Pantarsal Arthrodesis Using a Plantar Plate: Finite Element Analysis of Plate Position and Preliminary Results of Four Cases

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ABSTRACT

A finite element analysis was carried out to determine the optimal plate placement for pantarsal arthodesis. Three different plate placement scenarios were considered: cranial, lateral, and caudal. Under similar loading conditions, the finite element results showed that the cranial and lateral plates experienced stresses surrounding the metatarsal screws which may indicate screw loosening or failure. High stress concentrations were also noticed in both plates at the tarsocrural joint. In comparison, the caudal placed plate showed much lower stress levels, which suggests that this is the optimal plate position. Four dogs weighing in excess of 25Kg subsequently underwent pantarsal arthrodesis using a caudal plating technique. Successful arthrodesis occurred in all cases. The results of this study suggest that a caudal plate position is the preferable option in pantarsal arthodesis and warrants further investigation.

INTRODUCTION

The application of bone plates to the dorsal, medial, or lateral aspect of the tarsus has been reported for pantarsal arthrodesis [1-5]. Pantarsal arthrodesis using a number of other techniques have been reported in the literature: pin and tension band wire [6], lag screws [7], and transarticular external fixation [8,9]. Partial tarsal arthrodesis can be achieved using a plantar plating technique [10]. Adjunctive stability using coaptation has been recommended following arthrodesis with internal fixation [1,5,11].

Structural finite element analysis (FEA) has the potential to provide valuable information on bone-plate constructs and, in particular, can identify regions of high stress or strain and hence predict the likely locations of failure. The use of FEA to successfully model bone-plate constructs and identify regions where plate failure and/or screw pullout may occur has been proven in recent years [17-21]. A significant advantage offered by FEA is the ability to carry out "virtual prototyping" of various designs via computational models before the designs are put into service. In the case of bone-plate constructs, this allows for the pre-operative modeling of a number of different plate placement scenarios and the direct comparison of the structural effects of such scenarios in terms of: relative micro-motions, regions of high stress, and maximum stress levels. Comparison of the results from a number of finite element models of different plate placement scenarios allows for the selection of the optimal plate placement for a given loading and geometry.

From a mechanical perspective the cranial and lateral plate placement would seem to be non-ideal as the plate is not placed on the tension surface where it can be most effective. A caudal plate position offers the advantage of acting on the tension surface. The purpose of this study is to investigate if this is indeed the case. Initially, a finite element analysis was carried out to verify the mechanics of the problem. Four dogs subsequently underwent pantarsal arthrodesis with the plate in the caudal position.

The specific objective of this paper is to provide a comparative analysis of the three fixation constructs and to provide a scientific explanation for the improved performance of the plantar plate construct. Using the same assumptions for each FE model allows for a direct comparison of results between the models and may be used to select the most favorable design (in this case fixation construct). This methodology is standard practice in the FE industry. This study does not propose the use of bench tests or specific validation of the FEA models as the methods used have previously been validated by the authors in other work [20]. A secondary objective of this paper is to show how FEA can be used as a pre-clinical tool to predict optimal plate placement. Specific issues relating to the validation of such models against bench tests and other results have been covered in detail elsewhere [17, 19, 21].

METHODS AND MATERIALS

A finite element analysis study was undertaken in order to compare the structural effects of each of three plate placement scenarios during pantarsal arthodesis. An idealized model of the tarsus was used to simplify the analysis, where the tibia was modeled as a hollow elliptical tube and the tarsus/metatarsal construct was assumed to be a semi hollow tapered tube. The tarsus/metatarsal construct consisted of two distinct regions: a solid tubular section representing the calcaneus and talus and a hollow tapered tubular section representing a metatarsal. Dimensions for the bone geometries were taken from relevant radiographs of a 25Kg Collie breed dog. Three separate finite element models were built in order to analyse three different plate placement possibilities. In all cases the same distribution and types of screws were modeled: five 3.5mm screws in the tibial portion of the plate, two 3.5 mm screws through the solid tarsus, and four 2.7 mm screws in the hollow metatarsal. The implants were simplified by ignoring screw threads. Both bone and 316L implant were assumed to be linear elastic, homogenous, and isotropic. In the cranial and caudal cases, by taking advantage of symmetry, it was only necessary to model one half of the bone-plate-screw construct. A full model was required for the lateral placement as an appropriate symmetry plane did not exist.

