A NEW HYBRID CONCEPT FOR CFRP PEDICLE SCREWS: FINITE ELEMENT ANALYSIS

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ABSTRACT

Pedicle screw systems are widely used in spinal fusion surgery. Their application yields the fixation of certain parts of the human spine. Nowadays, pedicle screws are mainly made of titanium alloy due to its biocompatibility and its lower stiffness compared to stainless steel. Despite these facts, stress shielding is a common problem of metallic pedicle screws which leads to the degradation of surrounding bone. Due to the metallic behaviour of titanium, medical images show artefacts and the post-operative follow-up of patients is complicated. Concerning radiotherapy, the attenuation of X-rays due to the presence of metallic implants is another well-known disadvantage.

The present study aims at the development of a new metal-free pedicle screw system which shows no artefacts in medical imaging technologies (e.g. CT-scan, MRI). Patient follow-up is easier and uncertainties as well as risks of post-operative treatments are reduced. Furthermore, pedicle screws out of carbon fibre reinforced plastic (CFRP) lessen the effect of stress shielding so that bone degradation is alleviated. The new concept bases on an advanced material combination: an insert with high mechanical properties is combined with short fibres embedded in a PEEK matrix.

Conceptual models of the pedicle screw are compared by performing simulations in the finite element solver Abaqus. Screw parameters are examined and the effect of a conical screw shaft is studied more in detail. In order to analyse the interaction between the screw and the spine, the surrounding bone is also modelled. Here, it is important to distinguish between the cortical and the cancellous or spongious part of the bone due to their different mechanical properties and structures. The parametric model, written in the commonly used programming language *Python*, allows the adaptation of the screw shape, the bone dimensions and other parameters such as the contact formulation in an effective way.

1 INTRODUCTION

Due to their high stiffness to weight ratio, fibre reinforced plastics (FRP) are widely used in various industries such as in the aircraft or automobile sector. Besides, composites achieve increasing numbers of applications in the sports industry and also for medical products. The combination of different materials offers the possibility to join the advantages of each component. Fibres can be aligned along specific load paths so that the strength of the product can be increased while saving material and weight [1, 2].

Concerning medical applications, orthopaedic implants out of metal such as titanium have the disadvantage that their physical and mechanical properties differ with bone. Furthermore, there can be allergic reactions of the patient. Composites such as carbon fibre reinforced polyether ether ketone (CF-PEEK) usually have lower stiffness and strength values compared to commonly used metallic implant materials. When using stiff titanium implants, stress shielding is a common problem. The density of CF-PEEK is similar to that of bone so that the discomfort of patients is reduced [3, 4, 5]. CF-PEEK implants do not show any artefacts when medical imaging technologies are used such as computer tomography (CT) or magnetic resonance imaging (MRI) (Fig. 1). Due to the fact that they are radiolucent, patient follow-up and post-operative radiotherapy are easier [6, 7].

For several decades, pedicle screw systems have been used for treating spine degeneration and trauma. A pedicle screw system consists of the screw itself, a rod and a locking mechanism to fix the rod with the screw. It yields the fixation of certain spine segments following the statement: *no motion*

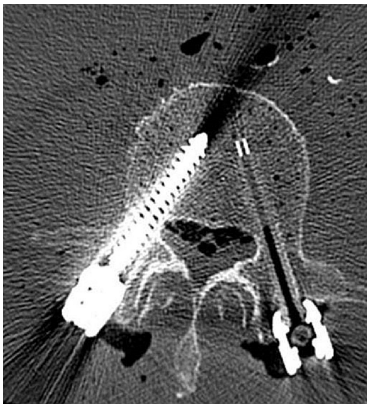

Figure 1: Artefacts in CT imaging: titanium (left) and CF-PEEK pedicle screw (right), source: icotec AG (Switzerland)

= *no pain* [8]. To restrict the movement of a certain part of the human spine, pedicle screws are subjected to bending and pullout forces [9].

