. *Schema* of ATFL reconstruction (a) and MPFL reconstruction (b). The tendon grafts were pulled at angles of 30° and 60°, respectively. The positional relationship between the IS and the tendon graft in the bone tunnel may have an effect on the fixation strength of the tendon graft because of the biomechanical environment alteration around the bone tunnel. ATFL: anterior talofibular ligament; MPFL: medial patellofemoral ligament; IS: interference screw.

In clinical settings, the direction of the traction force of a tendon graft may differ according to the conditions in the particular region. For example, Takao et al.[2] applied this technique to ATFL reconstruction with a gracilis autograft, and Miyamoto et al.[12] reported good clinical outcomes with the use of this technique; in those cases, the theoretical traction angle was approximately 30° (Figure 1(a)). Kumahashi et al.[1] also reported good clinical outcomes when they reconstructed an MPFL with the semitendinosus tendon using the IS technique and a theoretical traction angle of approximately 60° (Figure 1(b)). In these cases, an oblique pullout force is added to the tendon graft, and the positional relationship between the IS and the tendon graft in the bone tunnel may have an effect on the fixation strength.

We thus hypothesized that there is an optimal fixation technique for the IS in situations in which an oblique pullout force is applied to a tendon graft. We conducted the present study to determine the precise effects of the positional and length relationships between the IS and the tendon graft in the bone tunnel on the fixation strength in ligament reconstruction.

Materials and methods

Tendon graft preparation

Tendon grafts were made from 200 fresh Achilles tendons of male Japanese black cattle (24 months old, body weight 450–550 kg), the quality of which was strictly controlled (Hokuyo Meat Center, Shimane, Japan). The elastic module of a cattle tendon (0.6 $\pm$ 0.2 GPa[13]) is assumed to be the same as that of a human tendon (0.45 GPa).[14] Only the middle third of the Achilles tendon of 100 mm length were used, and the cross-sectional surface was trimmed in a circle uniformly until it could be passed through a stainless steel tube with an inside diameter of 5.0 mm and with <20.0 N maximum reactive force. The average diameter of the tendons was 4.7 mm (standard deviation 0.2). One end of each tendon graft was sutured with US Pharmacopeial Convention size 3–0 monofilament nylon suture thread. All specimens were kept at room temperature (24 C) and moistened with saline.

Bone and IS preparation

First, 200 fresh-frozen mature male porcine patellae were prepared at the host site (Hokuyo Meat Center, Shimane, Japan). Five of them were selected at random, and the trabecular thickness (Tb. Th) and the trabecular separation (Tb. Sp) were measured using a micro-computed tomography (CT) scanner (TOSCANER-30900μC,[3] Toshiba, Tokyo, Japan). The Tb. Th and the Tb. Sp values of the five patellae were 150.0 $\pm$ 31.5 μm and 549.3 $\pm$ 143.2 μm, respectively. After all soft tissues were dissected from the patellae, an all-pass bone tunnel (7.0 mm diameter) was created from the medial to the lateral side of each patella (Figure 2(a)).

Cannulated stainless steel headless screws (Takayama, Tokyo, Japan) were prepared as the ISs. The dimensions of the ISs were 5.0 mm in outer diameter, 4.1 mm in inner diameter, 0.8 mm in pitch, and 10.0 and 20.0 mm in length.

