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Analysis of Orthopedic Screws for Bone Fracture Fixations with Finite Element Method

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Abstract: In this study, the influence of the orthopedic screws engineering design such as profile shape and geometrical parameters on its biomechanical compatibility in terms of load sharing with adjacent bone tissue was investigated. The study was conducted on a set of three-dimensional finite element design models. A dimension less Stress Transfer Parameter (STP) was utilized for gauging the performances of the different screws according to its load sharing capabilities. Stress-transfer behavior was found to be linear for varying load magnitudes. The geometric properties investigated; pitch, thread length, width, major diameter and thread angle showed different influences on the three different profiles studied (triangular, trapezoidal and rectangular). The results indicated that 13 out of 32 screw designs produced were to achieve STP values greater than 0.3 of these, 6 were the rectangular profile. The best design was of the rectangular profile (Design no. 24) with an STP value of 0.4344. It was concluded that the best biomechanical properties were found in rectangular screw profiles. However, due to mix trends for the different properties, the careful combination and consideration towards pullout strength was necessary to obtain a design with the highest biocompatibility.

Key words: Orthopedic screw, bone fracture fixations, finite element method, stress transfer parameter, load sharing

INTRODUCTION

Bone screws are among the many clinically accepted orthopedic mechanical fixation devices for bone fractures or for stabilizing bone transplants. The nature of the fixation is such that the screw pierces through one bone fragment, holds it in place and compressing it with the other fragment when the screw is tightened. The screw does remain attached to the bony tissue after the fracture has been healed and thus apt to diminish the bone's strength and stiffness. The material of the metallic screw (elastic modulus of 100-200 GPa) is much higher than the bone (elastic modulus of 1-20 GPa) and thus will carry most of the shared load (Gefen, 2002).

Wolff's law of functional adaptation states that the thickness, number and orientation of the trabeculae will correspond to the distribution of mechanical stress on the bone (Mueller and Maluf, 2002). As such, the presence of a metallic bone screw will cause the bone to be atrophied in response to the diminishing load it is carrying (Gefen, 2002). Tissue typically atrophies at a faster rate than they hypertrophy (Kohrt, 1999). Bone mineral density may be lost in response to diminished physical stress; as much as 3% to 4% in the regions of the femoral neck and lumbar spine after 17 weeks of bed rest in healthy young man (Leblanc *et al.*, 1990). Several quantitative parameters, termed as stress-transfer parameters (STP) are utilized to characterize the load transfer between the screw and the cancellous bone. They provide a dimension less evaluation of the load sharing between a given fixation screw and the bone tissue in its immediate proximity. Two different STP, α and β are defined. The stress transfer from the first (upper most) thread of the screw, bearing an average stress of σ_{ft}, to the cancellous bone mass located directly above it, withstanding an average stress of σ_{fb}, is quantified by the α STP. The stress transfer from the subsequent threads of the screw (indexed as $j \geq 2$ to exclude the first thread) which bears the respective stresses of σ_{tj} to the bone mass (indexed I) that are found between these threads and are withstanding respective stresses of σ_{fi} is quantified by the β STP (Gefen, 2002).

The first thread carries a substantial load because the bone is compressed between the first thread of the fixation screw and the head of the screw. Subsequently, this may cause stress concentrations to appear above it.

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For this reason, STP evaluations of the screw-bone stress transfer are carried out separately for the first thread (Eq. 1) and for all the other threads (Eq. 2).

$$\alpha = \frac{\sigma_{fb}}{\sigma_{ft}} \tag{1}$$

$$\beta = \left(\frac{1}{N}\sum_{i=2}^{N}\sigma_{b_i} \Big/ \frac{1}{N}\sum_{j=2}^{N}\sigma_{t_j}\right) = \left(\sum_{i=2}^{N}\sigma_{b_i} \Big/ \sum_{j=2}^{N}\sigma_{t_j}\right) \tag{2}$$

The dimension less STP parameter is a convenient tool for evaluation of the stress transfer from any screw design to the surrounding bone. The ideal case calls for a screw made of a material with identical properties to those of the bone. This allows both the screw and bone to share similar loads and result in a near homogeneous stress transfer. In this case, stress shielding will be eliminated and the value of the above-defined STP (Eq. 1 and 2) will approach an optimal magnitude of unity.