A contact algorithm was used to define a tied contact between the screws and the plate and also between the screws and the bone. This means that the screws were perfectly bonded to the bone and the plate was bonded to the screws. This assumption has become standard in the FE analysis of bone-implant constructs in recent years [20,21] and is acceptable as the use of bonded contact will still identify regions of high stress where load is transferred from plate to screw or screw to bone. The assumption of tied contact is also valid when one considers that a screw is mechanically stable due to the fact that it embeds into the bone tissue and hence an extremely large frictional force is generated between the screw-threads and the bone tissue. As bone tissue is much softer and less stiff than steel, screw pullout or loosening can only occur by localized failure of the bone tissue around the screw threads. In a finite element model, such failure shows up as

Figure 1: *A) Overview of Finite Element Model of Pantarsal Arthodesis with Plate in Cranial Position; B) Finite Element Mesh*

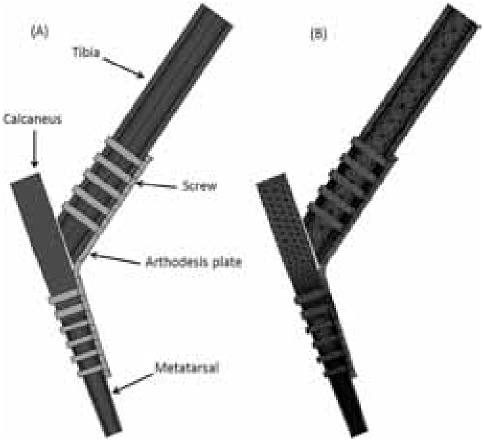


Figure 2*: A) Overview of Finite Element Model of Pantarsal Arthodesis with Plate in Lateral Position; B) Finite Element Mesh*

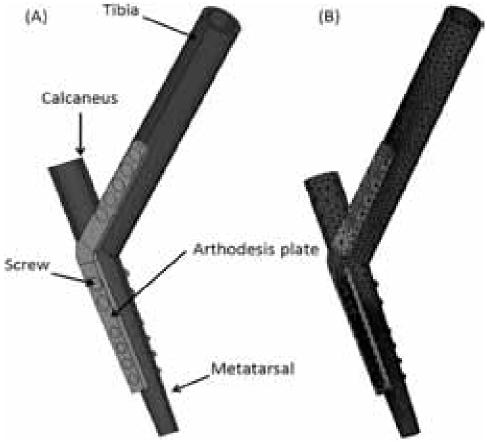
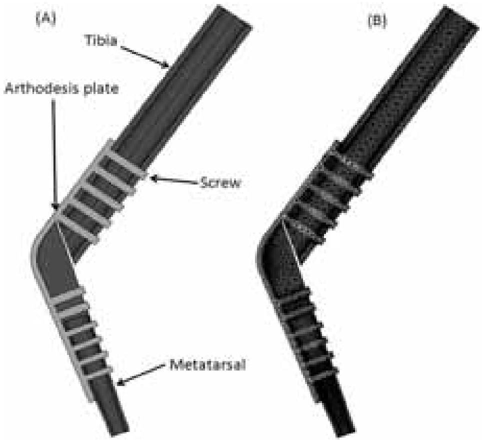


Figure 3: *A) Overview of Finite Element Model of Pantarsal Arthodesis with Plate in Caudal Position; B) Finite Element Mesh*



localized stress concentrations at the screw/bone interface, where the maximum stress exceeds the yield stress of bone. Yielding always precedes failure and, in the case of bone, the yield stress and failure stress are very close. By identifying portions of the bone model that exceed the yield stress, we are effectively identifying locations which will shortly fail by crushing and/or cracking of bone.

