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Finite element analysis of Puddu and Tomofix plate fixation for open wedge high tibial osteotomy

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ABSTRACT

The use of open wedge high tibial osteotomy (HTO) to correct varus deformity of the knee is well established. However, the stability of the various implants used in this procedure has not been previously demonstrated. In this study, the two most common types of plates were analysed (1) the Puddu plates that use the dynamic compression plate (DCP) concept, and (2) the Tomofix plate that uses the locking compression plate (LCP) concept. Three dimensional model of the tibia was reconstructed from computed tomography images obtained from the Medical Implant Technology Group datasets. Osteotomy and fixation models were simulated through computational processing. Simulated loading was applied at 60:40 ratios on the medial:lateral aspect during single limb stance. The model was fixed distally in all degrees of freedom. Simulated data generated from the micromotions, displacement and, implant stress were captured. At the prescribed loads, a higher displacement of 3.25 mm was observed for the Puddu plate model ($p < 0.001$). Coincidentally the amount of stresses subjected to this plate, 24.7 MPa, was also significantly lower ($p < 0.001$). There was significant negative correlation ($p < 0.001$) between implant stresses to that of the amount of fracture displacement which signifies a less stable fixation using Puddu plates. In conclusion, this study demonstrates that the Tomofix plate produces superior stability for bony fixation in HTO procedures.

Introduction

High tibial osteotomy (HTO) is a well established procedure used to treat uni-compartmental osteoarthritis of the knee.[1] Due to its success in treating this condition, the use of HTO has since been extended to include many other indications such as, correction of various angular knee deformities and ligamentous injury.[2] In addition, HTO have also been widely advocated for use in paediatric patients which includes correction of congenital malformation.[1–3] At present, there are two types of HTO which are commonly described: the medial open wedge HTO (OWHTO) and the closed-wedge HTO (CWHTO). It is apparent from most studies that OWHTO is more widely preferred owing to the lesser likelihood of developing complications; which may include peroneal nerve injury and disruption of the proximal tibiofibular joint.[4]

To maintain the stability of the OWHTO, specialized implants were introduced. The two most commonly described are the Tomofix and Puddu plates.[5] Although the former provides stability to the osteotomized tibia fixation using locking head screws (LHS), the Tomofix plates maintains its fixation on the bone using the fixed-angle plate concept.[6] However, the comparative biomechanics between these two different implants has not been demonstrated and analysed computationally.

One of the computational methods that has received wide acceptance in orthopaedics research is the Finite Element Analysis (FEA).[7–9] In this technique, three dimensional models of bone-implant construct are converted into finite elements with simulated physiological loads applied to analyse and predict the outcome of surgery. Various biomechanical studies via computer simulation have provided further insight into the stability and functionality of joints and bone construct.[7,10–13] Hence, the present study was conducted to determine the stability of these implants following OWHTO procedure through the use of finite element analysis.

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Materials and methods

Three dimensional model design

Three dimensional (3D) model of human tibia and fibula was reconstructed from two dimensional computed tomography (CT) image using 3D model reconstruction software (MIMIC 10.01, Materialise, Belgium). The CT image dataset was obtained by scanning the lower limb of a single male subject in one medical centre. An opening of 10 mm gap was simulated by removing a wedge-shaped bone piece from the proximal part of the tibia. The three dimensional models of both implants were designed according to the manufacturers' specifications using computer-aided design (CAD) software (SOLIDWORKS 2009 SP2.1, Dassault Systems, Massachusetts, USA). Two components make up both the Tomofix and Puddu plates, which is the plate and screws. The Tomofix plate system has a total of 8 screw holes: 5 of these are able to adapt either the LHS or conventional screws while the remaining three can only allow the LHS screws to be inserted. In the Puddu plate system, in addition to the plate and screw holes, a block configuration was incorporated into the plate design to allow additional support at the osteotomy. In this system, two conventional screws were used, which is commonly described in several literatures.[5,14,15]

The implants were then carefully positioned across the gap. A 10 mm wedge size Puddu plate was selected, and placed across the opening as shown in Fig. 1. The Tomofix was positioned as recommended by the manufacturer as demonstrated in Fig. 2.

