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Factors which may increase stresses at the pin-bone interface in external fixation: a finite element analysis study

O.O.A. Oni, ⁺M. Capper, and ⁺C. Soutis
Department of Orthopaedic Surgery, The Glenfield Hospital, Groby Road, Leicester LE3 9QP and ⁺Department of Engineering, University of Leicester, Leicester.

Summary
The pin-bone interface of the external fixation system has been studied using a finite element mode. The maximum stresses were observed in the near 'cortex' adjacent to the site of entry of the pin. This location coincides with the area where loosening is usually first observed radiologically. Other results indicate that the stress values are significantly increased by using deep threads and by using stainless steel instead of titanium.

Keywords: *Pin-bone interface, external fixation, finite element analysis pin-thread, cortical thickneses*

Résumé
D'interface entre la broche et los du systeme-de fixation externe a ete etudie en utilisant un model a element fin. Les stress maximum avait ete observes dans le cortext rapproche adjacent au site d'entrée de la broche. Cette location coincide avec la region eu le detachement est observe radiologiquement en premier lieu. D'autres resultats montrent que les valeurs de stress avaient augmente significativement en utilisant les cordes profoundes et en utilisant l'acier inoxydable au lieu du titanium.

Introduction

Finite element analysis (FEA) is a numerical approach used by engineers to analyse stresses and displacements in complex structures. In practice, the structure is subdivided into discrete segments which are interconnected by nodes. Thereafter, various parameters are calculated under specified conditions for each segment and the data obtained is 'summated' and used to define the mechanical characteristics of the entire structure. FEA allows an investigator to change parameters in a system in an easy and systematic manner and thereafter to observe the effects.

In an external fixator system, a 'bone' column is linked by a number of pins via clamps to a 'fixator' column. Compressive and tensile forces are produced in the pins which are resisted at the pin-bone and pin-clamp interfaces. The pin-bone interface is the least secure [1] and it is also the critical component, for if it fails, the whole system will eventually fail. The geometry of the external fixation system suggests that the pins carry large bending loads. [2]. These loads generate stresses at the pin-bone interface which may cause complications.

Pin tract infection and loosening are the principal complications of external skeletal fixation [3]. The pathogeneses of these complications have not yet been fully elucidated but may be related to high local stresses at the pin-bone interface [5].

Correspondence: Mr. O.O.A. Oni. Dept. of Orthopaedic Surgery, The Glenfield Hospital, Groby Rd., Leicester LE 3 9QP

In an attempt to provide hard relevant data, in this study the factors which may increase stresses at the pin-bone interface have been investigated using FEA techniques.

Materials and methods

A model of a pin embedded in cortical bone was crated using the FEMGEN pre-processing package (Fig. 1).