By searching for such regions of high stress in the finite element results, it is possible to identify where screw loosening or pullout will occur due to local damage. This will show up as a high stress concentration in the bone tissue surrounding a screw. Again, it is also possible to identify where plate fracture or screw fracture will occur by searching for stress concentrations which exceed the yield stress of steel in the implant geometries. In this study the yield stress of bone was assumed to be 100 MPa and the yield stress of 316L stainless steel was 290 MPa [20].

A force of 250 N was applied in the downward vertical direction to the proximal tibia in each case to model the weight of the animal acting through the tibia. In order to avoid singularities at the point of load application, the nodes making up the top surface of the tibia geometry were coupled in the appropriate degrees of freedom. In order to

***Figure 4:** Stress Concentraion Surrounding the First Screw Hole in the Metatarsal In the Cranial Configuration Indicating Localised Failure of Bone Tissue which would Cause Screw Pullout.*

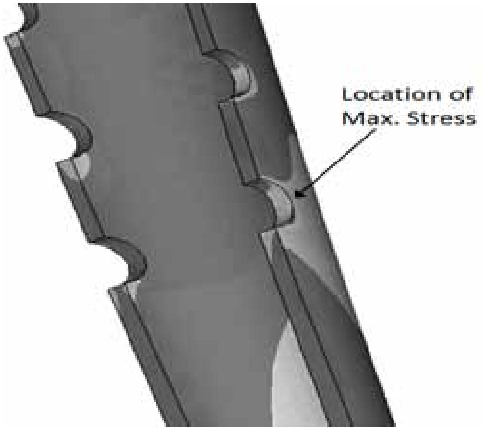


***Figure 5:** Stress Concentrations In the Implant In the Lateral Configuration Indicating Localised Failure of the Implant Material which would cause failure of the plate and screw heads to shear off*

model the load induced on the calcaneus from the gastrocnemius muscle, a second force acting parallel to the tibia in the proximal direction was applied to a central node on the proximal end of the calcaneus. Again, appropriate use of coupled nodes was made in order to avoid singularities, and hence avoid spurious results. The same loads were applied to each model to allow for direct comparison between the resultant stresses and strains in each placement scenario (except gastrocnemius pull in caudal model).

It is important to note that the FE models were not designed to provide a comprehensive imitation of the tarsus and implant, but rather to be used as a supplementary tool to provide insight into the effects of plate placement during arthrodesis. The models were designed to reflect the simplest shape that still retained the essential mechanics of the problem. Similarly, the assumptions made for the implants were due to the fact that this is a comparative analysis examining only the mechanical behavior of the models due to the plate position. All assumptions were made according to standard FE practice [17-21].

The finite element software suite ANSYS version 11 was used to carry out the FEA. Three-dimensional models of each implant-bone construct were generated from solid models of an idealized geometry of the tarsocrural joint. Figure 1 shows the geometry of the finite element model used to analyse cranial plate placement. In all cases, the plate was bent to an appropriate angle to match the relative angle between the tibia and metatarsals. The mesh was generated using ten node tetrahedral solid elements and the mesh density was appropriately increased around the screw holes where high stresses would be expected (Fig 1). Figures 2 and 3 show the corresponding finite element models for the plate placed in the lateral and caudal positions, respectively. The same bone model and loading was used in each case, as previously shown in figure 1.

In each case, it is evident that the tarsocrural joint is highly idealized. However, the fact that the same bone models were used in each of the three analyses allows for a direct comparison of all three plate-placement scenarios. It is clear that there is no load transfer through the tarsoocrural joint, as there is a gap between the bones at this location. This ensures that the plate alone carries the load across the joint in each case – this may be an extreme case but it effectively shows which plate configuration provides the optimal resistance to implant failure. An advanced surface-to-surface contact algorithm was employed between the screw shafts and the bone, which allowed for load transfer between the implant and bone. It has become standard practice to replace screw threads with an appropriate contact algorithm, a methodology used in references 17-21.