Material properties

In this study, the properties of titanium alloy were adopted into the simulated implant models. The Young's modulus (E) was set at 110,000 MPa with a Poisson's ratio (υ) of 0.3.[16] Both implants were modelled to incorporate linear elastic, isotropic and homogeneous properties. As for the tibia and fibula, the material properties were also assumed as linear elastic, isotropic and homogeneous material. Both tibia and fibula were modelled with an assumed Young's modulus, E = 20,000 MPa and Poisson ratio, υ = 0.3.[10] The cortical bone and medullary canal was not modelled in this study.[17] These parameters are summarized in Table 1.

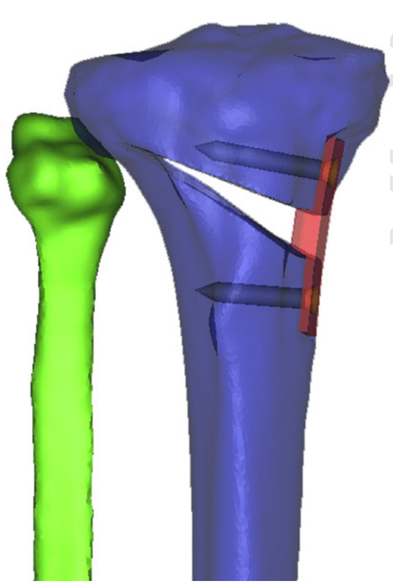

Fig. 1. Puddu plate positioning on 3D model of simulated open wedge high tibia osteotomy.

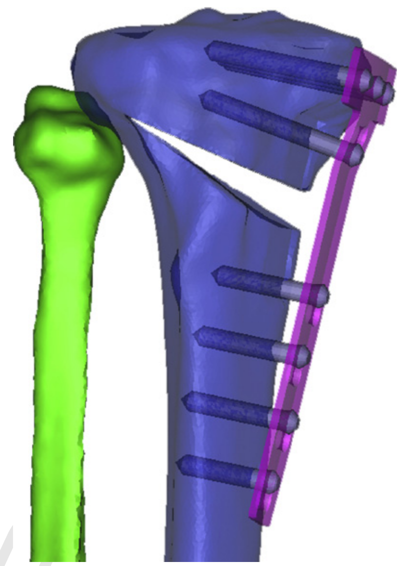

Fig. 2. Tomofix plate positioning on 3D model of simulated open wedge high tibia osteotomy bone.

Analysis

For finite element analysis, both the bones and implants were meshed using 1.0 mm sized tetrahedral mesh.[18] The distal end of the tibia was fixed in all degrees of freedom to prevent rigid body motions during the analysis. An axial force of 2500 N with a distribution of 60% to the medial compartment was applied to simulate the axial compressive load on the knee of an adult during single limb stance.[5,19] The effect of axial load sharing between tibia and fibula was simulated by linking the two bones with virtual mechanical rigid links.[20]

For the Puddu plate system, it was assumed that this plate system had a direct contact with the bone. The same contact properties were also assigned between the LHS and the bone. The contact between the plate and LHS was simulated to imitate strong contact attachment that mimics the locking screw mechanism. All friction coefficient values were set to 0.3.[21] The analysis was done using commercial finite element software (MARC, MSC.Software Corporation, California, USA) with the equivalent von Mises stress (EVMS), displacement of the model relative to the distal tibia, and micromotion of the implant relative to the bone (as a measure of relative fixation strength) used as the output measures. Statistical analysis was done using the IBM SPSS Statistics software using t-test.

Results

Higher amounts of displacement were observed in the Puddu plate system as compared to the Tomofix plate with a mean difference of 3.25 mm observed between the two ($p < 0.001$) (Table 2). The displacement appeared to be directed towards the anterior side of the tibia which was consistently observed in both systems (Fig. 3), decreasing as it approaches distally (Fig. 4).