2 METHODS

2.1 Thread design

There is a distinction between three principle thread types, namely triangular, trapezoidal and buttress thread. The triangular thread shape can be described by only two variables: proximal and distal half angle. For the trapezoidal thread shape, three variables are required, namely the two half angles and the length of the thread flank. The number of variables further increases for the buttress thread by considering the proximal and distal root radius. Thus, five variables are used to define the thread shape (Fig. 2). State-of-the-art pedicle screws usually have a buttress thread, so in this study, this advanced thread type is used for modelling the pedicle screw (Fig. 3).

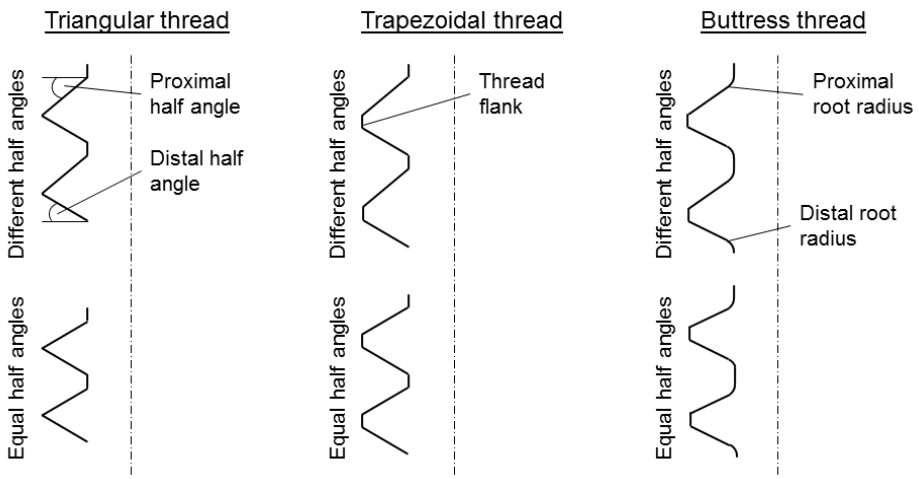

Figure 2: Different thread designs and their characteristics: triangular, trapezoidal and buttress thread

Considering the inner shaft of pedicle screws, both cylindrical and conical shapes are available on the market. Especially for conical screws the lower threads which lie within the spongious part of the bone have a bigger contact area than the upper threads within the cortical bone. Thus, osseointegration, which refers to the functional connection between living bone and the implant, is promoted in the spongious bone part. The pedicle is the strong part of the vertebrae and mostly consists of cortical bone.

In this study, both cylindrical and conical pedicle screws are considered. Independently of the shaft design, other variables such as the half angles and the outer diameter are kept constant over the whole

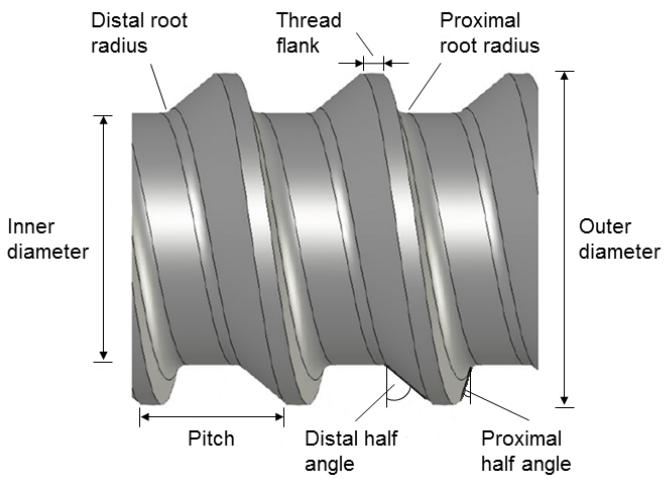

Figure 3: Geometry of a buttress thread

length of the thread of the screw.

2.2 Two-dimensional finite element model

A two-dimensional (2D) pedicle screw was modelled using a parametric Python script. Due to the parametric character, various studies can be performed without extensive preprocessing. The number of elements was kept low so that efficient simulations were possible because of the modelling in 2D. The finite element model was created in the commercial software Abaqus 2017 (Simulia, Dassault Systèmes). The pedicle screw was embedded into a bone block which consisted of two different layers: the cortical shell and the spongious part of the bone (Fig. 4A). The Young's modulus E_{cort} of the cortical and E_{spong} of the spongious bone were 12000 MPa and 100 MPa respectively [10]. The Poisson's ratio was 0.3 for the cortical and 0.2 for the spongious bone. Contact definitions were included in the model.