Idealized simulations should provide values of 0.96-0.99 for both STP while modeling different hypothetical screws with various profiles fabricated from a material with an elastic modulus identical to that of the cancellous bone (1 GPa). For bones with lower biomechanical compatibility, for example those significantly stiffer than bone, lower STP values are obtained. By this means, the dimension less STP can be utilized to investigate and benchmark the different types of screw designs and identify the parameters which are critical for better biomechanical performances (Gefen, 2002).

Cortical screws tend to have fine threads all along their shaft to anchor in cortical bone. Cancellous screws tend to have coarser threads and usually have a smooth, unthreaded portion which allows it to act as a lag screw. These coarser threads are designed to anchor in the softer medullary bone. Cannulation is the term for screws with a hollow shaft (Lavi, 2006). Cannulated screws were developed to allow more accurate placement of screws while the guide wire stabilizes the fracture or fusion site. It does require an increase of thread minor diameter to compensate for the material removed for cannulation (Brown *et al.*, 2000). Generally cortical screws should not be used in cancellous bone. However it does not follow that the cancellous screw should be used only in cancellous bone. A cortical screw will not be able to hold cancellous bone but a cancellous screw can work well in a cortical bone (Brown *et al.*, 2000).

MATERIALS AND METHODS

Stress transfer parameter: The biomechanical compatibility can be measured in terms of load transfer characteristics between screw and cancellous bone. Stress distributions in the screw thread are represented by von Mises equivalent stress whereas pressure will be applied to the screw thread to imitate the applied stress from the bone tissue. Figure 1 is an illustration of the loads acting upon a typical screw in fixation. The head of the screw is assumed to be mated to the fixated surface and constrained by its exerted tightening force, F_T. The screw shaft and its threads will undergo tensile stresses and elongate (σ_t), whereas the adjacent material volume undergoes compression (σ_b).

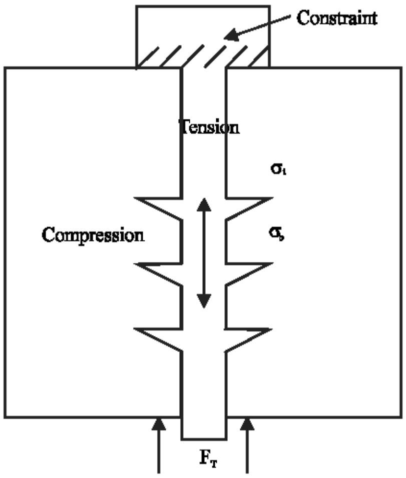

Fig. 1: A free body diagram of a tightened screw

Assuming that the stress is equally distributed on all surfaces, the stress-transfer parameter, γ is defined.

$$\gamma = \left(\sum_{i=1}^{N}\sigma_{b_i} \Big/ \sum_{j=1}^{N}\sigma_{t_j}\right) \tag{3}$$

σ_b = average stress in bone volume
σ_t = average stress in fixation screw thread

Bone screw design: The screws designs considered in this study are of the lag cancellous type, which has a threaded part and a smooth, unthreaded portion which gives its ‘lag’ properties. A lag screw is one which supplies inter-fragmental compression between the fragmented part and the main body. Cannulation is an included feature in the design of these screws due to the precision required by the surgeons for fixation positioning. Biomechanical compatibility is also influenced by the material of choice. Titanium alloy Ti-6Al-4V (Grade 5) STA with the modulus of elasticity 114 GPa and the Poisson ratio of 0.33 is the standard material used in the industry and thus selected for this analysis. Titanium alloy is known for its resistance to the highly corrosive nature of the body and considerate towards poor body tolerances to metallic dissolution. The

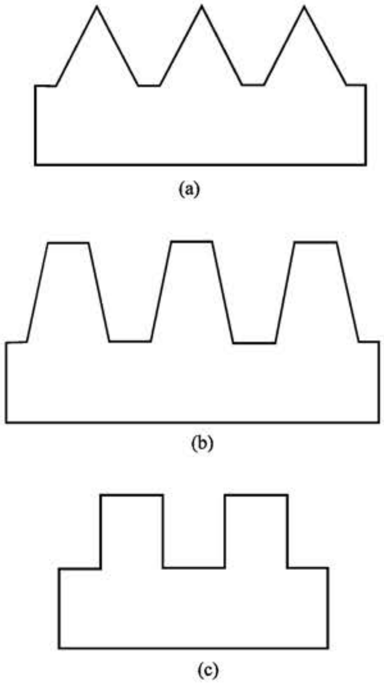

Fig. 2: (a) Triangular thread profile, (b) Trapezoidal thread profile and (c) Rectangular thread profile

