A Novel Iterative Method for Simulating Patient-Specific Optimal Deformation and Fit of Fracture Fixation Plates

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Abstract. This paper proposes a new iterative method to achieve an optimally fitting plate for pre-operative planning purposes. The proposed method involves integration of four commercially available software tools, Matlab, Rapidform2006, SolidWorks and ANSYS, each performing specific tasks to obtain a plate shape that fits optimally for an individual tibia and is mechanically safe. A typical challenge when crossing multiple platforms is to ensure correct data transfer. We present an example of the implementation of the proposed method to demonstrate successful data transfer between the four platforms and the feasibility of the method.

Introduction

Current trends in fracture fixation offers anatomically precontoured orthopedic plates targeted for specific anatomical sites as a means to restore the original anatomy of the bone and consequently the bone function [1-2]. A clinically non-optimal plate fit may lead to complications such as fracture malreduction or secondary surgery. In less extreme cases, non-optimal plate fit can cause plate protrusion [3], and therefore causing irritation for the patient, especially in the area where the soft tissue covering is thin.

Variations in bone morphology, whether within a population or between populations, may result in poorly fitting plates for individual patients [4-6]. This is mainly because the design basis is the average bone shape of a specific population. The mismatch between the plate and the patient's bone anatomy becomes more apparent when the plate is used outside of the intended population. To achieve surgically-optimal fit, surgeons need to perform intra-operative plate deformation.

Intra-operative plate deformation is typically an iterative process and increases surgery time. Furthermore, deformation may alter the mechanical and structural integrity of the plate, depending on the type and magnitude of the deformation [7], and possibly the number of repetitive bending performed at the same region. Although the bending and torsional limits of the plate used in this study were investigated previously through finite element analysis (FEA), they did not reflect the shape of a plate that is fitted on a tibia [8, 9].

In this study, we present an iterative method to obtain an optimally fitting distal tibial plate for an individual bone. The proposed approach uses four commercially available software packages, namely Matlab (Mathworks, Natick, Massachusetts, USA), RapidForm2006 (Inus Technology, Inc., Seoul, Korea), SolidWorks (Waltham, Massachusetts, USA) and ANSYS (ANSYS, Inc., Canonsburg, Pennsylvania, USA). The tasks involved positioning the plate onto a tibia, assessing plate fit, determining deformation parameters based on fit assessment results and simulating deformation using FEA. The proposed approach utilizes the triangular polygonal plate undersurface in RapidForm2006 and Matlab, and the solid model of the plate in SolidWorks and ANSYS. Due to the different file formats, correct data transfer is imperative for smooth transitions between the four platforms. Therefore the purpose of this paper is twofold. By presenting an example of the implementation of the proposed approach, we aim to (i) demonstrate successful data transfer between the different platforms and (ii) demonstrate the feasibility of the approach to obtain optimal plate fit for the selected case.

Materials and Method

Materials. A 3D model (.sldprt format) of a distal tibial plate, its undersurface (.stl format) and a 3D tibia model (.stl format) available from previous studies were utilized for this study [5, 9, 10].
Methods. The objective of the proposed iterative method is to obtain an optimal plate fit for an individual tibia. Briefly, the 3D models of the plate undersurface and the tibia are imported into Rapidform2006 where the plate is positioned on the tibia at a surgically correct position. Then both models are imported into Matlab for fit assessment, where the plate position is assessed against four clinically-based fit criteria [5]. The deformation is then determined and simulated based on the fit assessment results. The locations of loading and gripping areas are defined in SolidWorks and the geometric model is imported into ANSYS for finite element analysis (FEA). Finally, the data of the plate undersurface is extracted and imported back into Matlab and the iteration is repeated if required (Fig.1).