In order to decrease the number of designs, some variables were kept constant for the simulations such as the length of the screw (L = 45 mm), the pitch of the thread (P = 2.4 mm), the number of threads of the screw (n = 14) and different fillets to avoid sharp corners and potential stress singularities. In addition to that, the dimensions of the head of the screw were kept constant as well as the dimensions of the bone block and the thickness of the cortical layer. All other variables could be changed to gain information about the behaviour of the screw-bone model during loading.

The parametric model includes the possibility to realize a partitioned thread. The upper thread part can be modelled differently than the lower part. The position of the transition between these parts can also be changed. In this study, the transition between the upper and lower thread part took place after thread number four which is about the transition between cortical and spongious bone.

The parametric script allows the investigation of various screw materials such as titanium or short carbon fibre reinforced PEEK (sf-PEEK). The Young's modulus E_{sf} of the sf-PEEK material was 18000 MPa and the Poisson's ratio ν_{sf} was 0.3. Isotropic behaviour was assumed for this material. To further enhance the screw, an insert was realized with better mechanical material properties. The studies presented here focus on the sf-PEEK pedicle screw with the insert used for further reinforcement.

2.3 Three-dimensional finite element model

As mentioned in the beginning, primarily bending and pullout forces act on a pedicle screw. These forces were also considered in the finite element models and correspond to the bending and pullout loading case. A 3D-model was developed to adapt the loading condition of the two-dimensional to the three-dimensional model. It has to be mentioned, that for comparing studies the absolute loading value is of minor interest. Nonetheless, the loading conditions should be properly defined for the 2D-model. As a simplification, the thread of the 3D-screw was modelled axisymmetric and the bone material had a

cylindrical shape. Only half of the model was constructed to decrease the number of elements (Fig. 4B).