Table 1
Material properties of reconstructed 3D model.

Materials	Young's modulus, E (MPa)	Poisson ratio, υ
Puddu plate/Tomofix plate	110,000	0.3
Screws	110,000	0.3
Tibia	20,000	0.3
Fibula	20,000	0.3

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Table 2
Difference between Puddu and Tomofix for different biomechanical properties.

Variable	Group	Number of nodes (*N*)	Mean	SD	Mean difference	*p*-value
Displacement	Puddu	6872	15.24	10.78	3.25	0.001
	Tomofix	6872	11.99	7.45		
Implant stress	Puddu	3405	24.74	22.46	−20.75	0.001
	Tomofix	6119	45.49	39.71		
Model stress	Puddu	6231	1.11	1.73	0.53	0.001
	Tomofix	6231	0.58	0.31		

EVMS results demonstrated dissimilar stress pattern distributions in both constructs (Fig. 5). The stress distribution in the Tomofix system was comparatively higher to that of the Puddu plate. Stresses appear to be more concentrated at the corners of the Tomofix plate and, between the connection of the LHS and the plate itself. Stresses were also concentrated at the two distal screw holes close to the opening for the screw insertions. In the Puddu plate, stresses were mostly observed at the region around the wedge. Analyses of the stresses on the whole bone model with the implant showed that Tomofix plate had an average stress value of 45.5 MPa which was significantly ($p < 0.001$) higher to that of the Puddu plate system which was 24.7 MPa (Table 2). The average value was calculated from stress values of all nodes within the plate. The Tomofix fixation produced high concentrated stress at the lateral hinge of the osteotomy (Fig. 5g).

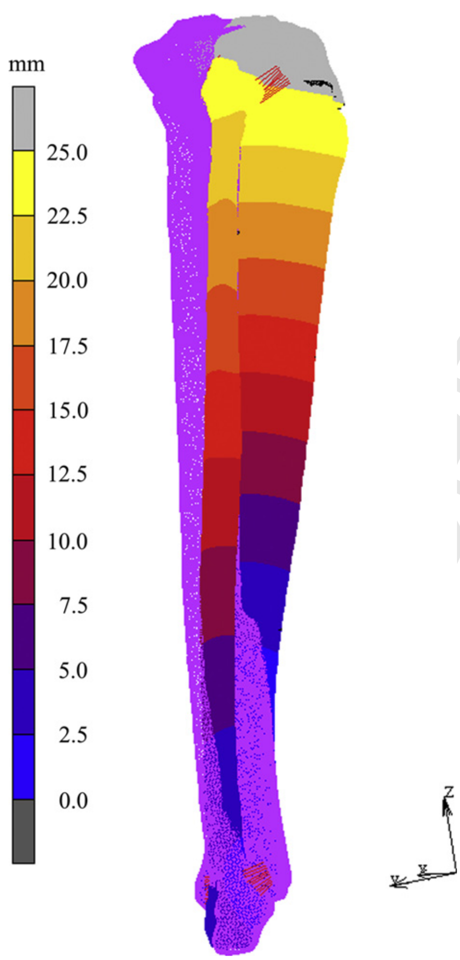

Fig. 3. Displacement direction of the Puddu system (lateral view of the tibia). The pink colour mesh is the original position and colour contour object is the model
Q2 after full load being applied. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

