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EXPERIMENTALLY VALIDATED NUMERICAL SIMULATION OF CONICAL PEDICLE SCREW PULLOUT

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SUMMARY

Finite element (FE) simulation of conical screw's pullout is complicated significantly by the fact that a pretension is imposed during screw insertion. The present study aims at developing and validating a new methodology to simulate conical screw pullout, incorporating the initial pretension imposed to the screw's hosting material. For this purpose conical screw's pullout was studied experimentally using synthetic bone and then simulated numerically. One of the key features of the FE analysis was the implementation of a cohesive-zone-material (CZM) model to simulate synthetic bone failure. Pretension generation was simulated by allowing the screw to expand inside a hole with smaller dimensions than the screw itself. Comparison between experimental and numerical results indicated that the FE model developed here can simulate reality with satisfactory accuracy and it can be used to predict conical screw's pullout force. After its validation the FE model was utilized to investigate the impact of conical angle to pullout force.

INTRODUCTION

There are indications in literature that pedicle screws with conical core can resist pure pullout loads more effectively than cylindrical screws [1, 2]. One of the main features of conical screws is that they compact the bone tissue in their vicinity as they are inserted into the bone (usually through cylindrical holes with smaller diameters than their maximum core diameter). In a previous attempt to simulate the effect of conical screw insertion into a cylindrical hole the elastic modulus of the screw's hosting material was modified based on the estimated density change [1, 2]. The main disadvantage of this approach is that the effect of bone compaction is predefined. In the context of the present study an original approach for the simulation of conical screw pullout behaviour is presented. Instead of altering the elastic modulus of their hosting material, conical screws are simulated to produce a pretension. The validity of this approach is assessed by comparing the numerical results with experimental ones.

METHODS

Two commercially available polyaxial screws for lumbar fixation (Romeo, Spineart) were used to perform ten pullout tests in total. These pedicle screws have a cylindrical part leading to a conical tip (Figure 1A). Their geometry and dimensions are similar to each other but they have significantly different conical angles (a_{con}=2.5° and 7.0°, respectively). As a result of this difference the screws have also different outer and core radius at the transition point from their conical to their cylindrical part. The two screws will be referred as Romeo2.5 and Romeo7.0, respectively.

Pullout testing was performed following the respective international experimental standard (ASTM-F543-02). The conical tip of the screws was inserted into blocks of Solid Rigid Polyurethane Foam (SRPF) with mechanical properties similar to osteoporotic cancelous bone (10pfc, Sawbones). Cylindrical holes with diameter equal to the small core diameter of the screws (namely the core diameter at their tip) were opened using a pillar drill to enable screw insertion. The SRPF blocks were fixed to the base of the loading frame (MTS Insight 10kN) with the aid of a metallic frame while the screw was suspended from the load cell (MTS 662.20D-04 Load Transducer) using a custom-made device (Figure 1B). The screws were pulled out of the SRPF blocks with a constant rate equal to 0.01 mm/s while the respective force was measured with a sampling rate of 10 Hz. The average value and standard deviation of pullout force, pullout displacement and stiffness was calculated for each one of the pedicle screws. Statistical significance was assessed with one way ANOVA (level of statistical significance $P<0.05$).

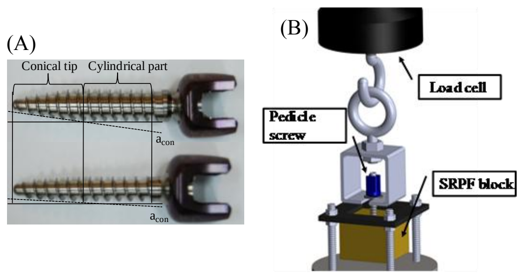

Figure 1: (A) The pedicle screws used for the completion of the pullout tests: Romeo7.0 (top), Romeo2.5 (bottom). (B) The experimental set-up for the pullout tests.

The pullout phenomenon was simulated with a 2D axisymmetric FE model of a bone screw and of its hosting material. The FE analysis was performed using ANSYS 12 software. The screw's hosting material was simulated as a linear elastic-perfectly plastic, homogenous and isotropic material. On the other hand the screw was considered to be rigid. Moreover, a CZM model was implemented for the simulation of the experimentally observed failure mode of the SRPF [3]. This methodology has been developed and validated in the context of a previous study [4].