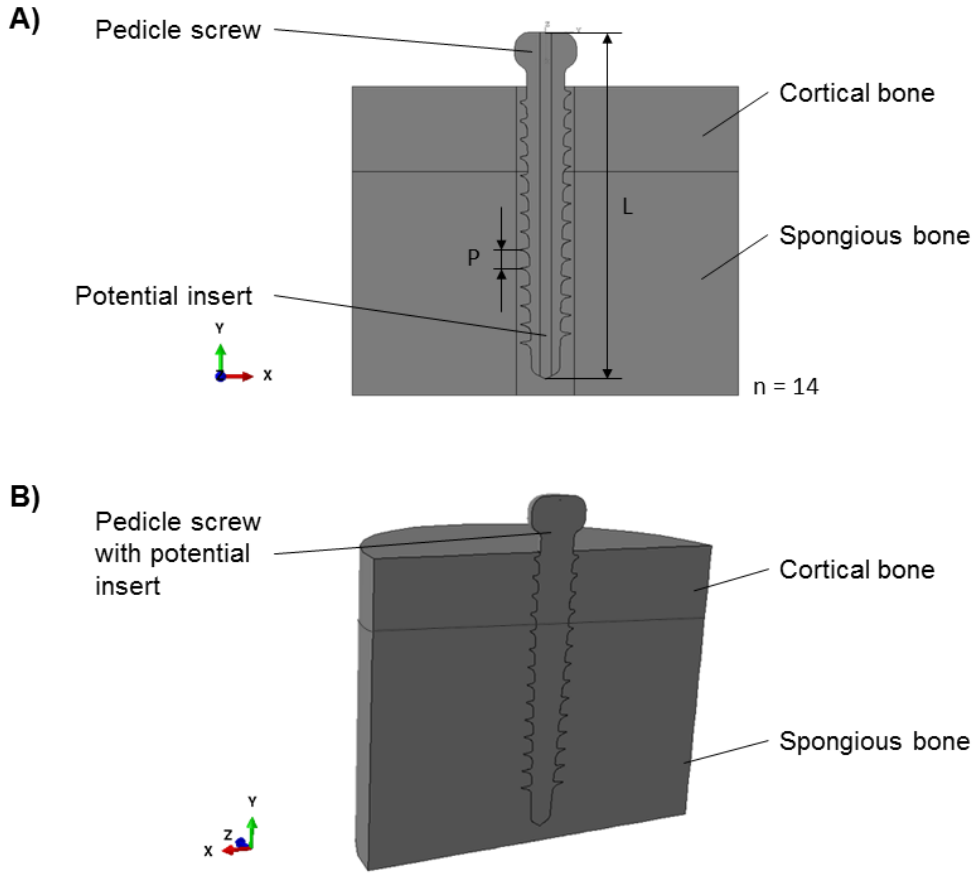

Figure 4: Two-dimensional parametric model (A) and three-dimensional model (B)

For the bending case, 1000 N were applied to the outer edge of the cortical bone of the 3D-model and the resultant displacement at this edge was examined. Here, the head of the screw was fully clamped and the displacement of the horizontal faces of the bone was restricted in y-direction to model a pure bending scenario. In the 2D-model, this displacement value was used to define the load. The boundary conditions were the same as in the 3D-model (Fig. 5A).

Similarly, a pullout load of 1000 N was applied to the lower edges of the screw head of the 3D-model. The vertical face of the bone was fully clamped in this case (Fig. 5B). Due to larger deformations of the two-dimensional bone block, the stress maximum inside the screw was taken as a reference to adjust the 2D pullout loading case to the 3D one. A focus lay on the pullout case in the study presented here.

2.4 Model validation

To validate the 2D pedicle screw model, a convergence study was performed. It was observed that with an increasing number of elements the results converged to an asymptotic value. To realize this examination, a representative set of elements was chosen within the center of the screw and the stress S_{11} in local 1-direction was examined. In this study, the number of elements of the screw increased from around 850 to 26000 elements and information was gained about how many elements are required to achieve adequate results. After this investigation, the whole screw-bone-model was meshed with around 48000 quadratic elements which correspond to around 145000 nodes dependent on the geometry parameters. The plane stress elements CPS8 and CPS6 were used for the element types. In the model, over 98 % of the elements were CPS8 elements.

In addition to the convergence study, the parametric 2D-model was compared to a model found in

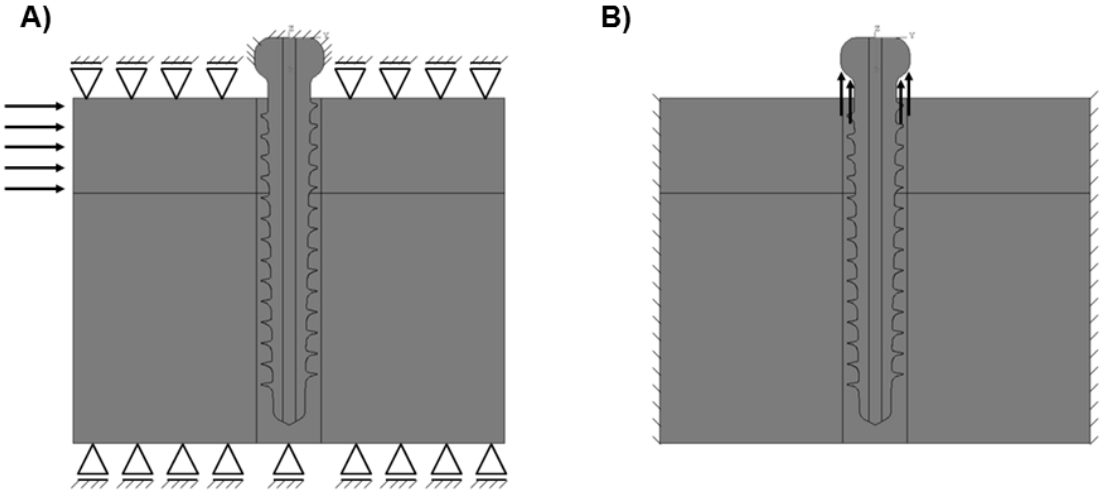

Figure 5: Boundary conditions for the bending (A) and the pullout loading case (B)

literature [11]. Haase et al. built up a two-dimensional finite element model in ANSYS to examine the phenomenon of stress shielding. The parametric model of this study was adapted to the model found in literature so they could be compared. It was observed that qualitatively and quantitatively the results matched to each other.