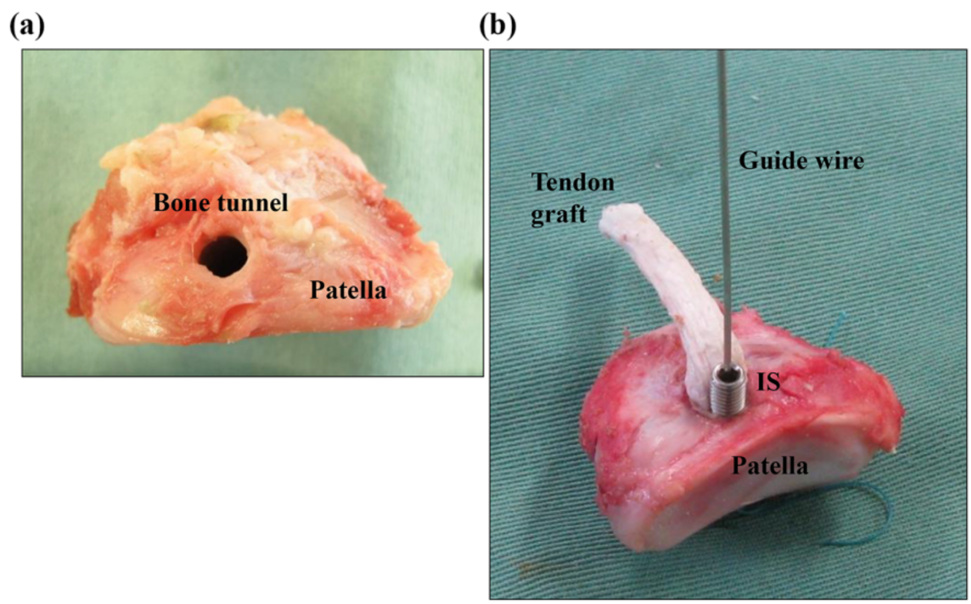

Figure 2. (a) Photograph of the patella and bone tunnel. (b) The fixing of the tendon graft using an IS. IS: interference screw.

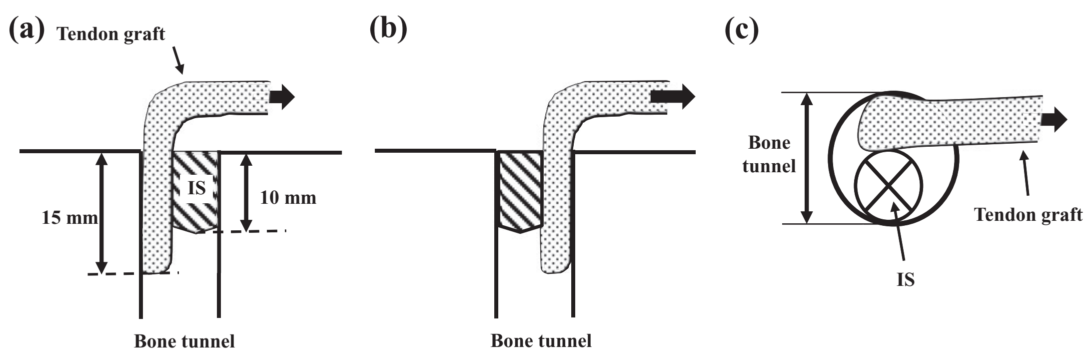

Figure 3. Schematic representation of the positional relationship between the IS and the tendon graft in the three groups. (a) and (b) Cross-sectional views of the bone tunnel. (c) A top-down view. Bold black arrow: The traction force. (a) The Anterior group. The IS was placed on the same side of the anchorage tunnel on which the tendon graft was loaded. (b) The Posterior group. The IS was placed on the side of the anchorage tunnel opposite that on which the tendon graft was loaded. (c) The Side group. The IS was placed next to the plane of the tendon graft. IS: interference screw.

The effect of the IS position

The tendon graft (15 mm on the sutured side) was inserted into the bone tunnel of the patella from the medial to the lateral side. After a 1.0-mm guidewire was inserted into the bone tunnel, the tendon graft was fixed with a 10-mm IS (Figure 2(b)). We classified the IS positions into three groups based on the positional relationship between the IS and the tendon graft. The IS was placed on the anterior (the Anterior group) or the posterior (the Posterior group) or the side (the Side group) of the tendon graft in relation to the pull-out direction (Figure 3(a) to (c)).

We performed a mechanical test using a tension meter (Instron 5565; Instron, Canton, MA, USA). In each group, the patella was clamped on the anteroposterior plane and then rotated around the center of the bone tunnel at 0°, 30°, 60°, or 90°, that is, the traction angle was defined as the angle between the axis of the bone tunnel and the actual traction axis (Figure 4). The end of the tendon graft was clamped, and the pullout strength of the tendon graft was measured for each angle with 10 specimens per group (total $n = 40$ per group). After the precondition of five cyclic loads between 1 N and 5 N, the load to failure was determined at a speed of 1 mm/s until the graft pulled out of the bone. The maximum load was defined as the load at which the force reached a peak (Figure 5). We compared the maximum pullout loads at each angle among the three IS-position groups.