The FE model of the screw was designed in a way that enabled the change of its radii and conical angle. At first the screw was simulated inside a cylindrical threaded hole with dimensions similar to the holes drilled for pullout testing. The initial dimensions of the screw FE model were modified so that it could fit inside this cylindrical threaded hole (Figure 2). More specifically the initial value of the big core diameter of the screw (namely the core diameter of the cylindrical part of the screw) was set equal to the threaded hole's core diameter. Simulation was performed in two steps: 1) Pretension generation and 2) pullout. Pretension generation was simulated by extending the screw's radii to reach their actual values. After the completion of this load step a displacement at the pullout direction was imposed to the screw until the "failure" of its hosting material. The accuracy of this FE model was assessed by comparing the numerical results for the Romeo2.5 and Romeo7.0 screws with the respective experimental ones. After its validation the FE model was utilized to investigate the impact of conical angle to pullout force.

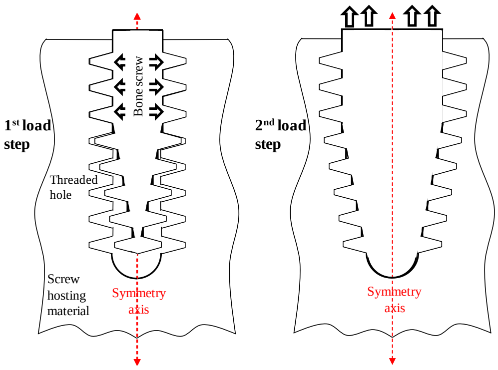

Figure 2: Schematic representation of the two load steps of the numerical simulation.

RESULTS AND DISCUSSION

The pullout tests indicated that the failure of the screw's hosting material occurs on an almost conical surface which connects the edges of the screw's threads. The material between the surface of failure and the surface of the screw is extracted from the block with the screw. One way ANOVA indicated that Romeo7.0 screw has statistically significant higher pullout force than the Romeo2.5 screw, while there are no statistically significant differences in terms of pullout displacement and stiffness. More specifically the pullout force measured for Romeo7.0 and Romeo2.5 screw was 385±7 N and 318±5 N respectively.

The numerical results appear to be in very good agreement with the respective experimental ones. In terms of pullout force the difference between experiment and FE simulation was less than 2.6%. The numerically calculated pullout force for the Romeo7.0 and the Romeo2.5 screw was 381 N and 326 N respectively. The stress field developed inside the synthetic bone at different stages of the simulation can be seen in Figure 3. The results of the parametric investigation of conical angle's impact on pullout force can be seen in Figure 4. As it can be seen pullout force increases nonlinearly with increasing conical angle.

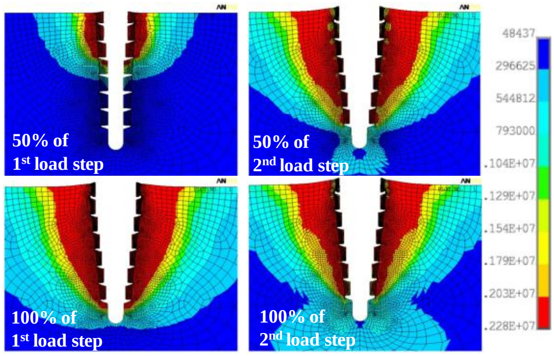

Figure 3: The Von Mises equivalent stress (Pa) developed around the screw at different stages of the simulation. Pretension development (left), pullout (right).

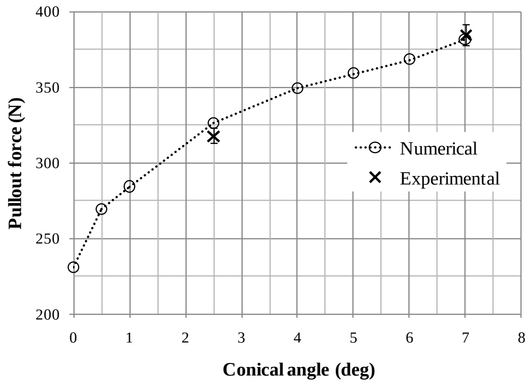

Figure 4: The numerically calculated pullout force for different values of the screw's conical angle and the experimental values for the Romeo2.5 and Romeo7.0 screws.

The present study aims at establishing a new methodology for the FE simulation of conical screw's pullout. For this purpose a combined experimental and numerical approach was followed. One of the key features of the numerical analysis was the implementation of a CZM model for the simulation of SRPF failure. The validity of this approach has been assessed for the case of conical screws pulled out of SRPF blocks [4]. The main prerequisite for using this methodology for conical screws is to know the geometrical domain where failure can occur [5]. The experimental results indicated that this prerequisite is met. Coming to an end it should be stressed out that the main limitation of the present study stems from the fact that synthetic bone is unable to simulate all aspects of the mechanical behaviour of cancelous bone.

CONCLUSIONS

The proposed methodology for integrating pretension development in the simulation of conical screw's pullout can simulate reality and predict pullout force with satisfactory accuracy. The FE model of a conical screw pullout out of a SRPF block can be used for design optimization.

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