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BIOMECHANICS

Can barb thread design improve the pullout strength of bone screws?

A BIOMECHANICAL STUDY AND FINITE ELEMENT EXPLANATION

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Aims

To draw a comparison of the pullout strengths of buttress thread, barb thread, and reverse buttress thread bone screws.

Methods

Buttress thread, barb thread, and reverse buttress thread bone screws were inserted into synthetic cancellous bone blocks. Five screw-block constructs per group were tested to failure in an axial pullout test. The pullout strengths were calculated and compared. A finite element analysis (FEA) was performed to explore the underlying failure mechanisms. FEA models of the three different screw-bone constructs were developed. A pullout force of 250 N was applied to the screw head with a fixed bone model. The compressive and tensile strain contours of the midsagittal plane of the three bone models were plotted and compared.

Results

The barb thread demonstrated the lowest pullout strength (mean 176.16 N (SD 3.10)) among the three thread types. It formed a considerably larger region with high tensile strains and a slightly smaller region with high compressive strains within the surrounding bone structure. The reverse buttress thread demonstrated the highest pullout strength (mean 254.69 N (SD 4.15)) among the three types of thread. It formed a considerably larger region with high compressive strains and a slightly smaller region with high tensile strains within the surrounding bone structure.

Conclusion

Bone screws with a reverse buttress thread design will significantly increase the pullout strength.

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Keywords: Pullout strength, Buttress thread, Barb thread, Reverse buttress thread, Biomechanical study, Finite element study

Article focus

- Can barb thread design improve the pullout strength of bone screws when compared with buttress thread and reverse buttress thread? What is the underlying mechanism?

Key messages

- Reverse buttress thread showed the best pullout strength.
- Proximal flank angle affects the pullout strength of bone screws by altering the compressive and tensile strain distribution at the surrounding bone.

Strengths and limitations

- We incorporated biomechanical test and finite element analysis (FEA) to explore the pullout strengths of bone screws with buttress thread, barb thread, and reverse buttress thread.
- Biomechanical test in the cadaveric bone sample is not included in this study.

Introduction

Lag screw, which is designed to achieve anatomical reduction and rigid fixation by compressing the fracture fragments, remains a standard choice for some simple

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fractures.[1] When applying lag screws to fix fractures, the ability of the lag screw to exert compression is extremely important for establishing and maintaining the stability of bone-implant constructs.[2] However, it may be difficult to establish sufficient compression due to the altered density and properties of the cancellous bone in the metaphyseal regions in cases involving the presence of osteoporosis.[3]

The screw's ability to exert compression is determined by the anchorage strength of the screw in the bone tissue, which can be evaluated by applying the axial pullout test.[4] There are two typical strategies employed to improve the pullout strength of bone screws. The first strategy is augmentation of the surrounding bone structure by administering bone cement, thus increasing the stiffness of the trabecular structure surrounding the screw threads.[5] Many biomechanical studies have demonstrated the mechanical superiority of augmentation of the local screw insertion point using bone cement.[6,7] The second strategy involves optimizing the screw thread parameters, thus increasing the contact area between the screw and the surrounding bone.[8,9] The effect of the outer diameter, inner diameter, pitch, thread width, and root radius on the pullout strength of the bone screw has been well studied and the results have proved consistent.[10-14] However, the influence of the proximal flank angle, which is defined in this study as the angle between the proximal core axis and the proximal thread flank, on the pullout strength of bone screws has not yet been explored to the authors' knowledge.

Based on the various proximal flank angles, there are three typical thread types encountered in bone screws. These include: the buttress thread, possessing a proximal flank angle of 90°; the barb thread design, possessing a proximal flank angle smaller than 90°; and the V-shape thread (or reverse buttress thread), possessing a proximal flank angle larger than 90°. Since Robert Danis proposed to replace the industrial V-shape thread with buttress thread, buttress thread became the standard thread profile for bone screws.[15] Currently, most medical device companies manufacture bone screws with the buttress thread, while some still use the V-shape thread design. The hypothesis of this study is that the barb thread possesses superior axial pullout strength to the buttress thread, while the reverse buttress thread possesses inferior axial pullout strength to the buttress thread. To verify this hypothesis, the axial pullout strengths of barb thread screws and reverse buttress thread screws were investigated and compared with buttress thread screws. Finite element analysis (FEA), which permits detailed evaluation of the strain and stress distribution of the bone-implant system,[16,17] was performed for each thread type to further explore the underlying stabilization mechanisms of screws with varying thread designs in terms of resisting axial pullout forces to explain the experimental findings.