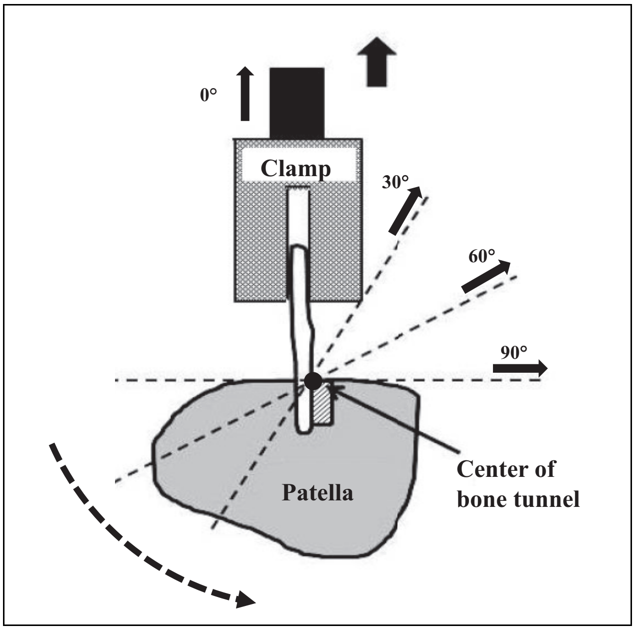

Figure 4. The patella was clamped on the anteroposterior plane and then rotated around the center of the bone tunnel at angles of 0°, 30°, 60°, and 90°. The pullout strength of the tendon graft was measured for each angle.

The relationship between the length of the tendon graft and that of the IS

Two other groups were defined according to the distance between the tendon graft and the IS in the bone tunnel: in the short-graft group, a 15-mm tendon graft was inserted into the bone tunnel and fixed with a 20-mm IS (Figure 6(a)); in the long-graft group, a 25-mm tendon graft was inserted into the bone tunnel and fixed with a 20-mm IS (Figure 6(b)). The mechanical test was performed following the method described above with 10 specimens per group, and the IS position was the same as that in the Anterior group (total $n = 40$ per group). We compared the maximum pull-out loads at each angle between the short-graft group and the long-graft group and between the long-graft group and the Anterior group.

Statistical analysis

All statistical analyses were performed using SPSS version 23 software (IBM, Armonk, NY, USA). The Kruskal–Wallis test and a post hoc test were used in all statistical analyses, and p values <0.05 were considered significant.

Results

In all specimens, the load-to-failure mode resulted in an initial elongation of the tendon graft, followed by slippage at the screw/tendon/bone interface at higher loads, until the graft exited the bone tunnel. The mean stiffness was 4.0 N/mm, with no significant differences among groups.

IS position

The maximum pullout loads of the Anterior group were superior to or equal to those of the Posterior and the Side groups (Figure 7). At the traction angle of 0°, the maximum pullout loads were 12.4 N (SD 3.3) in the Anterior group, 12.7 N (SD 3.0) in the Posterior group, and 12.6 N (SD 3.1) in the Side group, with no significant differences among groups (Anterior vs. Posterior, $p = 0.93$; Posterior vs. Side, $p = 0.96$; and Anterior vs. Side, $p = 0.96$).