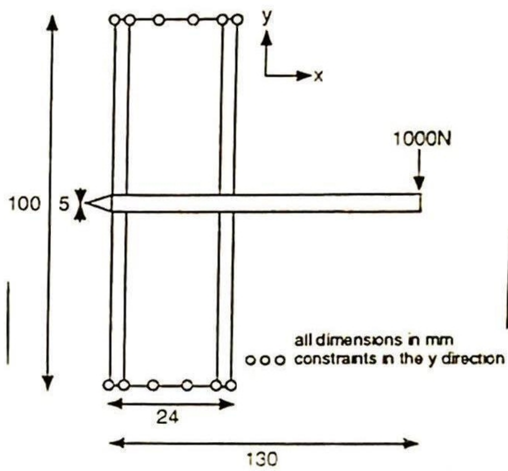


Fig. 1

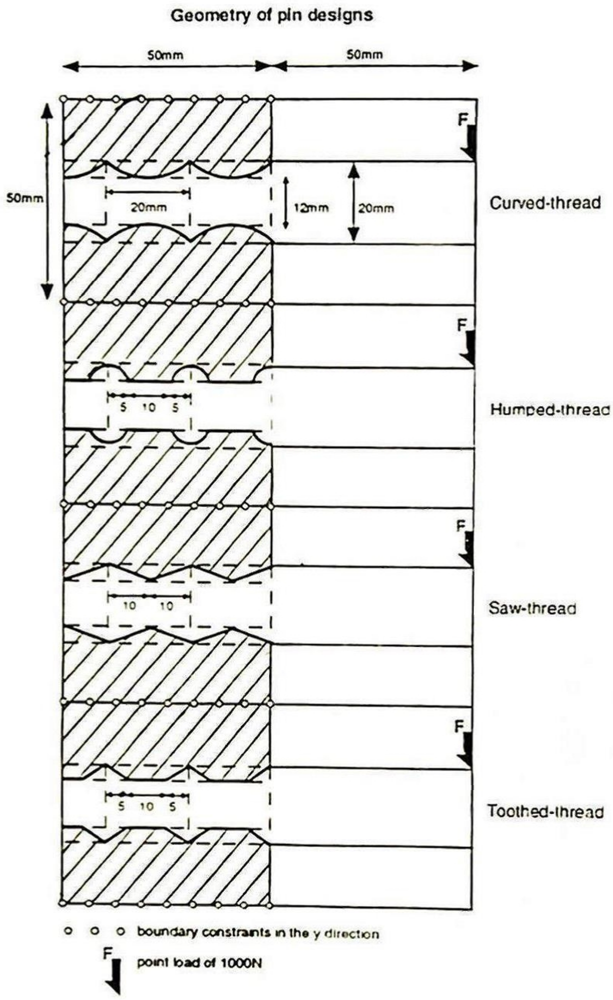
A mesh was generated for each model using four-noded quadrilateral plane stress elements. Material and physical properties were defined for bone according to Evans (1972) [6] and for pins made of stainless steel and Titanium, respectively. Constraints for the bone were applied in the Y-direction at its upper and lower surfaces and a force (100N) perpendicular to the pins was applied. The subsequent deflections and internal stresses were recorded. The analysis was carried out using the ABAQUS finite element computer software and the results were viewed using the FEMVIEW post processing package.

In order to identify the factors that may influence stress distribution at the pin-bone interface, direct and shear stress contours were obtained for different thread shapes/designs (forms), thread depths, pin materials, and cortical thicknesses..

1. Thread design

Radiographs of 6 different external fixator pins used in our local hospital were obtained and examined for their thread forms. Four varieties were identified and named curved-thread (Orthofix tapered pin), humped-thread (unnamed), saw-thread (Hoffman pin) and toothed-thread (Shearer pin) (Fig. 2) and modeled.

Figure 2:



2. **Thread depth**

Three types of pins were compared, namely smooth pin (Fig. 1), deep thread and shallow thread (Fig. 3).

Figure 3:

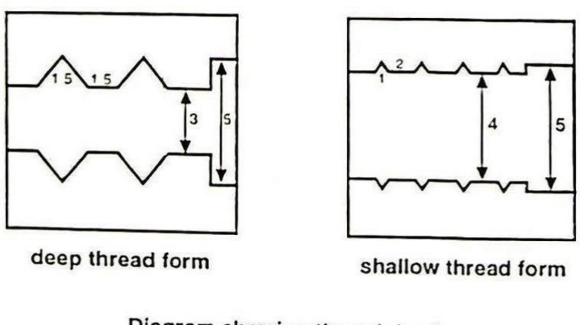


Diagram showing thread depths

3. **Pin material**

Titanium was compared with stainless steel using the deep thread model.

4. **Cortical thickness**

External fixators are used most frequently to treat fractures of the shafts of long bones. These bones comprise a marrow-filled cylinder of varying thicknesses. Therefore, a 6-mm thick bone cortex was compared with a 3-mm thick cortex using the shallow thread model.

Results

The largest displacement of the pin occurred at the site of its entry into the bone. The stresses generated by the applied force were not uniformly distributed within the bone. The maximum stresses were generally observed in the near 'cortex' adjacent to the side of entry of the pin and in relation to the threads. In the loading axis or Y-direction, the pin was in tension at the upper side and in compression at the lower side. The maximum stress was observed adjacent to the pin entry point and from there, stresses appeared to dissipate in all directions. The X-direction stresses were the largest in all cases and the critical point was also revealed to be around the entry point. Stress distribution was relatively symmetrical about the longitudinal axis of the pin. The maximum shear stress was observed within the pin itself but large compressive stresses were still noted adjacent to the pin entry site. Table 1 shows the maximum stress values (MN/m^2) generated by the different thread forms.