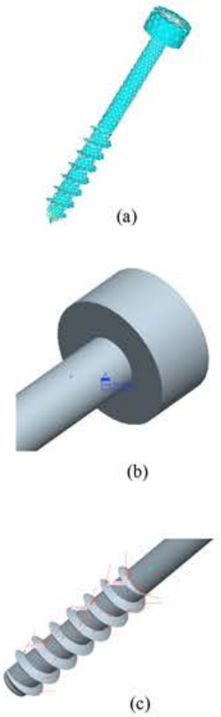

Fig. 3: (a) The resulting meshed solid model of a screw, (b) Applying the constraint on the finite element model and (c) Pressure load on the finite element model

basic dimensions of the screws are selected to represent the commercially available screws (Gefen, 2002). These parameters have been maintained throughout the screw designs: Screw head diameter 6.0 mm, screw head height 3.0 mm, shaft/minor diameter 2.5 mm, screw length 30.0 mm and screw cannulation diameter 1.35 mm.

The bio-mechanical compatibilities of three thread profiles will be investigated in this simulation. They are the triangular thread (Fig. 2a), trapezoidal thread profile (Fig. 2b), the square thread (Fig. 2c). The following parameters are altered for each screw design to investigate its effects on biomechanical compatibility: Thread pitch, thread length, thread angle, thread width and major diameter (major-minor diameter ratio).

The three profile shapes are listed as triangular, rectangular and trapezoidal. The thread pitch values (mm) investigated are from 2.00 to 2.75 for all screw threads. Thread angle is a geometrical factor only concerning the triangular and trapezoidal profiles. Thread length defines the length of which the part of screw will be threaded. The lengths used are 10, 15 and 20 mm. Major diameter and base width values are 4 and 0.5 mm with increments varying for each shape profile.

Meshing the model: The models of screw are meshed using ANSYS Meshtool. The element attributes; element type and material model are defined for the volume to be meshed. Free meshing with tetrahedral shapes is selected. The Smartsizing option is also turned on with the coarseness level of 6 to assist in the complex and difficult screw thread geometry. An example of the meshing process of screw design No. 2 is described below. The resulting finite element model contains 10420 elements, shown in Fig. 3a.

Constraints/boundary condition: For a structural analysis, one or several constraints must be defined for the finite element model before a solution can be obtained through the solver. For the screw thread, the constraint is placed at the bottom surface of the screw head (screw head land) which, in practice comes into contact with the bone surface. Figure 3b shows where the constraint will be placed on the screw thread finite element models. The constraint defines the surface to have a translation value of zero along x, y and z axis and rotation of 0° around the x, y and z axis.

Loading condition: Pressure loading is used in this analysis to represent the tensile stresses acting upon the screw thread in an actual bone fixation. For a parametric study, the force applied to each screw must be constant throughout the analysis. Since each screw design has a different surface area, the effective pressure can be calculated through the following equation. The resultant load application on the screw thread surfaces is shown in Fig. 3c, where the load is represented by the red arrows.

$$P_{eff} = \frac{F_T}{A_T} \qquad (4)$$

Where:

P_{eff} = Effective pressure experienced by screw thread
F_T = Tightening force to be applied
A_T = Surface area of screw thread

RESULTS AND DISCUSSIONS

STP value calculations: The output of the simulation is given as nodal von Mises stresses equivalent in unit Pascal. A sectioned view of the finite element model is produced to investigate the stress distribution in the shaft and thread of the screw. Figure 4 displays the simulation results for triangular thread screw for a load of 10 N. Stress transfer parameter is dimension less as it is the ratio the applied stress to the resultant stress in screw thread.

To obtain the Stress Transfer Parameter (STP) value, the following equation is used:

$$\gamma = (\sum_{i=1}^{N} \sigma_{b_i} / \sum_{j=1}^{N} \sigma_{t_j}) \qquad (5)$$

Investigating the linearity of STP value with respect to force: The first part of the analysis shows that STP values of screw threads are independent of the applied load. A load ranging from 10 N to 80 N with the increment of 10 N was tested on screw design No 1. The results are recorded and the nature of STP variation with respect to load is and plotted in Fig. 5a. From the plotted graph, we can see that the STP values tend to a linear and constant value. The data is further analyzed by obtaining the statistical values of variance and standard deviation.