At the 30° traction angle, the maximum pullout loads were 31.9 N (SD 8.3) in the Anterior group, 14.4 N (SD 3.6)

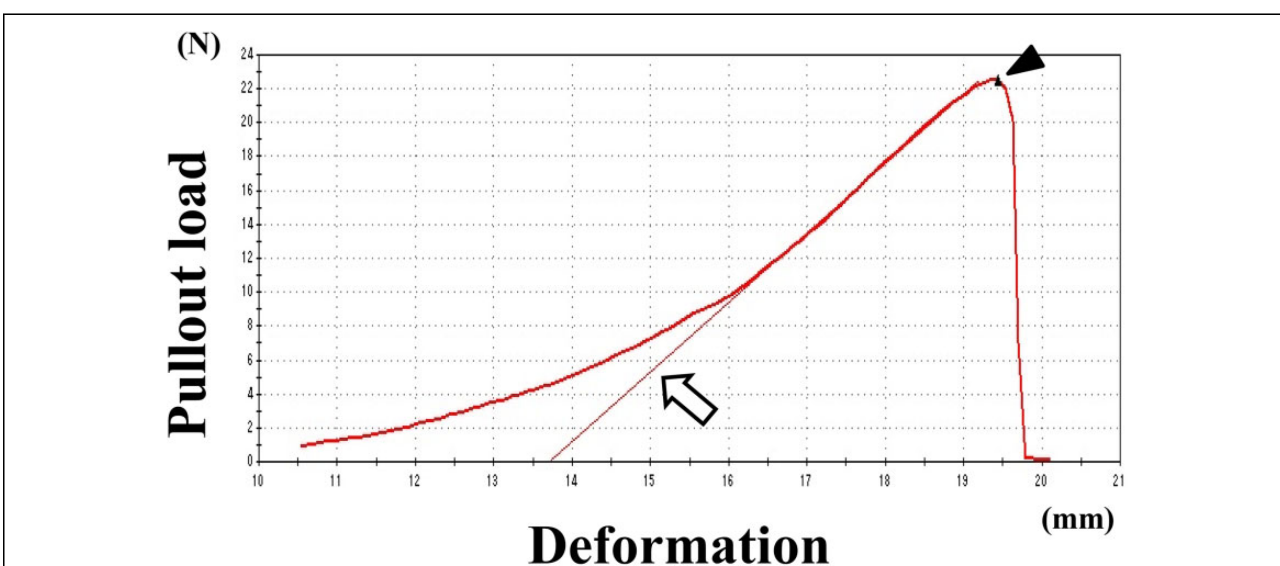

Figure 5. Pullout load–deformation curve. The load to failure was determined at a speed of 1 mm/s until the graft pulled out of the bone, and the maximum load was defined as the load at which the force reached a peak (black arrow head).

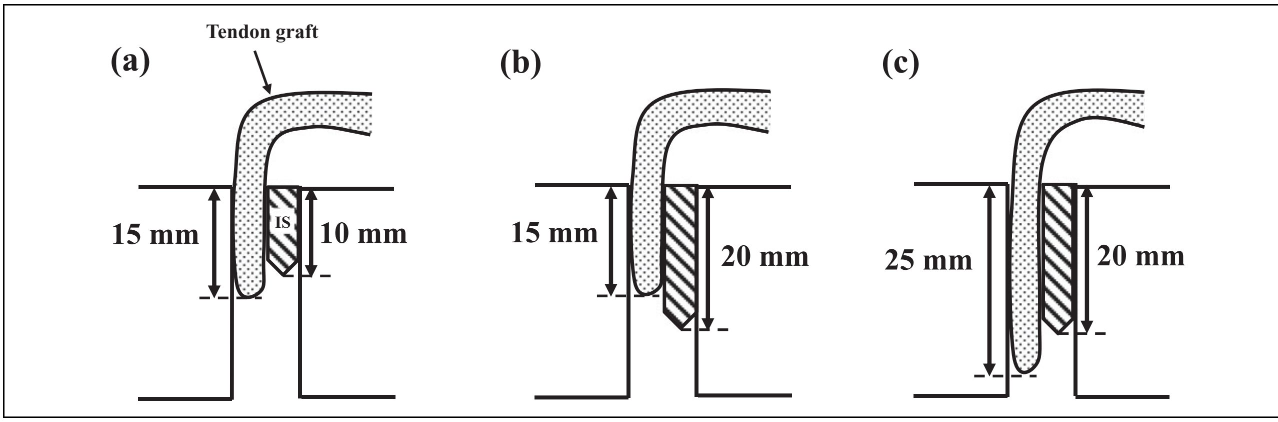

Figure 6. Schema of the short-graft and long-graft groups. (a) The short-graft group. A 15-mm tendon graft was inserted into the bone tunnel and fixed with a 20-mm IS. (b) The long-graft group. A 25-mm tendon graft was inserted into the bone tunnel and fixed with a 20-mm IS. The reference diagram is the schema of the Anterior group, the same as in Figure 3(a). IS: interference screw.