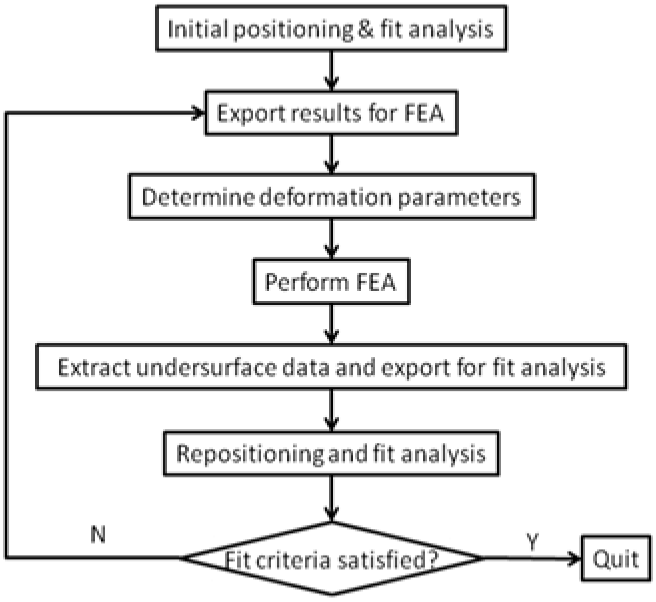

Fig.1. Flowchart of the proposed approach

The main data transfer occurs between ANSYS and Matlab because the positioning and fit assessment uses the undersurface, while FEA simulation uses the meshed solid model. The common data for both is the 3D coordinates of the meshed undersurface nodes. The coordinates of the nodes change when the plate is deformed. Each node is identified by a number. By updating the coordinates in Matlab, we can obtain the newly deformed shape. However, changes on the geometric model affect the nodes numbering. To prevent this, a default geometric model and undersurface were created as part of pre-processing steps.

Creating the default geometric model. The default geometric model requires sufficient details to allow for flexible and accurate definition of deformation parameters. To do this, the solid model was partitioned into several sections with finer sections in the fit assessment regions in SolidWorks. The newly partitioned model was saved as the default geometric model (Fig. 2). All deformation will be simulated in ANSYS using this model and the updated nodes coordinates will be transferred to Matlab for subsequent positioning and fit assessment.

Creating the default undersurface. The undersurface is used for positioning and fit assessment. First the undersurface nodes from the default geometric model were extracted in a text file format (.lis) detailing the nodes number and their 3D coordinate. The data was imported into Matlab for undersurface tessellation. Due to the limitation of the tessellation algorithm, unwanted faces were also created and were manually deleted. After tessellation, the nodes would have a second set of numbering specific to the newly tessellated undersurface. The original numbering extracted from the geometric model was matched to the second set of numbering to ensure that the correct data is updated after each deformation simulated in ANSYS.

The details of the steps within one iteration cycle are as follow:

Plate positioning and fit assessment. Plate positioning was performed using the trackball function in Rapidform2006. Next the bone and plate models were imported into Matlab for fit assessment using a previously developed automatic method [11]. The plate shape was assessed against four clinically-based fit criteria [5]: i) five regions in the distal section, each with maximum plate-bone distance of 2mm, ii) the middle-third region with maximum plate-bone distance of 6mm, iii) the proximal angle with maximum angle of 10° and iv) the proximal end with maximum plate-bone distance of 4mm. If all four fit criteria are satisfied, the plate shape is considered as optimally fitting and the iteration ends here.

Definition of deformation parameters and FEA. In a previous study, increasing the torsion of the shaft and reducing the inclination of the distal section were shown to improve the plate fit for a larger number of tibia [10]. However, as the optimized shapes were proposed with the view to manufacture the plates, the required deformations cannot be performed using bending apparatuses. In this study, the location and magnitude of deformation were determined based on the fit analysis results. However, when defining the deformation parameters for FEA simulation, we ascertained that the deformation is achievable using current bending apparatuses.

Deformation was then simulated using FEA in ANSYS as detailed in previous studies [8, 9]. In summary, material properties of stainless steel 316L and Ti-6Al-4V alloys were applied. The geometric model was generated in SolidWorks 2011 and imported into ANSYS workbench 13.0 (or 14.5). Boundary conditions were applied based on the fit assessment results (Fig. 2). With each simulation, FEA updates the shape of the plate for subsequent repositioning and fit assessment, and checks whether the deformation has an adverse effect on its mechanical integrity.

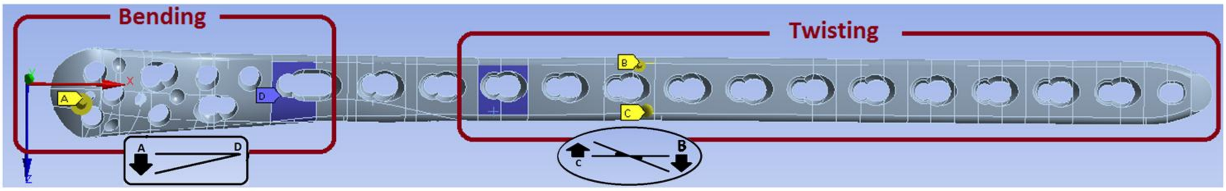

Fig. 2. Location of loading (A, B and C) and gripping (D) points defined on the geometric model.