The analysis of screw designs: As stated in the literature review, a higher STP value (the maximum value equals to 1) is desired as this will indicate a better load sharing property between the surrounding bone tissue and the fixation screw. The best possible STP value and highest biomechanical rating is 1. The effects of changing the profile geometry in various degrees are discussed in the following.

Screw thread length: The relationship between thread length and STP for the three profiles are obtained and shown in Fig. 5b. The triangular profile displays an overall decrease in STP values for an increase in thread length. The best STP value can be derived from a 15 mm thread length; the optimal length for triangular threads in this study. The lowest STP value is obtained for the 20 mm length. The rectangular profile displays a clear down trend in STP against increasing thread length. The increase of 10 mm in thread length reduces the STP from 0.3165 to 0.1823 or a 42.4% decrease. STP value data variance is found to be 3.19×10^{-6} and the standard deviation from the mean is calculated at 0.002. The standard deviation is considered small and negligible and it is acceptable to

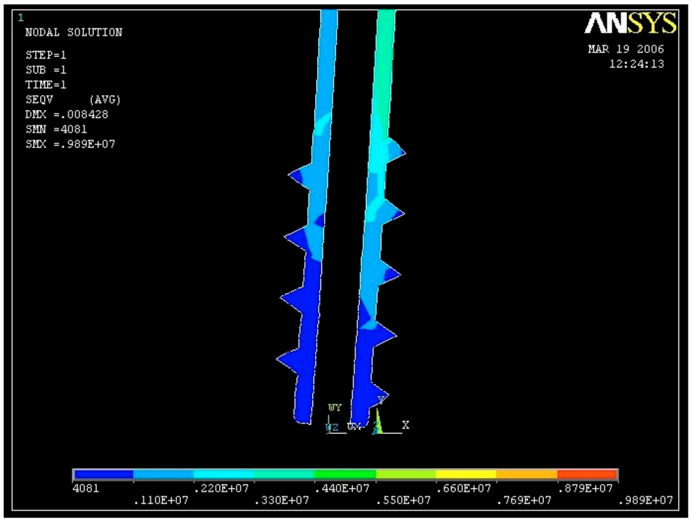

Fig. 4: Sectioned view of von Mises nodal stress distribution in screw thread

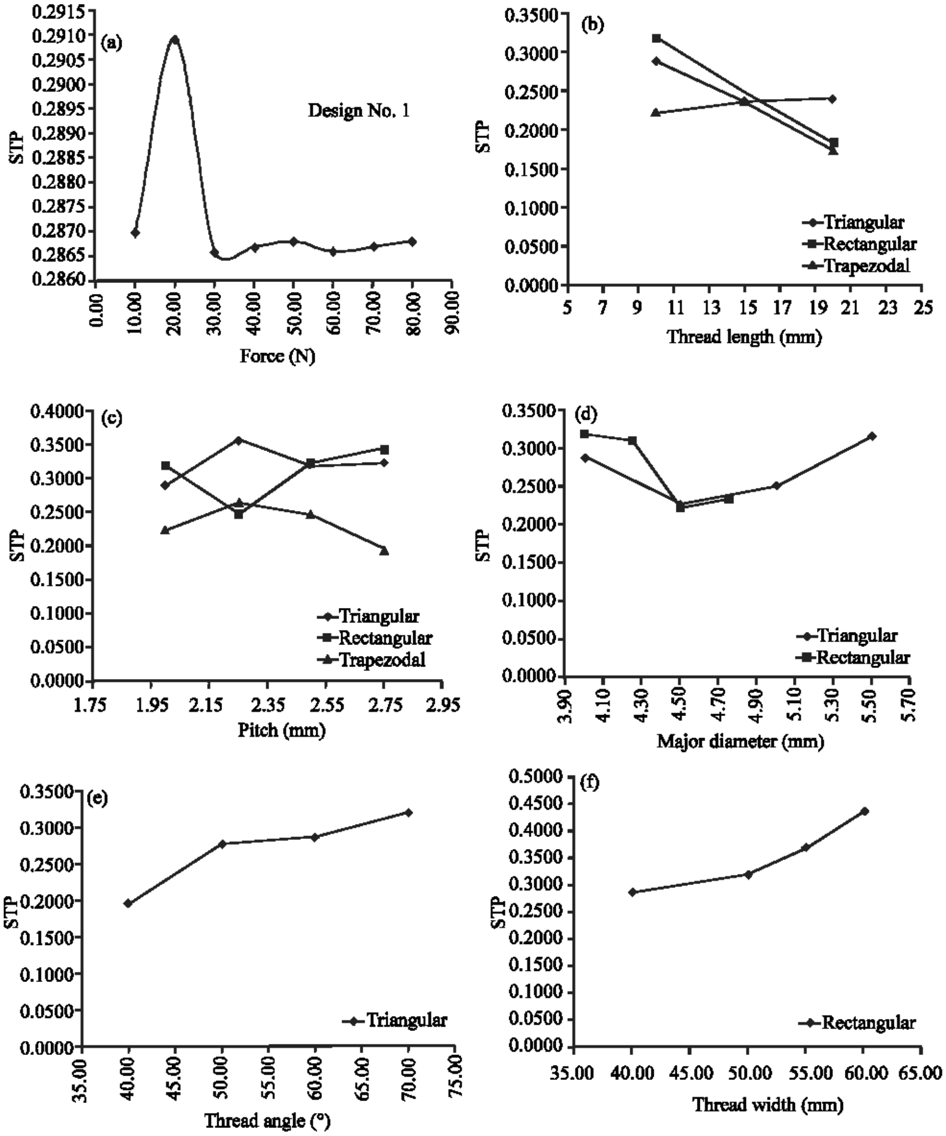

Fig. 5: (a) Applied force vs. STP values for design No. 1, (b) STP vs. Thread length, (c) STP vs. Thread pitch, (d) STP vs. Major diameter, (e) STP vs. Thread Angle and (f) STP vs. Thread width

conclude that STP values are sufficiently linear despite changing the values of loading. However, a significant amount of deformation was observed in the finite element solution at high loads. Therefore, the loading of 10 N has been selected for the subsequent screw design testing. Thread length affects the trapezoidal profile exactly in the opposite of the triangular profile. The 15 mm thread length gives the minimum STP value for trapezoidal profile. The graph suggests that there is a maximum value of STP achievable by means of adjusting the thread length. However, reducing thread length will also diminish its pull-out strength and thus the optimal STP for the smallest allowable pullout strength is a necessary consideration in screw design.