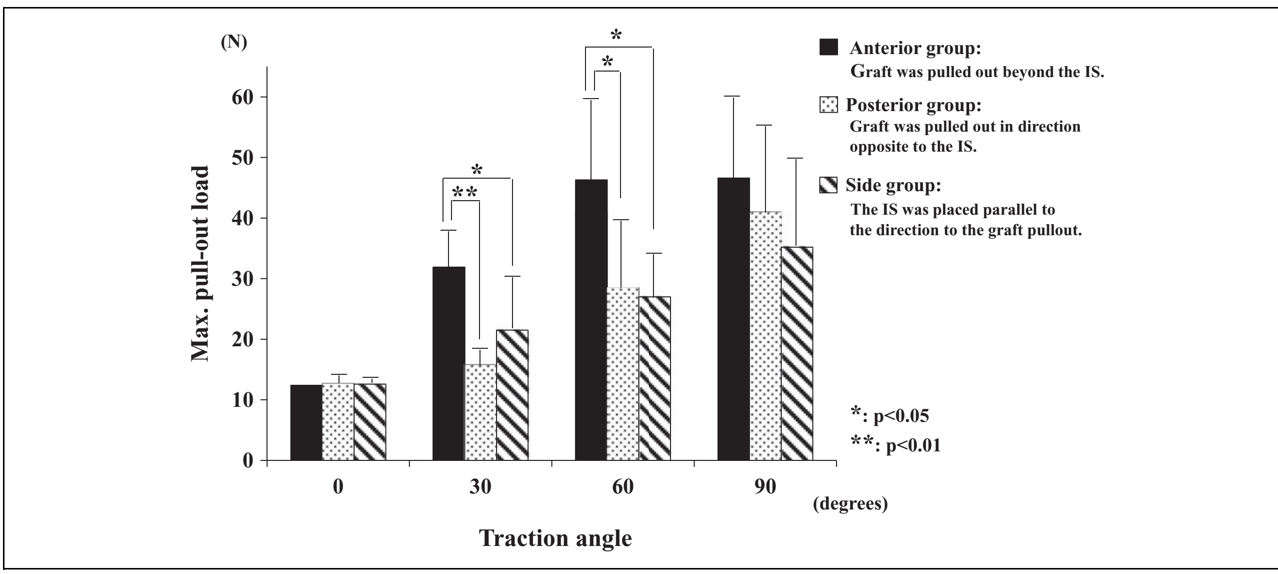

Figure 7. The mean maximum pullout loads of the Anterior, Posterior and Side groups at traction angles of 0°, 30°, 60°, and 90°. All values are mean ± SD.

in the Posterior group, and 21.5 N (SD 9.0) in the Side group. There were significant differences between the Anterior and the Posterior groups ($p = 0.0005$) and the Anterior and the Side groups ($p = 0.039$). At the 60° traction angle, the maximum pullout loads were 46.3 N (SD 9.1) in the Anterior group, 28.5 N (SD 12.0) in the Posterior group, and 27.0 N (SD 8.7) in the Side group. There were significant differences between the Anterior and the Posterior groups ($p = 0.047$) and the Anterior and Side groups ($p = 0.016$). At the traction angle of 90°, the maximum pullout loads were 46.6 N (SD 12.4) in the Anterior group, 41.0 (SD 12.1) in the Posterior group, and 35.2 N (SD 14.5) in the Side group. There were no significant differences among groups for this measure (Anterior vs. Posterior, $p = 0.54$; Posterior vs. Side, $p = 0.39$; Anterior vs. Side, $p = 0.059$).

Relationship between the length of the tendon graft and that of the IS

A tendon graft length longer than the IS provided superior fixation strength to a tendon graft length shorter than the IS, and this effect became pronounced as the traction angles increased (Figure 8). The different IS lengths resulted in no significant differences in fixation strength.