2.5 Conical shafts

To investigate the influence of the conical shaft of a pedicle screw, nine models with different conical shaft angles were created (Table 1). Here, all models were subjected to the pullout loading condition. In the table, the variables *conical angle 1* and *conical angle 2* refer to the shaft angles of the upper and lower thread part. The variable *cumulated angle* describes the sum of the conical angles. Model-1 represents a cylindrical screw whereas for model-2 and model-3 the first part of the thread is cylindrical and the lower part is conical. All other models have a conical upper and lower thread part. For all models, two common nodes were defined: *Node set 1* at the top and *Node set 2* at the tip of the screw. To compare the results, the screw with a cylindrical shaft (model-1) was taken as a reference.

	Model-1	**Model-2**	**Model-3**	**Model-4**	**Model-5**	**Model-6**	**Model-7**	**Model-8**	**Model-9**
Conical angle 1 in degrees	0	0	0	0.5	0.5	1.0	1.0	1.5	1.5
Conical angle 2 in degrees	0	1.0	2.5	0.5	1.0	1.0	1.5	1.5	2.0
Cumulated angle in degrees	0	1.0	2.5	1.0	1.5	2.0	2.5	3.0	3.5

Table 1: Conical shaft study − model overview

Dependent on the level of osseointegration, there can be mainly three types of contacts between the screw and the bone. A frictionless contact definition represents the initial state after the surgery when there is still no osseointegration between the screw and the bone. When osseointegration increases after some time there is friction between the screw and the bone. Here, this state was modelled by using a friction coefficient of 0.2 for the contact definition between screw and bone. A tie constraint was used to

simulate a completely osseointegrated screw. In this case, the screw sticks to the bone material and no relative motion is possible between them.

The properties of bone differ dependent on the age of the patient, the bone mineral density and other factors such as health condition or gender [12]. To study the influence of a stiffer spongious bone material, the Young's modulus E_{spong} was increased to 1000 MPa. A frictionless contact definition was used here and the pullout displacements were studied.

3 RESULTS

3.1 Different contact formulations

The contact between screw and bone was modelled frictionless for the first study. Fig. 6 shows the relative displacements in the screw axis direction. The displacement values of each model were related to the displacement value of the reference model-1. A value of zero is chosen for model-1 and in the figure, the difference to the reference is shown in percent.

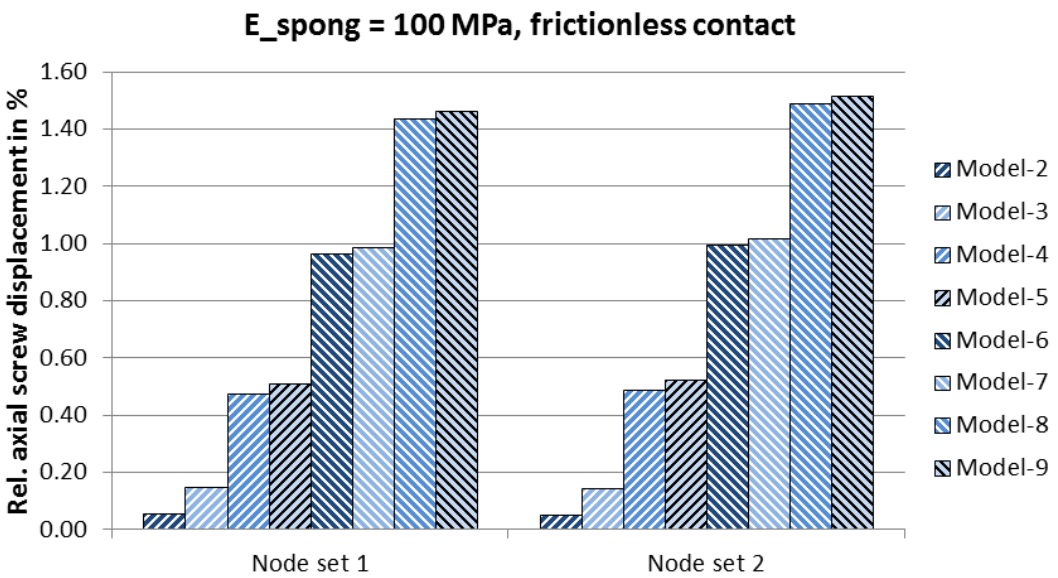

Figure 6: Relative displacement in axial screw direction - frictionless contact definition