Table 1: Maximum stresses (MN/m^2) generated by different thread forms

	XX stresses	YY stresses	XY stresses
Curved-thread	12.20	3.76	3.09
Humped-thread	12.60	3.03	4.18
Saw-thread	13.80	3.09	2.47
Toothed-thread	13.40	3.70	3.47

The maximum normal stresses generated by the different threads have similar values; the largest deviation being about 13% in the X-direction and 19% in the Y-direction. The maximum shear stress produced by the humped-thread was 70% higher than that generated by the saw-thread. As shown in Table 2, the smooth pin generated the lowest stresses.

Table 2: Maximum stresses (MN/m^2) generated by different thread depths.

	XX stresses	YY stresses	XY stresses
Smooth pin	5.54	4.23	1.59
Shallow thread	20.20	5.44	2.30
Deep thread	29.10	6.14	5.63

In addition, the shallow thread generated significantly lower stresses that the deep threads in all planes. Table 3 shows that the Titanium pin generated lower maximum normal stresses in the X-direction, but higher normal stresses in the Y-direction than the steel pin; the shear stresses were also lower in the Titanium pin than in the steel pin. Table 4 shows no significant differences between the 3 mm and the 6 mm cortices.

Table 3: Maximum stresses (MN/m^2) generated by different materials

	XX stresses	YY stresses	XY stresses
Steel pin	29.10	6.14	5.63
Titanium pin	24.90	6.65	5.58

Table 4: Maximum stresses (MN/m^2) by different cortical thicknesses

	XX stresses	YY stresses	XY stresses
6 – mm cortex	20.20	5.49	2.60
3 – mm cortex	20.20	5.44	2.30

Discussion

The results using this proprietary finite element software confirm the findings by Klip and Bosma (1978) [7] which suggest that the site of entry is the critical point in an external fixation system where excessive stresses are being generated. This is therefore the site where one would expect to observe the highest incidence of bone resorption. The effects of the bending stresses would be exaggerated by bending pre-load and could account for the increased incidence of loosening observed by Hyldahl et al. (1991) [8] in their experimental study. On the other hand, the bending effects could be resisted by adding to the pin a flange which rests on the bone surface as recently demonstrated by Oni et al. (1995) [9].

As expected, threaded pins generated larger stresses at the pin-bone interface compared with the smooth pin. In practice, however, a smooth pin has the disadvantage that it cannot create the holding power necessary to resist bend-out. This problem could be solved by introducing pins with shallow thread forms. These latter pins appear to generate lower stresses than the deep thread designs, which are currently in common use. Although there is a build up of stresses in relation to sharp crests and roots, the humped-thread generated the highest shear stresses. The toothed-thread generated higher shear stresses than the curved-thread and saw-thread designs which have shallower depths. This raises the possibility that thread depths may also be a factor.

Titanium was shown to have a smaller stress raising effect than stainless steel. Stainless steel (196 GPa) is stiffer than Titanium (110 GPa) and, therefore, in theory, should produce less deflection and, as a consequence, lower stresses. However, this is not the only material property used in finite element analysis. The poisson ratio is equally important and in this respect, titanium (0.35) has a ratio that is identical to that of bore and higher than that of stainless steel (0.30). Other advantages of Titanium include its light weight; it has only a tenth of the mass of a stainless steel pin of the same size. Therefore, its use could considerably reduce the weight of external fixation systems.

This study may be criticize for not using a 3-dimensional model. Although this is ideal, the analysis would have required more elements and the results would have been more complicated to analyse. Although 2-dimensional analyses do not fully simulate the clinical situation, they allow useful comparisons to be made concerning the effects of different factors on the stresses generated at the pin-bone interface. Using this finite element method, the stresses generated by each pin model and the effects of individual factors on these stresses could be observed at a glance. The main features are that areas of high stresses occur at the pin entry site and in relation to the geometry of the thread from. The data is potentially useful in the design of pins in that it shows which stresses need to be resisted and where they are located. In addition, it provides a pathogenetic mechanism for pin loosening.

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