The maximum pullout loads of the short-graft group and long-graft group, respectively, were 8.3 N (SD 2.0) and 18.0 N (SD 8.3) for 0°, 20.6 N (SD 4.5) and 39.8 N (SD 11.0) for 30°, 25.7 N (SD 9.6) and 54.8 N (SD 16.1) for 60°, and 35.5 N (SD 11.8) and 60.1 N (SD 15.8) for 90°, revealing significant differences for all four traction angles ($p = 0.007$, $p = 0.009$, $p = 0.002$, and $p = 0.003$, respectively). The maximum pullout loads of the long-graft group tended

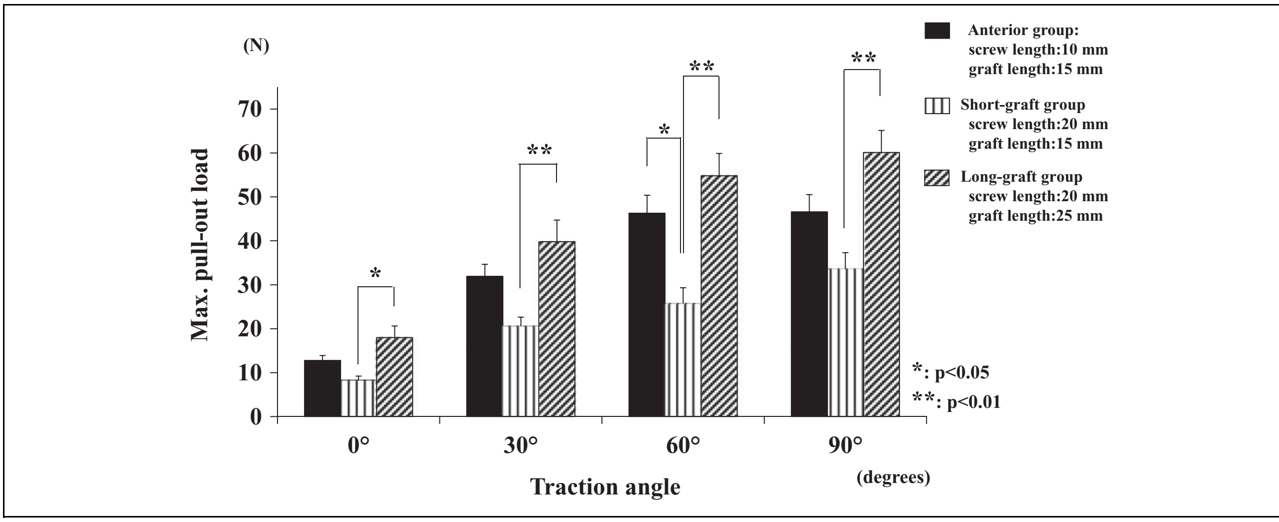

Figure 8. The mean maximum pullout loads of the short-graft and long-graft groups at traction angles of 0°, 30°, 60°, and 90°. All values are mean ± SD.

to be higher than those of the Anterior group for all traction angles, but there were no significant differences between the two groups (0°, $p = 0.17$; 30°, $p = 0.32$; 60°, $p = 0.46$; and 90°, $p = 0.052$).

The *differences* in the maximum pullout load between the short-graft group and long-graft group for the 30°, 60°, and 90° traction angles were two-, three-, and 2.7-folds higher than that for 0°, respectively.

Discussion

The most important finding of the present study was the confirmation of our hypothesis that an IS placed on the side of the anchorage tunnel on which the tendon graft is loaded can provide a higher level of fixation strength compared to an IS placed on a side of the anchorage tunnel opposite to that on which the tendon graft is loaded.

The use of an IS to fix a tendon graft in a bone tunnel is a straightforward and effective method, but there is concern about the initial fixation strength in this technique. The initial fixation strength of the tendon graft depends on the IS size and the relationship between the IS length and the tendon graft.[8–11] Regarding the length of the screw, it has been reported that the use of a longer screw resulted in higher maximum pullout loads.[8,9] On the other hand, Stalder et al.[4] showed that the pullout strength is increased with a short IS because a short IS can be caught on the tendon graft edge when a tendon graft longer than the IS is used.