Implementation of proposed iterative method. We selected a case where none of the fit criteria was satisfied to demonstrate the feasibility of the proposed approach. Based on the initial fit assessment results, we identified that twisting of the shaft and bending of the distal section were required for this plate and bone. In the first iteration, the shaft was twisted along its long axis by 7° and in the second iteration the distal section was bent by 2mm. (Fig. 2)

Results. After the first iteration, three fit criteria in the shaft were satisfied, except for the distal region (Fig.3a). In the second iteration, the plate had optimal fit after repositioning (Fig. 3b). Table 1 detailed the fit assessment results of the plate prior to deformation, and after the first and second iterations.

Table 1. Fit assessment results for one tibia before deformation, and after the first and second iterations of deformation.

Maximum distance/Angle at fit-assessed regions	Before deformation	First iteration	Second iteration
Proximal end region (mm)	4.30	3.03	2.42
Middle-third region (mm)	6.43	5.77	5.07
Proximal angle (°)	13.73	4.58	2.3
Distal sub-regions (mm):			
1	3.54	3.62	1.29
2	3.43	3.73	1.72
3	4.60	4.18	1.77
4	0.74	0.48	0.17
5	2.55	1.75	1.28

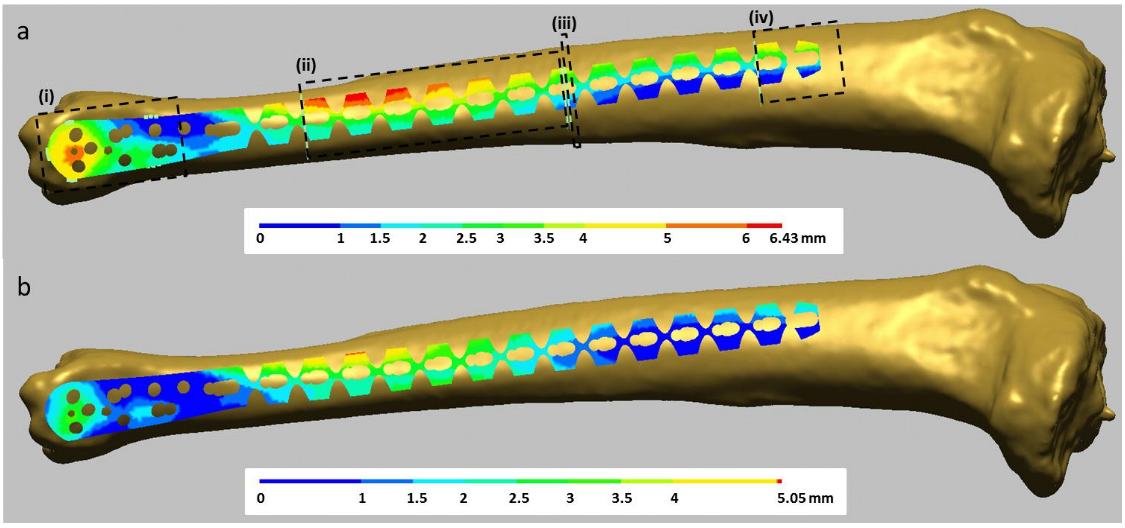

Fig. 3. Plate-bone distance map (a) before deformation and (b) after the second iteration. (i) to (iv) denote the fit assessment regions: (i) distal, (ii) middle third, (iii) proximal angle slice plane, and (iv) proximal end.

Discussion and conclusion

This paper introduces a novel iterative approach to obtain an optimally fitting distal tibial fixation plate through a cycle of plate positioning, fit assessment and FEA simulation steps. We demonstrated the feasibility of the proposed approach on a non-fit case selected from a previous study [11]. To achieve optimal fit, the plate underwent two iterations of deformations based on the finding of a previous study [10]. The process is not fully automated and requires an intact bone for positioning and fit assessment. Therefore, in its current form, the approach may be suitable for pre-operative planning for cases with an intact contralateral bone.

Extensive work is required to have a fully automated process, and to extend the approach for fractured bones. First, two components in the proposed approach would have to be automated, which are the plate positioning process, currently performed semi-automatically, and the process of defining the deformation parameters, currently performed manually. Both are part of our on-going work to develop a fully automated system. Despite the limitations, the current study demonstrated successful data transfer between multiple platforms which results in an optimally-fitting plate shape for an individual tibia. The proposed approach is easily transferable for implants of other anatomical sites subject to their respective fit criteria. In that way, automating the proposed approach would indeed contribute significantly toward providing patient-specific orthopedic fracture fixation implants.

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