A linear elastic isotropic material model was used for both bone (E=17.4 GPa, v=0.33) and stainless steel (E=210 GPa, v=0.27). These properties were determined from a statistical study of properties used in literature [17-21]. Three-dimensional solid finite elements were used to divide the geometry into an appropriate finite element mesh. According to standard practice, a mesh convergence study was undertaken in order to ensure that the mesh was suitably refined in each case.

Four dogs underwent pantarsal arthrodesis using a plantar plating technique between 2005 and 2008. Clinical assessment and outcome was performed by the operating surgeon and another veterinary surgeon. Confirmation of arthrodesis was verified using serial radiographs every three to four weeks (Fig 1 and 2). In each case, the dog was premedicated with medetomidine (Domitor; Pfizer) and butorphanol (Torbugesic: Fort Dodge). Anaesthesia was induced and maintained with isoflurane (Forane; Abbott laboratories). Preoperative cephalexin (Solvasol;Norbrook) was administered and maintained for at least seven days after surgery. Butorphanol (Torbugesic; Fort Dodge) or buprenorphine (Temgesic; Reckitt and Coleman) was administered daily for the first three days postoperatively. Meloxicam (Metacam; Boerhinger) was started preoperatively and used for seven days. Following a plantar incision, the calcaneus was exposed and cut in a circular shape to allow the plate to be contoured along the cut. The joints were opened and all cartilage removed using a round burr. A cancellous bone graft from the wing of the ilium was packed into the joint space. Trial placement of the plate bent to an angle of approximately 135 degrees was performed to ensure proper screw placement, especially in the metatarsals. Screws were inserted into the tibia (3.5mm) and tarsometartarsal area (3.5 mm/2.7mm). The dorsal piece of the calcaneus was screwed or pinned into the tarsal area. No coaptation was used postoperatively.

RESULTS

Plots of von Mises stress for each FE model clearly show the locations and magnitudes of the maximum stress in the implants and bones due to the particular plate placement being considered. The cranial and lateral positions clearly show increased stress in the bone surrounding the screw holes in the metatarsals, which would indicate possible localized failure of bone in these regions. Figure 4 shows an example of a stress concentration in the metatarsal at the first screw hole with the cranial plate. Such localized failure could lead to crushing and/or micro-cracks which would subsequently lead to screw loosening and eventually screw pull-out.

Further detailed examination of the screw and implant revealed regions that were stressed. These regions were at the screw head and shaft junctions (indicating possible shearing off of the screw heads) and at the central region of the plate at the tarsocrural joint (indicating possible plate failure at this location). Figure 5 shows an example of a stress concentration in the plate/screws for the lateral configuration.

The locations and types of predicted failure for each model can be summarized in as follows:

Plate Config.	Location of Max Stress	Type of Failure
Cranial	At distal metatarsal screw holes	Screw pullout or loosening
Lateral	At plate bend and nearby metatarsal screws	Screw heads shearing off and/or cracking of the plate at the bent region
Caudal	At distal metatarsal screw holes	None (all stresses below yield)

Table 1 Case details

Case	Age	Sex	Weight	Disease/ injury	Time to arthrodesis	Complica- tions
1. Labra- dor	2yrs	M	30Kg	Fractures	12 weeks	None
2. Collie	4yrs	F	25Kg	Shearing	20 weeks	Calcaneus loose
3. BeagleX	8yrs	F	27Kg	OA	18 weeks	Calcaneus loose
4. Rottwei- ler	2yrs	M	39Kg	OA	16 weeks	None

KEY
OA Osteoarthritis

All of the dogs weighed more than 25 Kg (Table 1). There were two males and two females with an age range of two to eight years and a mean age of four years. Two cases had severe osteoarthritis of the tarsocrural joint (Fig 6), one had a comminuted fracture of the talus and one medial tarsocrural shearing injury. In two cases, the osteotomised piece of the calcaneus was clinically detected to be loose at final check up. However, this did not cause a clinical problem. Successful arthrodesis occurred in all cases with no major complications with the implants for arthrodesis (Fig 7).