Methods

Biomechanical pullout test. Buttress thread, barb thread, and reverse buttress thread bone screws were designed and manufactured from 316 low carbon vacuum melt (LVM) stainless steel. The screws were all self-tapping with an identical thread pitch of 2.0 mm, major and minor diameter of 4.5 mm and 3.2 mm, respectively, screw length of 40 mm, and identical cutting flute design. The proximal flank angles were 90°, 45°, and 135° for buttress thread, barb thread, and reverse buttress thread screws, respectively. The angles of 45° and 135° were chosen as representatives for threads with proximal flank angle smaller and larger than 90°. All thread types possessed the same thread base width and thread depth of 0.65 mm. Thus, the areas of the individual thread profiles of the various thread designs used in this study were identical as shown in Figures 1a and 1c.

Solid rigid polyurethane foam blocks possessing a density of 0.16 g/cm^3 (Sawbones 10 PCF; Pacific Research Laboratories, Vashon, Washington, USA) were fixed with adhesive to ASTM F1839-08 to mimic human cancellous bone.[18] This particular foam block was chosen because it possessed a density within the range encountered in osteoporotic cancellous bone and has been validated using screw pullout tests in previous studies.[19,20]

For the axial pullout test as shown in Figure 2a, the polyurethane foam blocks were cut into cubes measuring 40 mm × 40 mm × 40 mm. A pilot hole was made all the way through the centre of each polyurethane foam cube with a 3.2 mm drill bit by a drill press. Three test groups were established, namely the buttress thread group, the barb thread group, and the reverse buttress thread group. Five screws were used per test group and were screwed 25 mm deep into the pre-drilled pilot holes in the polyurethane foam cubes. Subsequently, each screw-block construct was mounted on the load cell (1,000 N) of a MTS 858 Mini Bionix (MTS Systems Corporation, Eden Prairie, Minnesota, USA) hydraulic loading machine along with a custom-made jig to ensure controlled axial tension on the screw. The screws were forcibly extracted from the blocks until they had been shifted by 10 mm under a controlled displacement rate of 5 mm/minute, in accordance with the published standards.[21]

During the pullout test, the displacement was measured at the screw head. The displacement and the force required to achieve corresponding displacement were collected at a sampling rate of 10 Hz as the screws were pulled out axially from the foam block. The force-displacement curve was plotted and the stiffness, yield force, and ultimate force were calculated based on these data. Stiffness was calculated as the slope of a best-fit line for the linear region of the force-displacement curve. The linear region was defined as the curve at load-interval between 10 N and 110 N. Yield force was determined using a 0.015 mm offset parallel to the stiffness.[22] Stiffness, yield force, and ultimate force were compared between groups using a one-way analysis of variance

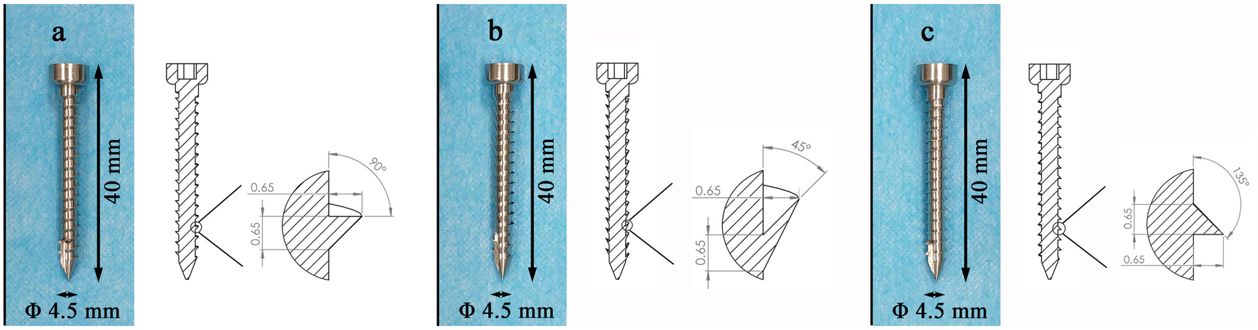

Fig. 1

Types of screws analyzed in this study included the a) buttress thread screw, b) barb thread screw, and c) reverse buttress thread screw.