Thread pitch: Increasing pitch reduces the number of complete thread revolutions and thus diminishes its pull-out strength. However, a high pitch is required for cancellous screws for it to anchor effectively into the spongy cancellous bone tissue which has a low modulus of elasticity (1~20MPa). Figure 5c shows that the relationship of trapezoidal and triangular profiles with respect to pitch share similar traits. A 2.25 mm pitch gives the maximum value of STP for both profiles; STP value of 0.35 for triangular and 0.26 for trapezoidal. As for rectangular profiles, the 2.25 mm pitch derives the lowest STP value, thus making it the least desirable pitch to use. The rectangular thread profile should be designed with a higher pitch value, as shown in the simulations to give 0.34 for a 2.75 mm pitch.

Major diameter: The effect of increasing thread major diameter was investigated for the triangular and rectangular profiles. The results are shown in Fig. 5d. With fixed minor diameters, the results from both profiles too did not display a clear preference to a trend. For the triangular profile, the major diameter of 5.5 mm yields the highest STP of 0.31. The 4.0 mm diameter screw yielded a 0.29 STP value but dipped dramatically for the subsequent diameter increment. Therefore, it is surmised that a minimum STP yielding screw diameter for the triangular profile is present. The same graph plot can be seen for the rectangular thread profile. An optimal major diameter may be selected in designing to obtain the highest STP value for the preferred pullout strength and stripping torque.

Thread angle (triangular profile): The trend for increasing the thread angle of triangular profiles is the increase STP values (Fig. 5e) and thus its biomechanical compatibility. Altering the thread angle alone in this profile while maintaining the screw thread major diameter calls means that the base width of the triangular profile too will increase. A large increase in the thread angle is not possible for a small fixed pitch value. To further increase the thread angle, the designer must consider increasing the screw thread pitch value as well. In the simulation of these designs, an increase from 40° to 70° thread angle shows a marked 96.16% rise in STP value.

Thread width (rectangular profile): The thread widths investigated for the rectangular profile are of 40, 50, 55 and 60 mm (Fig. 5f). The result of increasing the thread width from 40 to 60 mm was an overall rise in STP values from 0.28 to 0.43, or a 53.55% increase. It should be noted that this geometrical alteration also yielded the highest STP value of all the designs in this study.