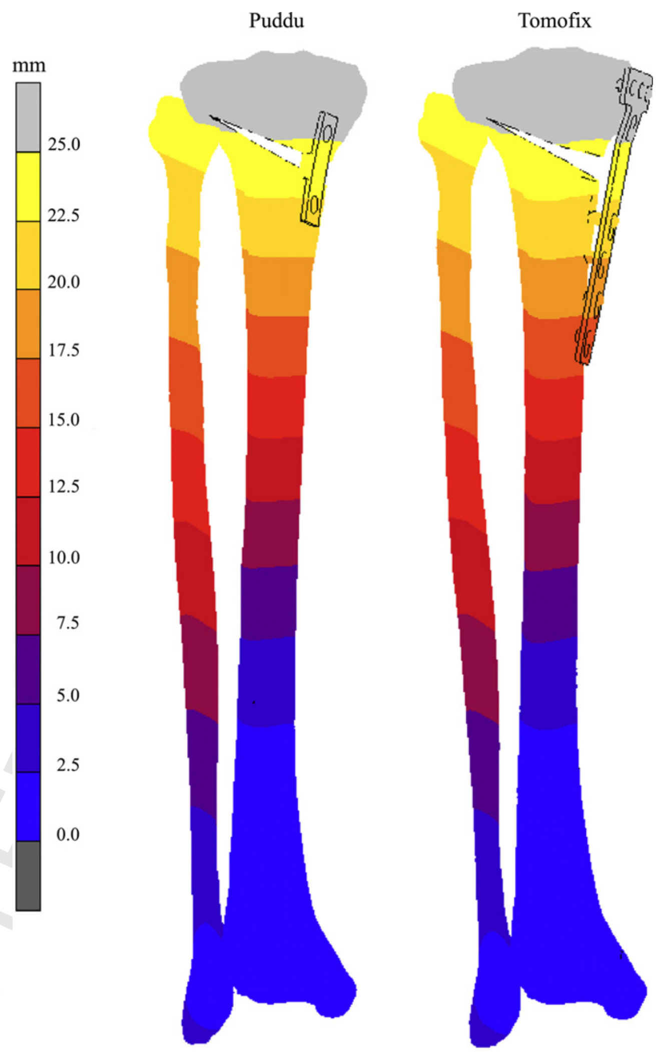

Fig. 4. Displacement result ~~acquires~~ from finite element for each model ~~that being analysed~~.

The micromotion analysis demonstrates that the Puddu plate underwent higher amounts of motion than that of the Tomofix plates (Fig. 6). Higher micromotion was observed on the surface of Puddu plate, which was in contact with the bone especially at the distal part of the plate. For the Tomofix plate, micromotion was more evident between the LHS and the bone, most notably in those that are placed near to the opening.

Discussion

Although the CWHTO was established earlier than the OWHTO, the disadvantages and complications arising from using the former have prompted many surgeons to switch to the latter. The reasons are many fold which include better stability and reduced incidence of peroneal nerve palsy.[22] A variety of specialized plates have been introduced for use in OWHTO however, two such implants remains ~~a~~ popular for many surgeons, i.e. the Tomofix system and the Puddu system. In the present study comparison between the Tomofix system which utilizes the locking compression plate (LCP) design,[23] and the Puddu plate which was designed with an incorporated wedge to maintain the gap on the bone showed good performance for maintaining stability due to their rigid construct.[24]

The characteristics of the load or stress distribution through the Tomofix and Puddu plates were observed. Using the equivalent von