With respect to the effect of the screw's diameter, it has been documented that the use of a smaller-diameter screw may predispose tendon slippage from the bone tunnel,[10] whereas the threads of larger screws can damage the graft.[15] However, in the mechanical tests of those studies, no regard was given to the traction angle. To the best of our knowledge, the effect of the positional relationship between the IS and the tendon graft at different traction angles was not examined before this study.

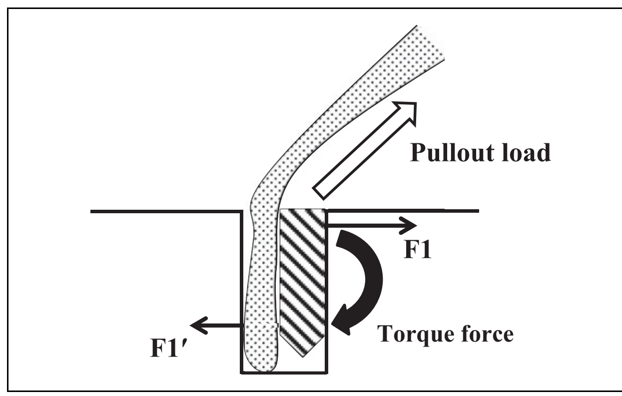

Figure 9. Torque force acting on the IS when the tendon graft is pulled. The horizontal component force vertical to the bone tunnel (F1) may be a transduced torque force of the IS and may behave as a crimping force of the IS on the tendon graft (F1′). IS: interference screw.

With regard to the IS position, the Anterior group achieved significantly higher strength compared to the Posterior and the Side groups at the traction angles of 30° and 60°, respectively. There were no significant differences between the Posterior and the Side groups at any traction angle. We speculate that the horizontal component force of the pullout load (F1 in Figure 9) may cause torque of the screw, thereby increasing its clamping effect against the bone tunnel (F1′ in Figure 9). In the Anterior group, this effect was seen at the traction angles of 30° and 60°. There were no significant differences among the groups at the traction angle of 90°, possibly because of the greater frictional force between the tendon graft and the edge of the bone tunnel.

If our hypothesis is correct, the effect of the IS position would disappear or lessen when the IS is longer than the tendon graft. To investigate this, we evaluate the relationship between the length of the tendon graft and the length of the IS. Our results revealed that the fixation strength was significantly higher at all traction angles when the IS was shorter than the tendon graft. In addition, our comparison of the short-graft group with the Posterior and the Side groups demonstrated that in those three groups the IS theoretically exerts no crimping force on the tendon graft (cf. F1' in Figure 9), and there were no significant differences in pullout load among the groups. These findings support our hypothesis.

On the other hand, the contact area between the IS and the tendon graft of the short-graft group was narrower than that of the long-graft group, and this difference might have had an effect on the fixation strength. In fact, the fixation strength of the long-graft group showed a tendency to be stronger than that of the Anterior group, but the difference was not significant. This difference may be the effect of the contact area. However, the Anterior group strongly tended to have a higher fixation strength than the short-graft group for all degrees of traction and a significantly higher strength at 60°, even though the contact area of the Anterior group was narrower than that of the short-graft group. Based on these findings, we speculate that a longer implant length increases the fixation strength, but this effect would be smaller than that of the IS position.

Even at the 0° traction angle, the maximum pullout load of the long-graft group was higher than that of short-graft group. Stalder et al.[4] showed that better fixation strength is achieved if the tip of the IS does not extend past the end of the tendon graft, and they theorized that if the end of the tendon graft is caught at the tip of the IS, the fixation strength is affected. We believe that the pullout load difference for the 0° traction angle observed in the present study reflects this idea, although the difference in the contact area as described earlier is considerable. The remaining loads, for which the pullout load of the 0° traction angle was subtracted from that of the other traction angles, may indicate the proper crimping forces described above. We thus suspect that the fixation strength of the tendon graft afforded by the IS is dominantly associated with two more components affecting the overall fixation strength in addition to the screw length and diameter: (1) the fixation strength obtained when the end of the tendon graft is caught at the tip of the IS and (2) the crimping strength of the tendon graft provided by the rotation of the IS.

