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Comparing Finite Element Models of the Foot for Predicting Plantar Pressure in the Clinic

Steven Lankheet [1-4], Femke Schröder [1-3], Kilian Kappert [4], Elgun Zeegers [2], Wouter Ten Cate [4], Zeinab Kamal [5], Edsko Hekman [3] and Malte Asseln [3].
[1] Medical 3D lab, Medical Spectrum Twente, Enschede, The Netherlands
[2] Department of Orthopedic Surgery, Medical Spectrum Twente, Enschede, The Netherlands
[3] Department of Biomechanical Engineering, University of Twente, Enschede, The Netherlands
[4] Department of Vascular surgery, Ziekenhuis Groep Twente, Hengelo, The Netherlands
[5] Department of Oral and Maxillofacial Surgery, University Medical Centre Groningen, 3D Lab, University of Groningen, Groningen, The Netherlands.
Stevenlankheet@mst.nl

Abstract

Predicting plantar pressure using personalized finite element (FE) biomechanical models of the patient's anatomy holds significant promise for aiding in virtual surgical planning and predicting clinical outcomes. While sophisticated FE models have been described in literature, they are not suitable for routine clinical care as the personalization is complex and the model calculation is computationally intensive. Therefore, an automatically generated FE biomechanical model of the foot is presented, offering an efficient alternative for clinical application, and it is qualitatively compared against a computationally intensive sophisticated FE model previously published by our group.

1 Introduction

Various foot pathologies, such as complex foot deformities, are associated with high peaks in the plantar pressure (PP). These pressure points not only induce pain but can also impede mobility and lead to wounds [1]. When conventional therapies prove inadequate, surgical intervention is needed to correct the foot deformity. Virtual surgical planning (VSP) can be a valuable tool for surgeons [2]. Currently, it is based on CT images by correcting foot angles. Here, predicting the post operative PP distribution using biomechanical FE models could be helpful in creating a truly beneficial VSP

FE models have been developed and studied for their utility in understanding diabetic ulceration [3], offloading capabilities [3], and overall PP prediction [4]. However, the creation of patient-specific and geometrically detailed models is complex and time-consuming, involving (manual) segmentation and annotation of anatomical features. In addition, these detailed models come with high computational costs. These limitations are major bottlenecks hindering the routine clinical application, as a "new model" and its calculations are needed for each patient.

To address this challenge, we present a fully automated workflow for a low-computational-cost biomechanical FE model in the open-source software FEBio, herein referred to as "simplified model". Our hypothesis is that such a simplified FE model can offer already clinically relevant insights, making it a viable option for routine clinical application. As a first step, we qualitatively compared the predictions of our simplified model against a more sophisticated model previously published by our group, herein referred to as "sophisticated model".

2 Methods

The simplified foot model was based on the same CT images that was used in the sophisticated model by Kamal et al. (weight: 67 kg, foot in neutral posture) [4]. Segmentation of bones and soft tissue envelope (skin) was performed using Materialise Mimics 25.0 (Materialise, Leuven, Belgium) and exported as polygonal meshes. Afterwards, the bones were merged into one unified part. Subsequently, the segmentations underwent remeshing using 3Matic 17.0 (Materialise, Leuven, Belgium) and exported as STL files, meshes were re-meshed at edge lengths of 2,5 mm, 3mm and 4 mm. The workflow to create the FEBio input file was developed in MATLAB R2023b (MathWorks Inc., Natick, USA) using the functions of the Gibbon toolbox [5]. The soft tissue was modelled using the Ogden material with parameters $c1=0.082652$ and $m1=17.71$ according to literature [6]. The bone was modelled as rigid and fully constrained. The frictional coefficient was set at 0.6, similar to Kamal et al. [4].

3 Results

The simplified FEBio model was successfully generated automatically, and the computation of PP was completed in approximately 36 minutes on a personal laptop (for the 4 mm edge length meshes). A ground reaction force of 657N was applied, which yielded a PP distribution comparable to that of the sophisticated model, as illustrated in Figure 1. Visual comparison reveals that difference in the PP between the two models is predominantly at the lateral metatarsal heads. In this region, the simplified model predicted a lower pressure over a smaller contact area. However, both models showed the same locations for the highest pressure, situated at the heel and the medial metatarsal heads. Figure 2 shows the comparison of the effect in edge length on the PP.