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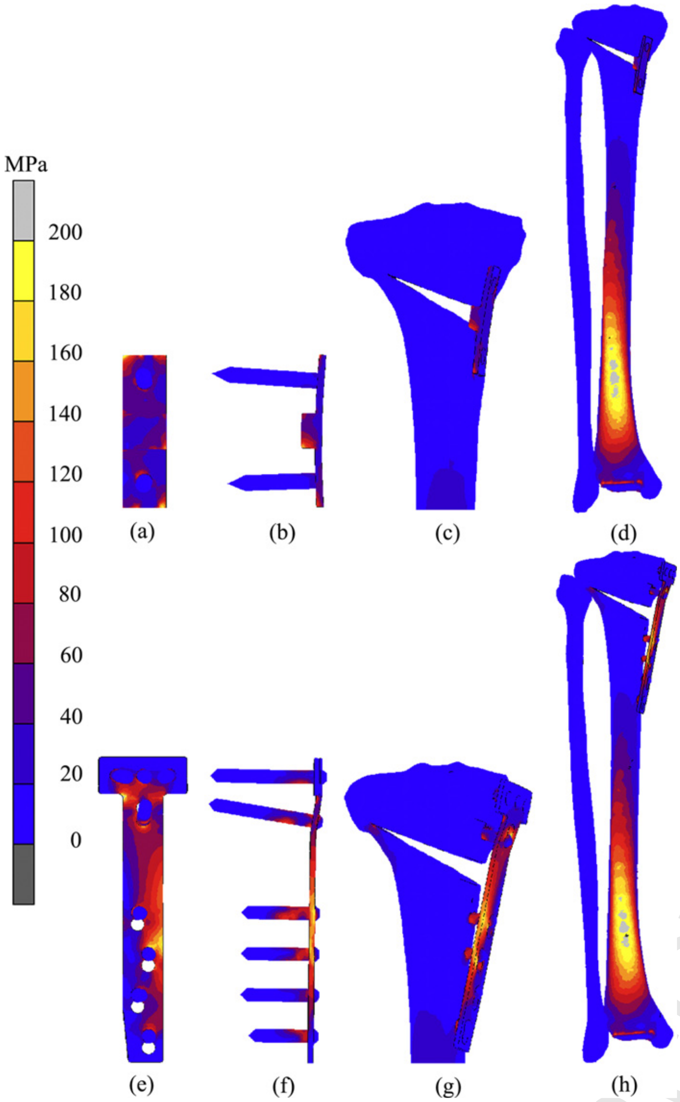

Fig. 5. Equivalent von Mises stress (EVMS) distribution along the model. Bottom view of plates (a), (e). Plates side view (b), (f). Anterior view of fixation models (c), (d), (g), (h).

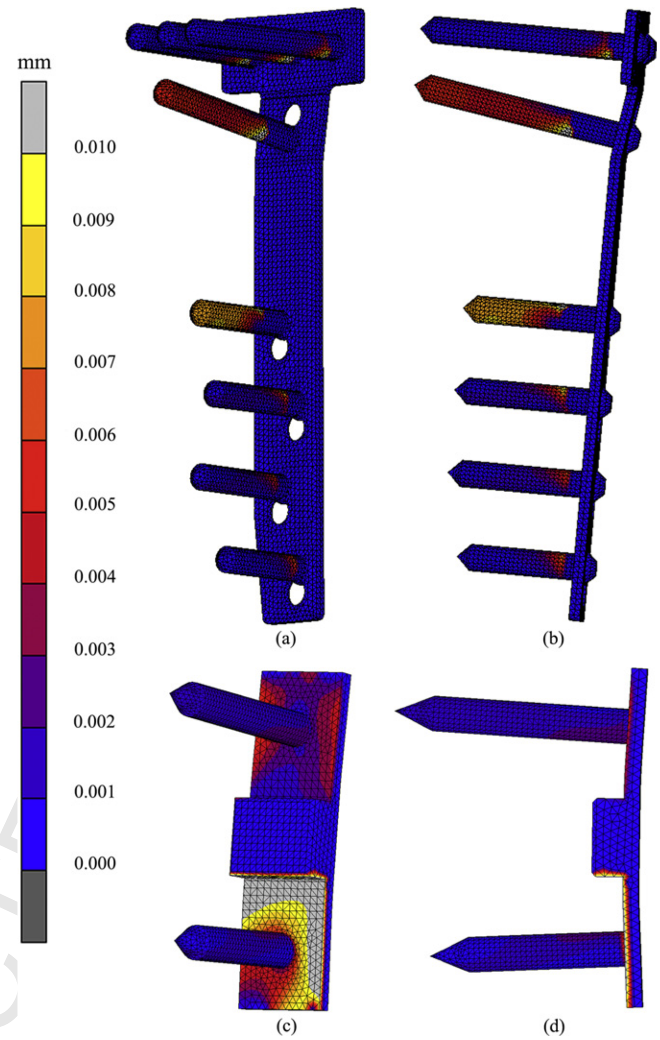

Fig. 6. Micromotion result for the Tomofix plate (a), (b) and Puddu plate (c), (d).

