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Numerical simulation of bone screw induced pretension: The cases of under-tapping and conical profile

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ABSTRACT

Even though screw induced pretension impacts the holding strength of bone screws, its implementation into the numerical simulation of the pullout phenomenon remains a problem with no apparent solution. The present study aims at developing a new methodology to simulate screw induced pretension for the cases of: (a) cylindrical screws inserted with under-tapping and (b) conical screws. For this purpose pullout was studied experimentally using synthetic bone and then simulated numerically. Synthetic bone failure was simulated using a bilinear cohesive zone material model. Pretension generation was simulated by allowing the screw to expand inside a hole with smaller dimensions or different shape than the screw itself. The finite element models developed here were validated against experimental results and then utilized to investigate the impact of under-tapping and conical angle. The results indicated that pretension can indeed increase a screw's pullout force but only up to a certain degree. Under-tapping increased cylindrical screws' pullout force up to 12%, 15% and 17% for synthetic bones of density equal to 0.08 g cm^{-3}, 0.16 g cm^{-3} and 0.28 g cm^{-3}, respectively. Inserting a conical screw into a cylindrical hole increased pullout force up to 11%. In any case an optimum level of screw induced pretension exists.

1. Introduction

Despite the extensive use of pedicle screws and the significant advances in the field of spinal stabilization the possibility of screw loosening and pullout remains and is even higher in the case of osteoporotic patients [1–3].

There are strong indications in the literature that the pretension developed in the vicinity of bone screws during their insertion can significantly influence their pullout strength. Experimental studies performed on synthetic [4] or cadaveric [5,6] bone specimens showed that the holding strength of a cylindrical screw can be improved by under-tapping; namely by inserting the screw into a cylindrical threaded hole which is smaller than the screw itself. Screw insertion with under-tapping causes the core diameter of the threaded hole to expand and the screw hosting material in the vicinity of the screw to compact. In this case the screw's hosting material is compacted uniformly along the length of the screw.

In a previous experimental investigation [4] performed by authors of the present study, it was found that using a tap that is one size smaller than the screw, can increase the pullout force by 9%. Further reduction of the threaded hole dimensions did not result in any statistically significant change of the pullout force.

A combined experimental and numerical analysis of the pullout behaviour of cylindrical self-tapping screws was performed by Wu et al. [7]. The authors of this study designed an axisymmetric finite element (FE) model of a screw is inserted into a threaded hole with dimensions and shape identical to the screw itself. The pretension generated during screw insertion was simulated by introducing a temperature change. Even though their model appears to be capable of generating an initial pretension inside the screw's hosting material, the way this capability was utilized is not clear. Numerical results are presented only for cases where the radius of the pilot hole is equal to the screw's core radius.

Moreover, screws with conical core were found to have higher pullout strengths than cylindrical screws with similar thread shape and size [8–13]. Screws with conical core are inserted into cylindrical holes with diameters smaller than the maximum core diameter of the screw. In this case, screw insertion results in a non-uniform compaction of the screw's hosting material. Indeed the screw's hosting material that is closer to the screw's entry site is compacted more than that closer to the screw's tip.

In a previous attempt to simulate the effect of bone compaction in the vicinity of a conical screw is inserted into a cylindrical hole,

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the elastic modulus of the screw's hosting material was modified based on an estimate of its volume reduction [8,9]. The main disadvantage of this approach is that the effect of bone compaction is predefined.

Another interesting approach to the numerical simulation of the pretension that is developed in the vicinity of an implant was presented by Janssen et al. [14] for the case of press-fit acetabular implants. The authors of this study simulated the insertion of the implant as a separate load step.

Considering all the above, the present study aims at developing a reliable and accurate technique to integrate the screw induced pretension to the numerical simulation of the pullout phenomenon. The accuracy of the numerical analyses performed here was assessed by comparing numerical and experimental results for four different screw insertion scenarios.

One of the key features for the numerical assessment of a screw's pullout strength is the simulation of the screw's hosting material failure [7,15–17]. For the purpose of the present study the failure of the screw's hosting material was simulated using a bilinear cohesive zone material model [15,18]. The validity of this technique for the simulation of screw pullout has been previously established for cylindrical screws are inserted into blocks of synthetic bone without any pretension [15]. Its accuracy has also been validated for different densities of synthetic bone [19].

