Title:
Towards a Foot Bio-model for Performing Finite Element Analysis for Footwear Design Optimization using a Cloud Infrastructure

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Introduction:
The work presented in this paper is part of a research project which focuses on the development of cost-effective and accurate computer-aided design and engineering (CAD/CAE) tools for the determination and optimization of design parameters used for the production of comfort footwear (project acronym: OPT-SHOES). The evaluation of these parameters necessitates the development of (a) highly-accurate foot and shoe models, (b) appropriate FEM of the foot and shoe components, and (c) highly-accurate simulation tools based on human behavioral models for performing FEA.

In the present paper, we focus mainly on the production of a bio-model of the human foot from dense CT scans. The produced bio-foot includes material properties for hard and soft tissues. We present a thorough overview of existing approaches and methodologies and the results of four reconstruction approaches. For the reconstruction process two commercial software and two methods based on Poisson surface reconstruction are employed. All produced foot bio-models are compared and discussed with respect to their application for FE analysis. For the simulation purposes between foot, footwear and the ground, we have developed a set of material properties for the footwear and ground structures. These material properties are used in a preliminary FE analysis that it is presented in this paper. Finally, the proposed architecture of the cloud infrastructure of the developed system is analyzed and discussed.

Human foot reconstruction:
The human foot consists of 26 bones, 33 joints and various muscles, ligaments and tendons that are all surrounded by soft tissues like vessels, nerves, and the skin. The construction of human soft and hard-tissue bio-models is considered in a reverse engineering framework as a reconstruction process that is based on non-invasive imaging techniques. Computed Tomography (CT), Magnetic Resonance Imaging (MRI) and Ultrasounds are frequently used for this purpose since they provide structural information, physical properties and geometric data of human body through a series of tomographic images.

Geometric modeling of the foot bones

The main steps for the construction of a 3D bio-model involve: (i) image acquisition mainly through CT or MRI scans, (ii) image processing and (iii) 3D reconstruction of the tissues. Image processing stage involves image segmentation to regions of interest that best describe the boundaries and the inner parts of the tissue to be constructed. Every pixel of each image takes grayscale values which are interpreted as different intensity values. Segmentation of medical images is a difficult task because of the complexity of human tissues, the image noise, and the ambiguity of image data that frequently include pixels with overlapping or close scalar values resulting in an inaccurate representation of tissue contours [2]. Currently, semi-automated segmentation approaches are preferred, which employ processing methods such as the snake technique and the edge-based segmentation combined with manual intervention mainly in pre-processing stage for the image thresholding and in post-processing stage for further image readjustments.

In this work, we present a complete reconstruction of foot bones using four different approaches. The first approach is based on the commercial software MIMICS (see Fig.1). The second follows a Reverse Engineering (RE) methodology where a point-cloud is extracted for each bone from CT scans. Then basic RE techniques are applied to reconstruct the bone surface by using the commercial software Geomagic. The last two approaches are using the Poisson surface reconstruction method [3]. The purpose of this section is to highlight the most critical phases of each reconstruction process and to compare the resulting foot bio-models with respect to their application in FE analysis.

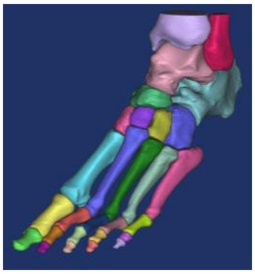

Fig.1: The foot bone structure produced using the MIMICS software.

Assignment of material properties for foot bio-models

Deciding on the mechanical properties of the hard and soft human tissues is an important part for the FEA systems involving the human foot. Finite elements analysts of the human foot, tend to distinguish five distinct types of tissue, i.e. bony structures, ligaments, cartilage, plantar fascia and soft tissue. Though, anatomically not fully accurate, this view is considered a reasonable approximation to modeling the human foot. Up until now, hard tissue materials have been considered isotropic and linear-elastic, whereas soft tissues as materials possessing either a non-linear visco-elastic or hyperelastic behavior. The measured or estimated values for material properties differ quite often depending on the method of measurement or theoretical model used, respectively [1]. This work presents a set of materials tested with FE analysis tools for computing various biomechanical properties of the human foot.

Assignment of material properties of ground/floor and footwear

The foot is expected to be in contact with the ground/floor (bare foot to ground contact) and the footwear (foot – footwear to ground contact). Typically, in many simulation cases the aim is to estimate the transfer of ground reaction forces to the foot, therefore the most significant part of footwear is the lower subassembly. This paper, summarizes artificial materials, which account for most modern worldwide footwear production. For each material the Poisson property, young modules and density are given in order to be ready for various simulation purposes using FE analysis.

<u>Preliminary FE Analysis for footwear design:</u>

We have used a simplified 3D bio-model of the foot which consists of the bones structure and the soft tissue structure that are assumed bonded for these trial runs. The goal of the trial runs is to investigate the convergence of the model with respect to non-linear material models for the soft tissue and the sole material modeled as a flat pad. Three different foot positions, corresponding to three gait positions, were modelled and the maximum plantar pressure value was used in order to evaluate the proper load-step for the non-linear analysis. In all cases, the FE analysis converged to a feasible solution confirming the validity of the proposed material properties and models.

Cloud application:

To increase the availability, reliability and performance of the proposed system we employ cloud-based architecture. In this paper, we demonstrate the proposed architecture by analyzing the basic services that are implemented on the cloud infrastructure and on the client side.

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