Quantification of the Influence of Orthopedic Insole in ex-vivo Feet

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Abstract

1. Introduction

Rheumatoid arthritis is an autoimmune inflammation affecting 0.77% of the population (Stolt et al., 2017). The disease causes erosion of the joints and the surrounding tissues. The first symptoms appear on the front of the foot in 90% of cases. This results in intense pain, toe deformities, and loss of functionality. On a daily basis, it is a highly disabling condition, causing difficulties in walking and maintaining balance.

Non-pharmacological treatment using orthotic insoles helps alleviate pain. Wearing custom insoles allows for offloading the pressure area during walking and while standing still. The variability of insoles lies in the choice of material, which can be more or less soft, as well as in the geometry, with the addition of a dome of material near the pressure area.

Although the effects of insoles have been demonstrated on foot segment movements (Tenten-Diepenmaat et al., 2019), plantar pressure, and pain reduction, the impact of insole design on the biomechanical behaviour inside the foot is poorly characterised. No link has been made between local shape variation and possible relief of perceived pain. A better understanding of how perceived pain for a given patient is related to mechanical metrics and how these are affected by the insole design could lead to a more rational treatment of the disease.

The study of the mechanical behaviour inside the foot in a patient-specific way requires a priori knowledge of the bone shapes and positions at rest, and a computational model to estimate bone displacements for a particular loading scenario. The numerical models reported in the literature use generic bone geometries to simplify calculations (Chen et al., 2010). Other models focus on the effect of the insole on the metatarsophalangeal joint (Spirka et al., 2014). Even though patient-specific models of complete foot-insole interaction have been developed to study foot biomechanics during the gait cycle (Kroupa et al., 2020), they are not suitable for studying the influence of orthopedic insoles due to computational time constraints.

The objective of this study is thus to develop a comprehensive model of the insole's effect on the internal biomechanics of the foot, using a combined approach of tomography and finite element modelling.

2. Materials and Methods

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A generic template model of the foot, including the geometry of each bone and the location of ligament insertions, was constructed by manual segmentation of the Visible Human Project. A series of CT scans were performed on 3 patients under different mechanical loading conditions on the bare foot.

The position of each bone in the unloaded reference configuration was manually segmented. To avoid manually segmenting each loaded configuration, the skeletal configuration of each loaded state was obtained by separating the bones from the soft tissues through threshold-based segmentation. The position of the bones was then determined using an optimisation-based method that minimises the minimum distance between the bones obtained from manual segmentation in the reference configuration and the skeletal configuration. This minimisation seeks a rigid transformation that aligns two point clouds, with optimisation carried out using Sequential Least SQuare Programming (SLSQP) minimisation from the SciPy Python package.

To avoid manually placing each ligament onto the bone geometry, a mesh-morphing technique was employed. Each bone of the generic template model, including the location of ligament insertions, was deformed to match the patient-specific bones. First, a rigid alignment of the two feet was performed, bone by bone. The source geometry was then approximated to the target through a normal projection and smoothing routine. RBF mesh-morphing was subsequently carried out using inverse multiquadratic functions. This mesh-morphing technique allows for semi-automatic interpolation of the patient-specific ligament positions on the bones.

The geometry thus constructed was imported into Abaqus for finite element analysis. The bone meshes were considered as rigid bodies, and the cartilages were represented by the dilation of their surfaces in the joint regions. The passive behaviour of the ligaments and muscles was incorporated by adding linear spring elements in tension. Soft tissues were modelled as a homogeneous hyperelastic material with a Ogden strain energy function. Two contacts were considered: the contact between the bones and the contact between the plantar surface and the ground.

The boundary conditions were determined by analysing the bone displacements in both the reference and loaded configurations. The calibration of ligament stiffness was then achieved by minimising the static equilibrium for the various loading conditions.

3. Results

The results of bone registration was checked visually and yielded satisfactory positioning. The average Haursdoff distance between the mesh-morphed bone and the target bone geometry is 0.06 mm with a standard deviation of 0.09 mm. A visual inspection validated the interpolated positioning of the ligaments compared to anatomical atlases.

Seventy-four ligaments were modelled and their deformation computed. The impact of insole on ligaments deformation was assessed, 49% of the ligaments exhibited a significant difference in strain between the bare foot and the foot with an insole. Deep transverse metatarsal ligaments connecting adjacent metatarsal heads exhibited a strain reduction equal to 3%. The most deformed ligament is tibiotalar part of deltoid ligament with a strain equal to 0.41.

Shearing stresses applie;d under the metatarsal heads fat pad were assessed. Larger shears appeared under the medial sesamoid bones with a maximum shear stress equal to 6.1MPa.

4. Dicussion

The results show that a complete barefoot-ground interaction model can be constructed. It is a first step before including an insole. However, due to the computational intensity of even simple loadings, the model must be simplified in order to represent a full walking cycle. Several simplification hypotheses will be studied to limit the computational cost. As it is known that the midfoot is stiffened by the shoe during walking, this can be represented numerically. Not all ligaments play an equally significant role in foot biomechanics, so it may be sufficient to model only the main ligaments. The impact of the constitutive law of soft tissues on the mechanical response will also be investigated.

Furthermore, the contact with the ground is properly managed numerically. The addition of an intermediate insole with variable geometry and material is a similar issue and will allow for the study of its impact on the internal biomechanics of the foot. The numerical model thus constructed should be able to provide a set of parameters related to the insole that minimises a given biomechanical criterion.

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