Our study has some limitations. First, animal materials were used as a surrogate for human bone and tendon, and future experiments on human bone would better represent typical variations in bone quality and anatomy. However, a porcine bone model is well established in this context, and the similarity of porcine patellae to young human knee bones has been demonstrated.[16–18] The elastic modules of porcine bone and human bone have been measured at 18.0 $\pm$ 5.6 GPa and 17.0 GPa, respectively.[14,19] The microarchitecture of the human bone has been measured as 100–200 μm in Tb.Th and 600–900 μm in Tb.Sp,[20] and these measurements are similar to those of porcine bone as described earlier. In the light of these data, porcine bone is considered analogous to human bone in its physical properties. In addition, we used the Achilles tendons of male Japanese black cattle as a surrogate for human tendons. Previous research determined that the elastic module of cattle tendon is 0.6 $\pm$ 0.2 GPa,[13] whereas that of a human tendon is approximately 0.45 GPa.[14] We thus believe that cattle tendons can mimic human tendons at least in biomechanical tests.

Second, this was an in vitro study and therefore did not replicate functional loading and did not take into consideration in vivo variables such as graft healing and graft relaxation. A cyclic loading test might be necessary to simulate postoperative rehabilitation in which the graft construct is subjected to repetitive loading during the critical time period at which biological incorporation has not yet occurred. Nevertheless, we believe that the strength using a single pullout test ultimately provides sufficient information to reveal the effect of the positional relationship between the IS and the tendon graft in the bone tunnel.

Third, the screws and tendon grafts for the bone tunnels were thinner than those in a clinical setting. Specifically, the diameters of the IS and the graft were each equal to the bone tunnel diameter minus 2 mm. Therefore, the maximum pullout load showed values lower than that expected in a clinical setting (all <100 N). In a clinical setting, the maximum pullout strength must reach a magnitude that replicates those achieved here (>300 N).[21] We chose the present set-up to clarify the relationship between the IS and the tendon graft in the bone tunnel. Weiler et al.[11] showed that the maximum pull-out loads obtained when the diameter of the screw was equal to the graft diameter plus 1 mm were significantly higher than those obtained when the screw diameter equaled the graft diameter. It is possible that in clinical settings there would be no effect on the correlation between the IS position and graft tendon position in the bone tunnel because the IS (which is fixed tightly into the bone tunnel) does not undergo torque force like that shown in Figure 9. Theoretically, there is a certain amount of loosening of the IS in the bone tunnel when the IS, which is a hard material, is surrounded by tendon and bone, which are soft biomaterials. Therefore, the correlation between the fixation strength of a graft tendon and the IS position in the bone tunnel has important clinical implications. We believe that stronger fixation may be provided when the appropriate IS position is used in the bone tunnel in addition to the appropriate setup.

Fourth, the ISs used in our study were not medical IS screws, and the specifications of the two ISs are different; for example, the dimensions of the 5.0 cannulated TJ screw system (Meira, Aichi, Japan) are 5.0 mm in outer diameter, 3.5 mm in inner diameter, and 1.25 mm in pitch. However, the contribution of the inner diameter and pitch of the screw is lower than that of the outer diameter in terms of the strength of the screw-to-bone fixation.[22–24] To the best of our knowledge, there have been no reports focusing on the relationship between the dimensions of the IS and the tendon fixation. Therefore, we do not think that the differences in IS specifications have an effect on the universality of our present contention, which is the correlation between the fixation strength of the graft tendon and the IS position in the bone tunnel.

Conclusion

The positional and length relationships between the IS and the tendon graft in a bone tunnel affect the fixation strength. Based on our present findings, we conclude that the IS should be placed on the same side of the anchorage tunnel on which the tendon graft is loaded and that the tendon graft should be longer than the IS.

Declaration of conflicting interests

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