Thread profile: From this study, the best thread profile for biomechanical compatibility cannot be concluded as certain designs from each profile type does exhibit acceptable levels of biomechanical compatibility. However, in the scope of this study it is found that the rectangular profile demonstrates the best biomechanical compatibility (with STP value of 0.43) followed by trapezoidal (with STP value of 0.39) as shown in Table 1. The best triangular profile design produced in this research paper with the STP of 0.33.

Table1: Results of the FE analysis on different screw designs

Design No.	Profile shape	Thread pitch (mm)	Thread angle (°)	Thread length (mm)	Major diameter (mm)	Base width (mm)	STP
1	Triangular	2.00	60.00	10.00	4.00	-	0.2870
2	Triangular	2.00	60.00	15.00	4.00	-	0.2346
3	Triangular	2.00	60.00	20.00	4.00	-	0.2392
4	Triangular	2.25	60.00	10.00	4.00	-	0.3535
5	Triangular	2.50	60.00	10.00	4.00	-	0.3171
6	Triangular	2.75	60.00	10.00	4.00	-	0.3204
7	Triangular	2.00	60.00	10.00	4.50	-	0.2263
8	Triangular	2.00	60.00	10.00	5.00	-	0.2498
9	Triangular	2.00	60.00	10.00	5.50	-	0.3144
10	Triangular	2.00	40.00	10.00	4.00	-	0.1957
11	Triangular	2.00	50.00	10.00	4.00	-	0.2777
12	Triangular	2.00	70.00	10.00	4.00	-	0.3200
13	Rectangular	2.00	-	10.00	4.00	0.50	0.3165
14	Rectangular	2.00	-	15.00	4.00	0.50	0.2475
15	Rectangular	2.00	-	20.00	4.00	0.50	0.1823
16	Rectangular	2.25	-	15.00	4.00	0.50	0.2454
17	Rectangular	2.50	-	15.00	4.00	0.50	0.3198
18	Rectangular	2.75	-	15.00	4.00	0.50	0.3423
19	Rectangular	2.00	-	10.00	4.25	0.50	0.3085
20	Rectangular	2.00	-	10.00	4.50	0.50	0.2218
21	Rectangular	2.00	-	10.00	4.75	0.50	0.2334
22	Rectangular	2.00	-	10.00	4.00	0.40	0.2829
23	Rectangular	2.00	-	10.00	4.00	0.55	0.3659
24	Rectangular	2.00	-	10.00	4.00	0.60	0.4344
25	Trapezoidal	2.00	30.00	10.00	4.00	0.50	0.2213
26	Trapezoidal	2.00	30.00	15.00	4.00	0.50	0.2344
27	Trapezoidal	2.00	30.00	20.00	4.00	0.50	0.1730
28	Trapezoidal	2.25	30.00	15.00	4.00	0.50	0.2609
29	Trapezoidal	2.50	30.00	15.00	4.00	0.50	0.2449
30	Trapezoidal	2.75	30.00	15.00	4.00	0.50	0.1951
31	Trapezoidal	2.00	30.00	10.00	4.00	0.60	0.3911
32	Trapezoidal	2.00	20.00	10.00	4.50	0.60	0.3301

CONCLUSIONS

The performance of orthopedic screws designs in term of biomechanical compatibility is based on its ability to transfer stress with equal distribution between the threads and the surrounding bone tissue. This effectively prevents the occurrence of stress shielding and subsequent bone strength loss. A total number of 32 screw designs were produced in this study, representing triangular, trapezoidal and rectangular profiles of different geometrical dimensions. The biomechanical compatibility of a fixation screw is directly linked to its stress transfer ability and thus measurable by the means of a STP value. A method proposed by Gefen (2002), the stress transfer parameter is the ratio of compressive stresses in the bone to the tensile stresses in the screw thread. Finite element method was employed to simulate the tightening of the orthopedic screws in bone by placing the screw in tension. A thorough parametric study of geometrically different screw profile designs is done by isolating each geometric property and applying the similar conditions for each case. The effects of altering each characteristic has been studied and recorded. ANSYS allows the import of solid models generated by various CAD software and its meshing tools successfully convert complex geometrical shapes into finite element models. The geometrical properties investigated are screw thread length, thread pitch, major diameter, thread angle and thread width. The study shows that each property has a profound effect on STP value. The trends displayed in the results are usually an increase, decrease, maximum or minimum with the respect to dimension change. The best design obtained from this study is of the rectangular profile. Of the 13 designs that show an STP value >0.30, 6 of these designs belong to the triangular profile.

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