It can be observed that the conical angle of the upper thread part has a major influence on the screw displacement. When the upper conical angle increases, the relative displacement value also increases. The conical angle of the lower thread part does not have a big influence on the displacement value as can be seen in the figure. This thread part is mainly located in the spongious bone. Generally, with a bigger conical angle the displacement of the screw increases. The behaviour of the displacement values of node set 1 and 2 is quite the same.

As mentioned above, two other states of screw-bone-interaction are possible after the surgery dependent on the level of osseointegration. These two other states of contact formulation were modelled and the relative axial screw displacement was examined (Fig. 7).

Compared to the results of the frictionless study, there are only minor differences when using a friction coefficient for the contact formulation as far as relative values are considered. However, the absolute values for the axial displacement slightly decrease. In the tie constraint study, the differences to the reference model (model-1) are smaller as can be seen in Fig. 7. As a summary, it can be pointed out that the interaction definition influences the pullout behaviour of the pedicle screw. A cylindrical screw showed the lowest displacement values independently of the contact formulation.

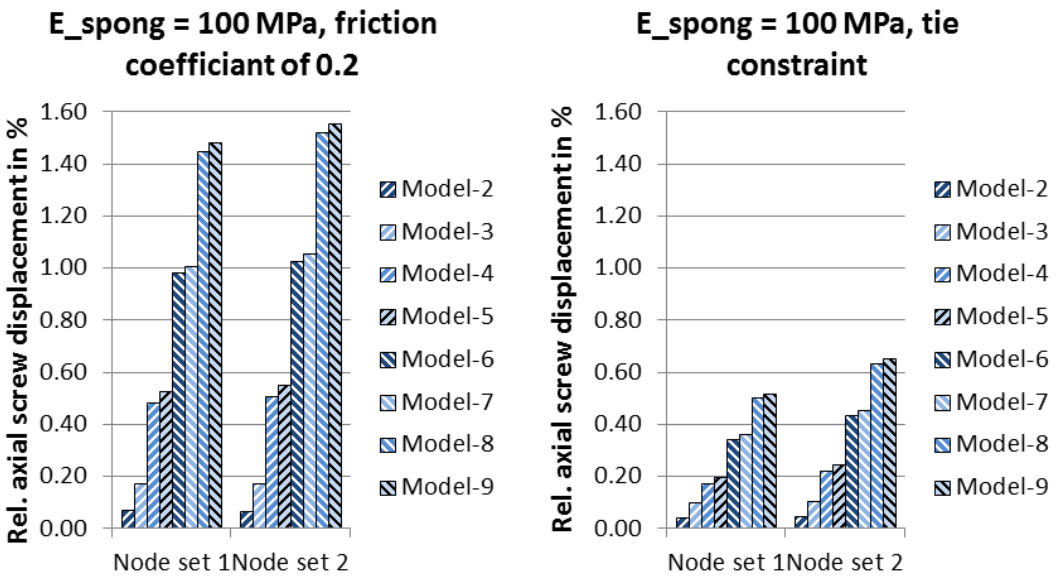

Figure 7: Relative displacement in axial screw direction - frictional behaviour (left) and tie constraint (right)

3.2 Increased bone stiffness

To account for a stiffer bone material, the Young's modulus of the spongious bone was increased (cf. chapter 2.5) and the effect of the displacement value was studied. The results show that not only the upper but also the lower conical angle had a major influence on the pullout behaviour (Fig. 8).