2. Materials and methods

2.1. Experimental study

Pullout tests were performed with the use of solid rigid polyurethane foam (SRPF) blocks with density equal to 0.16 g cm^{-3} and material properties similar to osteoporotic cancellous bone (10 pcf SRPF, Sawbones, Worldwide, Pacific Research Laboratories Inc.) and two commercially available pedicle screws, namely Romeo® polyaxial screws for lumbar fixation (Spineart, International Center Cointrin, Genève, Suisse). The two screws used for the completion of the pullout tests are shown in Fig. 1. As it can be seen, their thread can be divided into two parts of similar lengths: a cylindrical one and a conical one ($L_{con} = L_{cyl} \approx 20$ mm). The main geometrical features of the aforementioned screws are also shown in Fig. 1 while their values are presented in Table 1. As one can see the two screws have the same pitch (P), the same outer and core radius at their tips ($\mathrm{OR_{min}}$ and $\mathrm{CR_{min}}$, respectively) and throughout their length they have the same thread depth ($D = \mathrm{OR} - \mathrm{CR}$) and thread inclination angles (a_1/a_2). On the contrary the two screws have significantly different conical angles (a_{con}) and as a result of that they also have different outer and core radius at the transition point from the conical to the cylindrical part of the screw ($\mathrm{OR_{max}}$ and $\mathrm{CR_{max}}$, respectively). From this point on the pedicle screw with $a_{con} = 2.5^\circ$ and 7.0° will be referred to as Romeo 2.5 and Romeo 7.0, respectively.

The conical part of the aforementioned screws was inserted into the SRPF blocks through cylindrical holes that were previously prepared using a pillar drill. The insertion depth of the screws was equal to 20 mm. The radius of the cylindrical holes was equal to the minimum core radius of the screws that is equal to 1.3 mm.

The pullout tests were performed following pertinent international experimental standard (ASTM-F543-02) [20] according to which, the SRPF blocks were fixed to the base of the loading frame (MTS Insight 10 kN, MTS Systems Corp., Eden Prairie, MN) with the aid of a metallic frame while the screw was suspended from the load cell (MTS 10 kN Load Transducer) using a custom-made device (Fig. 2). The screw was pulled out of the SRPF block with a constant rate equal to 0.01 mm/s while the respective force was measured with a sampling rate of 10 Hz.

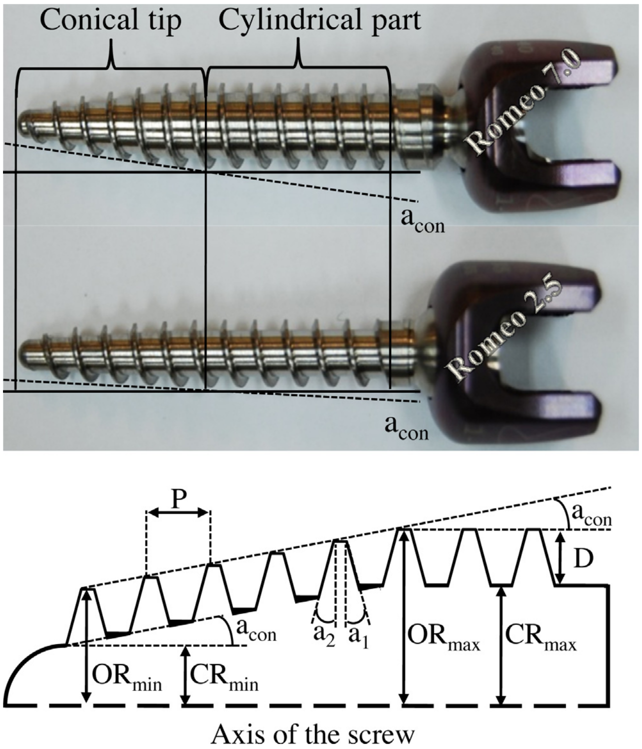

Fig. 1. The pedicle screws used for the realization of the pullout tests (up) and the basic geometrical features of the conical pedicle screws used (down).

Ten tests were performed in total (five tests for each screw) to calculate the mean value and the standard deviation of the pullout force, pullout displacement and the corresponding stiffness for each screw. The results for the two screws were compared to each other and their statistical significance was evaluated following one way analysis of variance (ANOVA). The level of statistical significance was considered to be equal to 0.05.

2.2. FE modelling and validation

For the purposes of the present study two different FE models were designed using ANSYS12 software: one FE model for the simulation of under-tapping and cylindrical screw pullout and another

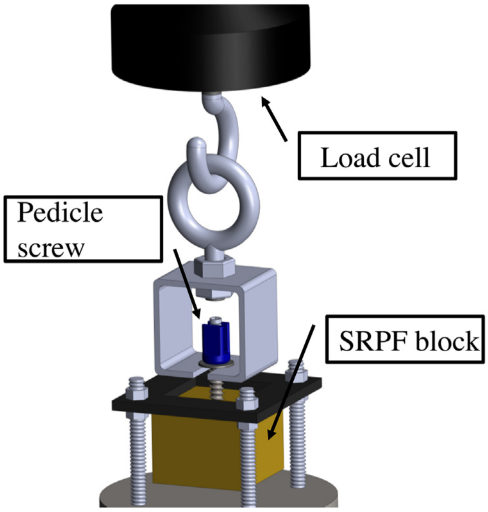

Fig. 2. Schematic representation of the experimental set-up.