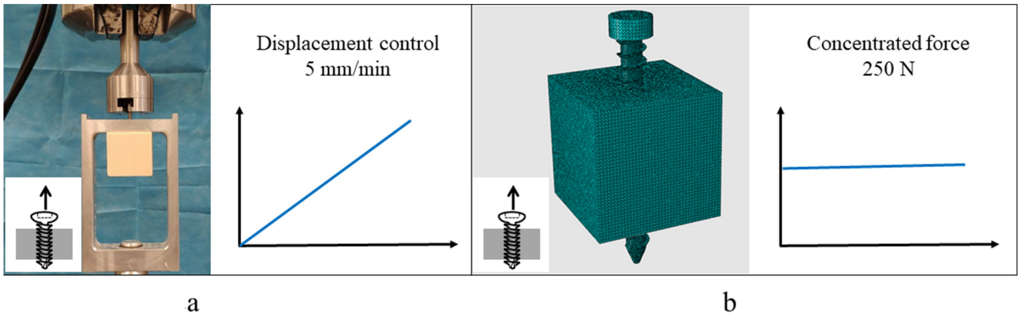

Fig. 2

The experiment conducted in this study included tests performed using a) a biomechanical pullout test setup and b) a finite element model of the pullout test.

Table I. Material properties for bone and screw used in this study.

Material	Young's modulus, MPa	Poisson's ratio
Bone	260	0.29
Screw	205,000	0.3

(ANOVA) technique. Values of $p < 0.05$ were considered significant for all tests of the hypothesis.

Finite element analysis. A 3D cube model with dimensions of 20 mm × 20 mm × 20 mm was created to represent the cancellous bone. 3D models of buttress thread, barb thread, and reverse buttress thread compression bone screws as described previously in the paper were created.

These geometries were used to create 3D finite element models in the ABAQUS software suite (6.13/CAE; Simulia, Providence, Rhode Island, USA). Each screw model was placed at the centre of the cube model to mimic the screw embedded within the cancellous bone as shown in Figure 2b. The material properties of the bone used in this study were defined to be linear elastic, homogeneous, and isotropic, and to represent osteoporotic cancellous bone.[23] The screws were defined to be constructed of stainless steel and were modelled as a homogeneous isotropic material.[24] These material properties for bone and screw are summarized in Table I. The screw-bone contact interfaces were modelled as sliding interactions using a Coulomb friction coefficient of 0.3.[25] According to the maximum pullout force of the three different bone screws found in the pullout test, a constant, concentrated force of 250 N was applied to each screw head with the surrounding four surfaces of the bone model fixed in place. Quasi-static (implicit) analysis was conducted using geometrical nonlinearity (ABAQUS/Standard).

Because strain distribution in the bone was the main concern in this study, quadratic tetrahedral elements were used to model the bone, while linear tetrahedral elements were used to model the screws. The approximate number of elements used in the bone and screw of the buttress thread group, the barb thread group, and the reverse buttress thread group were 753,972 and 280,621, 786,978 and 281,075, and 734,306 and 281,190, respectively. All bone models incorporated refinement for the bone material in close proximity to, and surrounding, the screw. The element edge length around the screw holes was 0.02 mm. A mesh convergence study was conducted and appropriate mesh resolutions for different parts of the model were determined based on their influence on the highest maximum principal strain exerted on the bone. Doubling the number of elements in the bone changed the highest maximum principal strain exerted on the bone by 0.96%, 1.03%, and 0.93% for the buttress thread, barb thread, and reverse buttress thread insertion models, respectively. As a consequence of this improved resolution, this particular FEA model was used in the analysis.