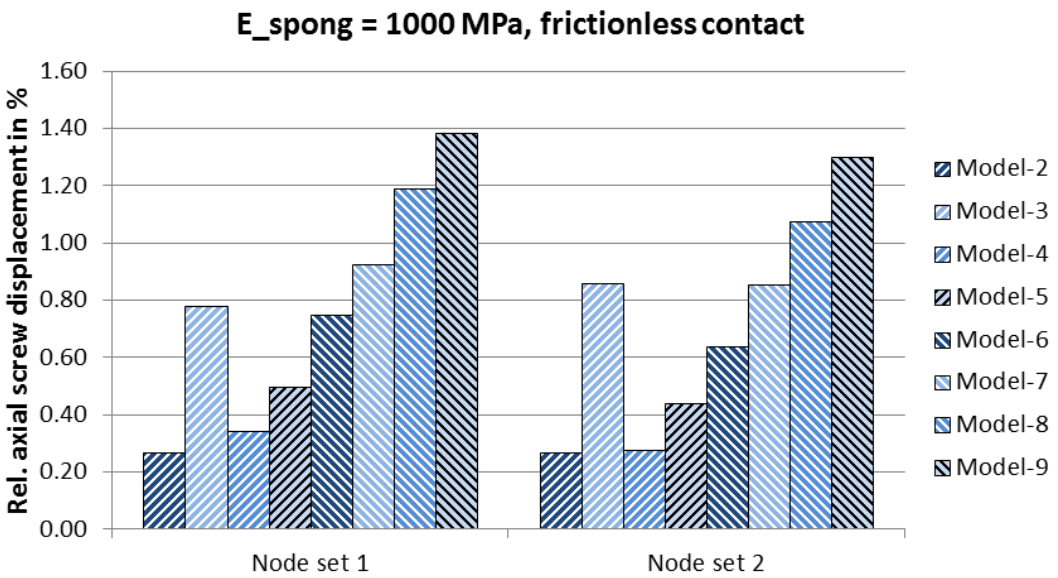

Figure 8: Relative displacement in axial screw direction - increased spongious bone stiffness

Here, the sum of the angles (referred to as *cumulated angle*) can be chosen as an indicator: Model-3 has a cumulated angle of 2.5° and rather fits model-6 and model-7 with a cumulated angle of 2.0° and 2.5° (Table 1). Due to the increased stiffness of the spongious bone, more resistance against pullout is gained in the lower thread part. With higher values of the conical angles, the axial screw displacements increased also in this case.

3.3 Comparison among performed studies

To compare the different studies among each other, the first study with a Young's modulus E_{spong} of 100 MPa and a frictionless contact was taken as a reference. A percentage value of 100 was assigned to it and the other studies were related to this reference study-1 (Table 2).

	Study-1	**Study-2**	**Study-3**	**Study-4**
Rel. axial screw displacement in %	100	97.90	59.37	51.10

Study-1: E_{spong} = 100 MPa, frictionless contact
Study-2: E_{spong} = 100 MPa, friction coefficient of 0.2
Study-3: E_{spong} = 100 MPa, tie constraint
Study-4: E_{spong} = 1000 MPa, frictionless contact

Table 2: Relative axial screw displacement among different studies

When friction was included in the model definition (study-2), the axial screw displacement slightly decreases to 97.90 % of the reference screw displacements. For a tie constraint, considered in study-3, only around 60 % are reached. The results indicate around the half of the reference displacement value for a stiffer spongious bone material (study-4).

4 DISCUSSION

The study about the change of the conical angle showed that for a cylindrical screw the lowest displacement values were reached. With increasing values for the conical angles, the displacement values increased compared to the cylindrical reference model. Especially when the stiffness of the spongious bone is low, the upper conical angle in the cortical layer had a major influence. With increased stiffness of the spongious bone, also the lower conical angle became significant.

The largest displacement values are reached by a frictionless contact definition. With increased friction, the resistance against pullout is higher. A fully osseointegrated screw was modelled by using a tie constraint definition for the screw-bone-interaction. Here, the lowest absolute displacement values were reached.

5 CONCLUSION

It has to be pointed out that these results have been obtained with a specific model configuration. However, to increase the significance of this study, different modifications of the initial model were performed. In reality, there is a distinction between three different screw-bone-states dependent on the level of osseointegration. These states have been considered in this study. Furthermore, the properties of the spongious bone were increased to account for different bone qualities.

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