DISCUSSION

The finite element results are not surprising given that in the cranial position, the plate is located on the compression surface of the plate-bone construct. Therefore, it is subjected to significant compressive bending forces when weight is placed on the limb. These forces will cause the plate to attempt to decrease its internal angle, which will result in stresses at the bend in the plate. As the proximal screws have a larger diameter and are embedded in more bone, due to the larger size of the tibia, failure of the distal metatarsal screws due to loosening or pull-out is to be expected.

In the lateral position, the plate is a stiffer orientation due to the fact that its longer cross sectional axis is in the plane of bending and hence failure of the plate is less likely. In this case, however, shearing of the screw heads becomes more of a problem as the much stiffer plate transfers load to the bones via the more vunerable screws. Distal metatarsal screw loosening was a possibility in this configuration.

The caudal plate position showed the advantages of being placed on the tension side of the bone-implant construct. Although stress concentrations were noted at the plate bend and around the distal metatarsal screw holes, in this case they were lower than those experienced in the two other plate positions. It can therefore be said that the caudal position is the mechanically preferable position for tarsal arthrodesis.

The modeling and loading conditions applied had assumptions that need to be taken into consideration when analyzing the results. The fact that there was no validation of the FEA using bench testing should also be recognized as a potential weakness of this study. In the opinion of the authors, the weaknesses of the FEA component of the study should not detract from the findings in any significant way.

Pantarsal and partial tarsal arthrodesis are salvage procedures that can be used to treat conditions such as severe tarsal fractures, intractable tarsal pain, and shearing injuries [5]. Pantarsal arthrodesis requires articluar cartilage removal and bone grafting of the talocrural, intertarsal, and tarsometatarsal joints. Rigid fixation with concomitant management of the the soft tissue envelope

Figure 6: *Preoperative view showing severe osteoarthritis*

Figure 7: *12 week postoperative view showing plate position and arhtrodesis*

are further requirements to acheive fusion fo these joints.

Complication rates up to 80% have been reported with tarsal arthrodesis procedures. These can include angular and rotational deformity, implant failure, dehiscence, and pedal necrosis [6,1,3,4,5,12]. Pedal necrosis is a devastating complication and has been reported mainly in association with medial plate application and debridement of the tarsometatarsal joint, which may injure the perforating metatarsal and/or dorsal pedal arteries. The four cases in this study did not have any major complications. Two of the cases had a palpable free calcaneus at the final clinical examination, but this was not of any obvious clinical significance. To prevent nonunion of the osteotomised piece of calcaneus, pin and wire fixation may be inadequate. More aggressive preparation of the apposing bone surfaces and fixation with a screw rather than a pin are possible recommendations to overcome the nonunion of the osteotomised piece.

In man, debilitating post-traumatic arthritis is the most common indication for ankle arthrodesis [13]. It is also indicated for primary osteoarthritis, pain secondary to joint infection, inflammatory arthropathies such as rheumatoid arthritis, and gout. Infrequently, it is used in Charcot-Marie-Tooth disease, Charcot arthropathy, and for failed ankle replacement. The advent of arthroscopic ankle arthrodesis in 1983 [14] resulted in higher fusion rates, faster union, and less morbidity [15,16]

CONCLUSIONS

The FE results clearly show that caudal plate placement is the preferable option. Lateral plate placement risks failure of the implant and/or screws, while cranial plate placement has a greater risk of screw loosening and pullout. Placing the plate on the plantar aspect results in lower complication rates in the preliminary results of this case report. Apart from the mechanical advantage of putting the plate on the plantar aspect, there may also be less soft tissue problems, such as dehiscence.

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