The maximum and minimum principal strain contours of the midsagittal plane of the three bone models were

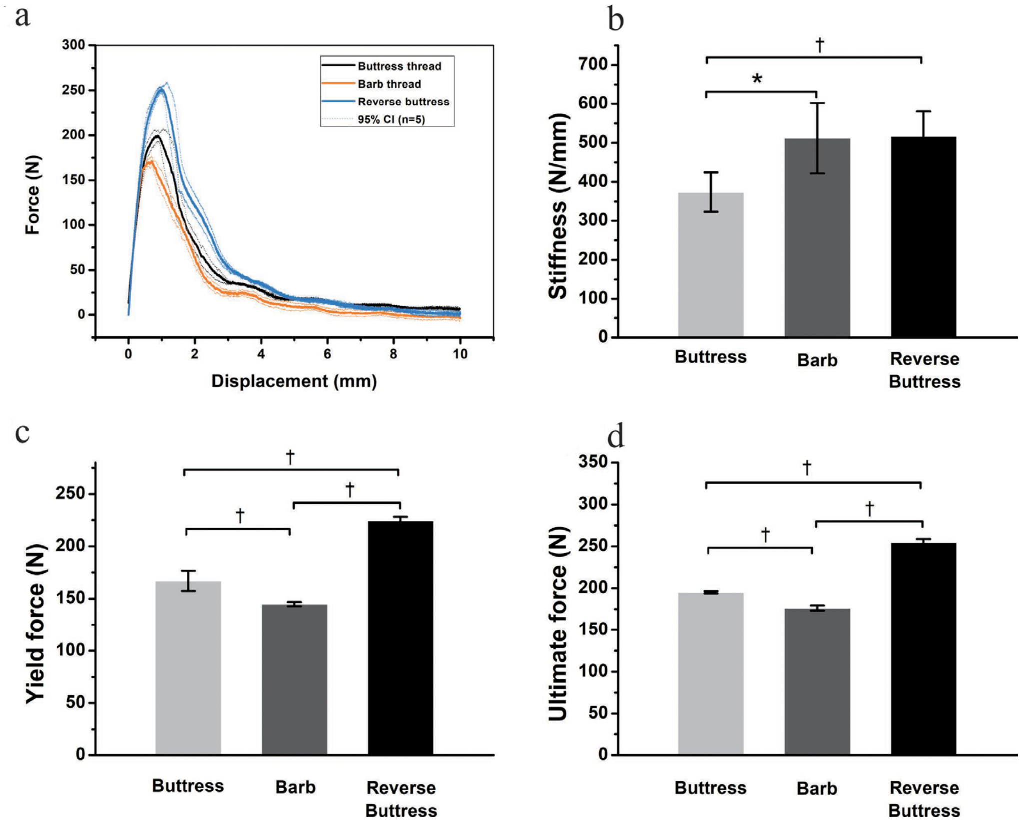

Fig. 3

The graphs pictured above show a comparison between the axial pullout strength of buttress thread, barb thread, and reverse buttress thread screws in terms of: a) force versus displacement; b) stiffness; c) yield force; and d) ultimate force. Mean values and SDs of the measured values are presented above (n = 5). *p < 0.05, †p < 0.01; one-way analysis of variance (ANOVA). CI, confidence interval.

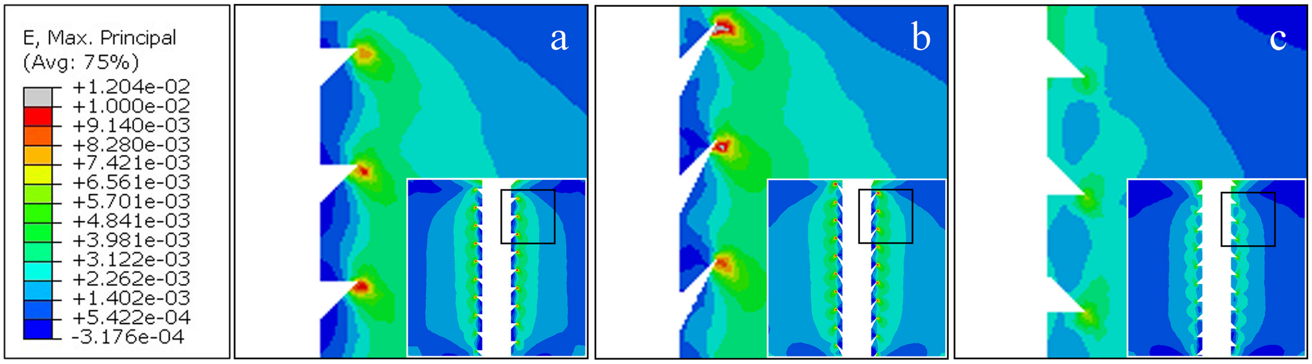

Fig. 4

These colour plots show the maximum principal strain contours of the midsagittal plane of the bone samples associated with a) the buttress thread screw, b) the barb thread screw, and c) the reverse buttress thread screw.