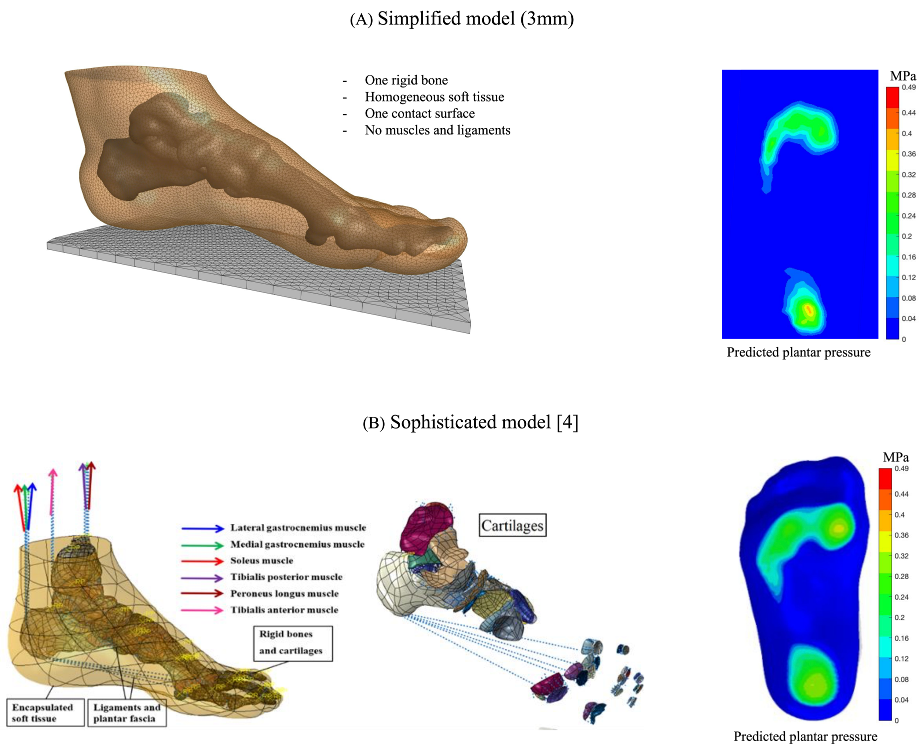

Fig 1: Finite element models and Plantar pressure predictions of the same patient of the Simplified FE model implemented in FEBio, for the 3 mm mesh (A) and the sophisticated detailed model from Kamal et al. implemented in Abaqus (B)[4].

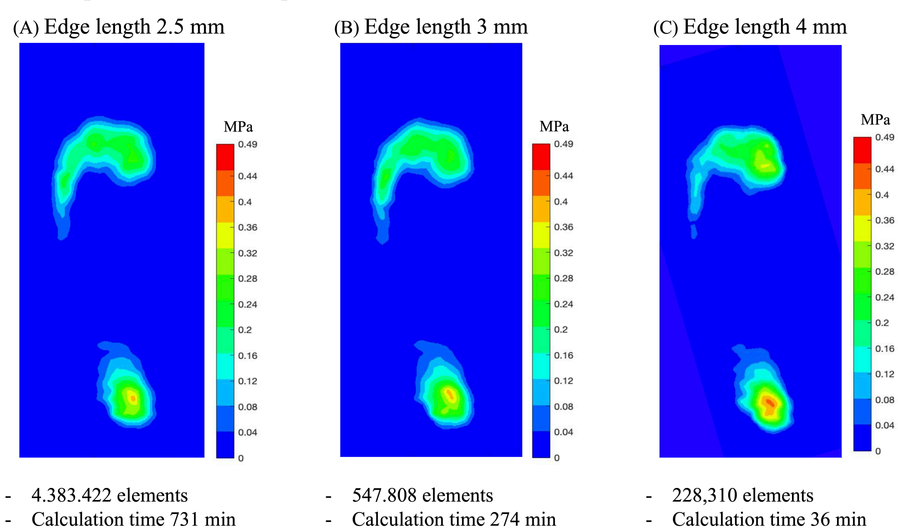

Fig 2: Plantar pressure prediction of the same patient using the simplified FE model with polygonal meshes with edge lengths of 2.5 mm (A), 3 mm (B), and 4 mm (C). The number of elements of the soft tissue and the calculation time is presented for each mesh

4 Discussion

The fully automated workflow of the simplified FE model produced results visually comparable to the sophisticated model by Kamal et al.[4]. The model based on the 3 mm edge length showed the best prediction with a reasonable calculation time. Despite the slight differences the plantar pressure magnitudes between the models, the results revealed similar locations of the peak pressure areas obtained by both models. In our simplified model, the mesh processing and model creation were entirely automated without any other input data, eliminating the need for additional measures like gait analysis.

Prior studies, including Telfer et al., emphasized the need of patient-specific FE models for predicting PP [1,5]. While Telfer et al. used clinical measurements like ultrasound for their model development and personalization [5], our approach relies solely on CT scans, which are standard for patients undergoing reconstructive foot surgery. They found that better representing the anatomy increased the accuracy of the prediction. However, they did not predict the pressure of the complete plantar surface.

The developed simplified FE model and conducted study must be considered within certain limitations. Despite the simplification, there are differences between the sophisticated and simplified model, such as the soft tissue representation as the Ogden material from FEBio cannot be directly compared to the linear elastic material in Abaqus. Moreover, the simplified model is only suited for quasi-static analysis and t cannot predict pressure distribution during gait. However, even the prediction of standing pressure is clinically relevant. In addition, the model could be extended to include shod simulation or by adding complexity, such as segmenting bones into hind-, mid-, and forefoot sections.

Despite the limitations, the predicted pressure distribution using a simplified biomechanical FE model would be a viable tool in the creation of a VSP for corrective foot surgery, as currently in clinical practice the effect of the planned correction on the PP is only speculated. Using our developed workflow, the virtually planned foot correction could be validated by calculating the plantar pressure in the planned position and comparing it to the preoperative plantar pressure.

5 Conclusion

Predicting plantar pressure using a simplified biomechanical FE foot model solely based on patient anatomy appears feasible for routine clinical application through our fully automated workflow. The predicted pressure distribution was similar to a sophisticated FE model. However, further evaluation is needed to determine the accuracy in different patients and the clinical benefit.

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