Mises stress (EVMS) analyses, Tomofix system underwent higher amount of stress than the Puddu plate system. This can be explained by the fact that the Tomofix which utilizes the LHS provide a better anchorage than its Puddu plate, thereby displacing the stresses transmitted by the body weight.[23] In addition, the angular stability of the LHS is more rigid than the conventional screws used in Puddu plates.[23] Although it may show that loading via the Tomofix will produce better stability with their rigid fixation, in clinical applications this may be a disadvantage as the stress shielding effect may cause severe osteoporosis in the long term as demonstrated in previous reports.[10,16,25] This however, has yet to be determined in any known studies, as data for the threshold that causes bone to undergo osteoporosis have not been previously established.

It is interesting to note that in both systems, stresses are generated within a region located namely on the anterior-distal side of the tibia. Further analyses suggest that the stress appears to be equally distributed to approximately within an area located at 1/3 of the anterior tibia surface. This may be attributed by the slender appearance of the tibia itself, which is also observed in previous studies.[18] However, a contrasting effect is observed when EVMS analysis was conducted. The micromotion appears to be greater in the Puddu system with differences between the systems to be as high as 14 μm under the applied static condition The value is expected to be higher during normal physiological cyclic loading. This is important as large amount of relative micromotion may result in implant loosening and lost of fracture stability.[11,19,26] However, small amounts of motion may be good for fracture healing.[27] Excessive displacement of the bone construct such as bending and torsion of the bone fragment relative to the distal bone may result in failure of the implant.[28–30] According to Aro and Chao, the change in the structural properties as well as the configuration by which an internal fixation device is designed may provide certain benefits but it may be the case that the loss of certain fundamental working principles may need to be accepted.[31,32] In this study, this principle appears to be applicable. The rigidity of the Tomofix implant in this study appears to be compensated with the loss of micromotion, which may lead to possibility of non-union and failure of fracture fixation when the micromotion becomes greater.

There are several limitations to the present study. Firstly, although higher amounts of stresses are generated within the Tomofix system, our study could not determine if these forces would exceed the limits of the implant design. However, our static analysis showed a maximum stress of 262.47 MPa which is less than the strength of the material.[33] Data regarding these implants are presently lacking and therefore will need to be established using biomechanical testing models. While the present study establishes the amount of micromotion which exist in both model designs, the optimal physiological amount necessary to promote tissue regeneration appears to be deluded. Again, this is attributed to the lack of published data to allow a reasonable comparison to be made. The bone model in this study was created using cortical bone properties to preserve simulation time as suggested by Peleg et al.[17] Only ~~statics condition~~ can be simulated as the idealistic dynamic motion of the joint was too prohibitive in terms of computing resources and time. Rigid mechanical link was also used in the study to simulate the tibiofibular joint which may not represent the actual joint ~~condition~~. Future studies can explore a more suitable representation of the joint as well as analysing the system under cyclic loading. Lastly, although the implant is subjected to an assumed normal human weight of 70 kg, data obtained from higher amounts of loads may be necessary to prove the effectiveness of either implant during normal function. This is important considering that the daily human activity requires the knees to undergo stresses beyond that which is observed during standing. For example, in climbing stairs, the load applied to these implants may reach up to 3 times the normal body weight.[34] In addition, while it has been generally assumed that the normal body weight of a person is 70 kg, data appears to support the notion that the present population is getting heavier and thus data of larger loads would provide better representation of normal conditions.[27]

Conclusion

While this study has demonstrated that the use of Tomofix plates provides better rigidity and therefore stability than the Puddu plate system, the stress experienced in the Tomofix plates may be of concern especially in view that this implant may fail. In addition, because of the smaller micromotion experienced in the Tomofix plates, it may be the case that fixation using this implant may lead to non-union of the osteotomized site. However, without the normal data that determines the threshold to cause implant failure or for fracture non-union to occur, these concerns may be unwarranted. Further studies would therefore be needed to prove that these concerns are valid before refuting that the Tomofix plate is superior, as shown by its rigidity and stability to secure the osteotomized site in HTO procedures.

Conflict of interest

None declared.

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