plotted to compare the tensile strain and compressive strain distribution, respectively. The volumes of bone exceeding a maximum principal strain of 0.6% and minimum principal strain of 0.8% were calculated to compare the size of relatively high tensile strain and compressive strain regions between the three bone models. A maximum principal strain of 0.6% is equivalent to the yield tensile strain of osteoporotic cancellous bone.[23] The selected bone experienced a maximum principal strain in excess of 0.6%, and thus represented bones damaged by the high tensile strain. A minimum principal strain of 0.8% is equivalent to the yield compressive strain of osteoporotic cancellous bone.[23] The selected bone experienced a minimum principal strain in excess of 0.8%, and thus represented bones damaged by high compressive strain.

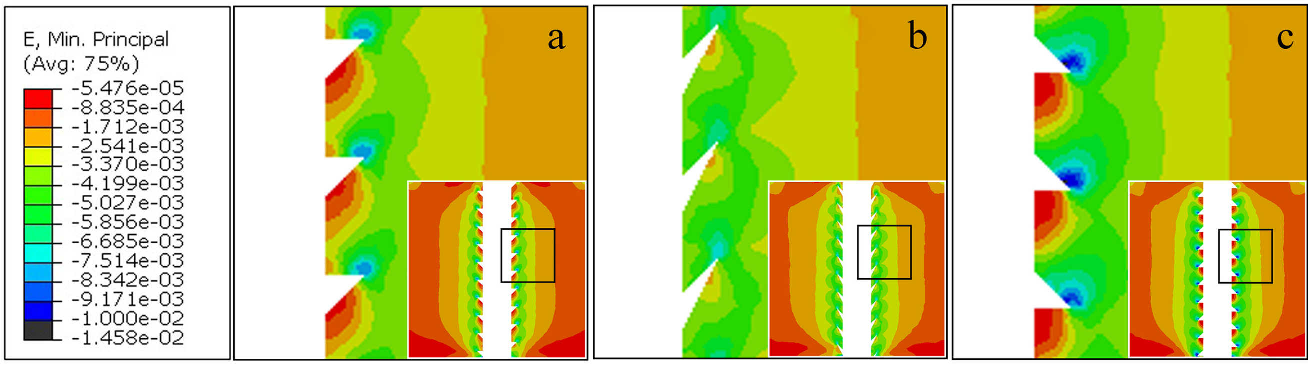

Fig. 5

These colour plots show the minimum principal strain contours of the midsagittal plane of the bone samples associated with a) the buttress thread screw, b) the barb thread screw, and c) the reverse buttress thread screw.

Results

Biomechanical pullout test. The force-displacement curves for the axial pullout tests are shown in Figure 3a. The curves showed that the reverse buttress thread performed more effectively than the buttress thread, while the barb thread performed less effectively than the buttress thread while under axial pullout. The three important parameters of the curve, namely stiffness, yield force, and ultimate force, are shown in Figures 3b and 3d. The mean stiffness of the buttress thread, barb thread, and reverse buttress thread was 373.62 N/mm (SD 50.89), 512.04 N/mm (SD 90.28), and 516.95 N/mm (SD 63.37), respectively (Figure 3b). The mean yield force of the buttress thread, barb thread, and reverse buttress thread was 166.99 N (SD 9.63), 144.75 N (SD 1.96), and 224.39 N (SD 3.80), respectively. The mean ultimate force of the buttress thread, barb thread, and reverse buttress thread was 195.16 N (SD 1.41), 176.16 N (SD 3.10), and 254.69 N (SD 4.15), respectively (Figures 3c and 3d).

Finite element analysis. The maximum principal strain contours of the midsagittal plane of the three bone models are shown in Figures 4a and 4c to reveal the tensile strain distribution. The red-coloured areas indicate regions of relatively high tensile strain concentrations. The tensile strain concentrations were clear in the buttress thread group and the barb thread group and were located under the distal thread flank in both groups. However, for the reverse buttress thread group, no evident tensile strain concentration was noted.

The minimum principal strain contours of the midsagittal plane of the three bone models are shown in Figures 5a and 5c to reveal the compressive strain distribution. The blue-coloured areas indicate areas of relatively high compressive strain concentration. High compressive strain concentrations were found on the proximal thread flank of the buttress thread and the reverse buttress thread groups. This effect was more pronounced in the reverse buttress thread group. However, no evident compressive strain concentration was noted for the barb thread group.

The volume of bone containing a maximum principal strain greater than 0.6% was 33.66 mm^3, 37.71 mm^3, and 7.0 mm^3 for the buttress thread group, barb thread group, and reverse buttress thread group, respectively (Figure 6a). The volume of bone containing a minimum principal strain greater than 0.8% was 5.7 mm^3, 1.5 mm^3, and 18.99 mm^3 for the buttress thread group, barb thread group, and reverse buttress thread group, respectively (Figure 6b).

Discussion

Several studies have been performed to investigate the effect of thread profiles on the pullout strength of bone screws. Geng et al[26,27] found in an FEA study that a V-shaped and a broader square-shaped thread generated significantly less stress compared with a thin and narrower square thread in cancellous bone.[26,27] A biomechanical pullout test performed by Kim et al[28] found that a V-shaped thread showed higher pullout strength than buttress thread and square thread pedicle screws in synthetic cancellous bone.[28] Several FEA studies have demonstrated that a square thread has superior pullout performance because it leads to less stress concentration compared with the V-shaped and buttress thread profiles.[29,30] A FEA study and a biomechanical pullout test revealed that the reverse buttress thread had superior performance in a pullout test.[31,32] However, a biomechanical pullout test showed that trapezoidal fluted mini-implants had higher pullout strength compared with the reverse buttress thread and buttress thread.[33] In short, the results of the above FEA and biomechanical pullout studies are inconsistent, which is attributed to the varied testing setups and loading conditions of the different studies. Their results therefore need to be interpreted carefully.

In our study, the areas of individual thread profiles of the various thread designs were identical to ensure that the same amount of bone was removed when the screw was inserted. The results of the biomechanical pullout test performed in this study showed that the reverse buttress thread displayed superior pullout strength, whereas the barb thread demonstrated inferior pullout

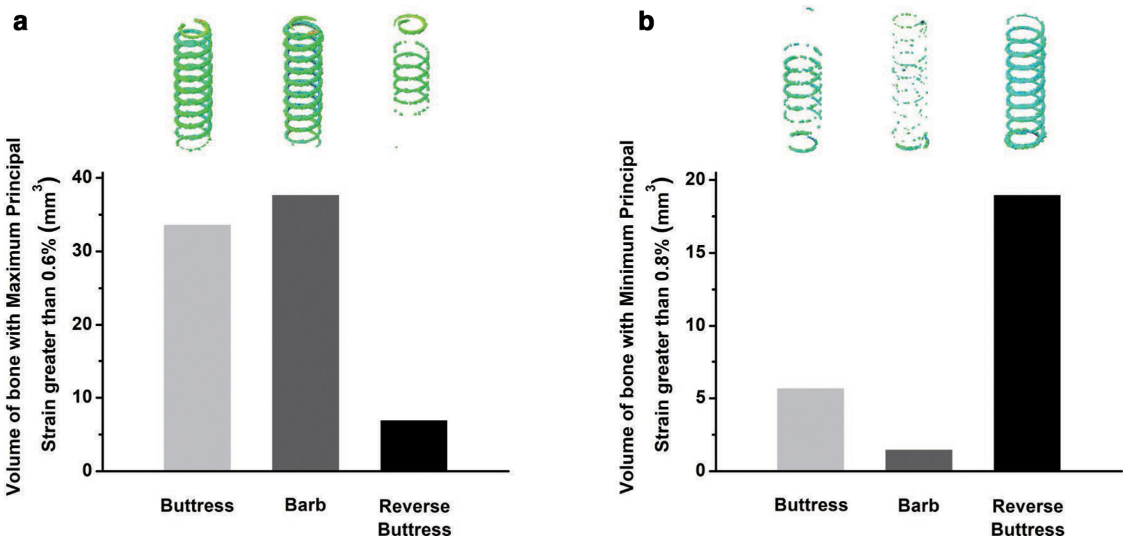

Fig. 6

These graphs show: a) the volume of bone of the three bone models (buttress thread screw, barb thread screw, and reverse buttress thread screw) in which the tensile strain exceeded 0.6%; and b) the compressive strain exceeded 0.8%.

strength compared with the standard buttress thread in the cancellous bone models. The mean pullout strength of the reverse buttress thread was 254.69 N (SD 4.15), representing an increase of 30.5% compared with that of the standard buttress thread (mean 195.16 N (SD 1.41)). However, the mean pullout strength of the barb thread was 176.16 N (SD 3.10), representing a decrease of 9.7% compared with that of the standard buttress thread. These findings contradict our hypothesis that the barb thread design can grab bone tissue more efficiently to produce superior pullout strength, whereas the reverse buttress thread is inferior in pullout strength because it cannot grab bone tissue effectively.

3D FEAs were performed to explore the underlying mechanism involved and further explain the significant results of the biomechanical test. The use of the simpler and quicker 2D axisymmetric model is an option that has been used successfully for modelling the human lumen.[34] However, bone screw does not have an axisymmetric geometry. 2D axisymmetric analysis of bone screw cannot totally simulate its real loading condition when being pulled out. The strain contours revealed that under axial pullout force, the bone surrounding the screw formed a relatively high compressive strain area on the proximal thread flank and a relatively high tensile strain area under the distal thread flank, as shown in Figures 4 and 5. The proximal flank angle of the thread could affect the size of the high compressive strain region and the high tensile strain region. Among the three thread types, the buttress thread possessed moderately high compressive strain and high tensile strain regions, as shown in Figure 6. The barb thread had the largest high tensile strain region and the smallest high compressive strain region, whereas the reverse buttress thread had the largest high compressive strain region and the smallest high tensile strain region, as shown in Figure 6. This was further demonstrated in a bone screw biomechanical study by Wang et al,[35] in which the authors found more compressive damaged bone between obliquely angled screw threads than non-obliquely angled screw threads.

Bone tissue is known to possess higher compression strength than tensile strength,[23,36] which means that bone is more easily damaged by tensile strain than compressive strain. Furthermore, bone damaged by compressive strain can be compressed into a much denser mass, which, in turn, will provide some protection against the screw pulling out any further.[37,38] However, this protection effect does not occur in areas of bone damaged by tensile strain. Thread types that can transform the pullout force predominantly into compressive strain and limit the exposure of the surrounding bone to tensile strain can therefore lead to superior pullout strength performance. The geometrical features of the reverse buttress thread design reduce its ability to grab bone tissue effectively because of the slide out effect; however, they do allow it to form a much larger high compressive strain area on the proximal thread flank and a much smaller high tensile strain area under the distal thread flank while being exposed to pullout forces, resulting in superior pullout strength. The geometrical features of the barb thread allow it to grab bone tissue more effectively, but this improved grabbing action is not optimal for bone tissue that is vulnerable to tensile strain because the barb thread can transform more pullout force into tensile strain under the distal thread flank. However, in the case of soft tissue that can better resist tensile strain, the barbed geometrical features can fully exert their grabbing function. For this reason, barbed sutures are used widely with good results in clinical applications.[39,40]

The maximum principal strain criterion is proven to be a better bone fracture predictor[41] and has been applied widely for predicting screw loosening.[42] Therefore, principal strain was used for the comparisons in this study. This FEA study found that a substantially larger part of the bone was exposed to strain levels in excess of the yield point of the maximum principal strain around the barb thread screw. By contrast, a smaller part of the bone was exposed around the reverse buttress thread screw, as shown in Figure 6a. This indicated that the barb thread was more vulnerable to screw loosening, whereas the reverse buttress thread was stabler under the same axial pullout force, further validating the result of the biomechanical test. This result also meant that tensile strain may represent a suboptimal type of strain to apply to bone tissue when resisting axial pullout of a screw. However, the bone damaged by compressive strain demonstrated a reverse trend in the biomechanical pullout test, further indicating that compressive strain may represent the optimal type of strain to apply to bone tissue when resisting axial pullout of a bone screw.

This study has limitations. Synthetic osteoporotic bones were used as substitutes for human osteoporotic cancellous bone. Such biomechanical studies performed with polyurethane foam blocks cannot fully replicate in vivo conditions, and this should be considered when attempting to draw conclusions. However, owing to large natural variations in apparent density, trabeculae orientation, and mechanical properties of cancellous bone within and among specimens, numerous tests are required to isolate the effects of screw design when cancellous bone is used in the testing procedure. The use of synthetic cancellous bone simplified the experimental setup, thus limiting the experimental error. Further biomechanical testing in cadaveric cancellous bone needs to be performed to corroborate the findings of this study.

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