INTERNAL STRESSES, SHEAR STRESSES AND PLANTAR PRESSURES OF 3D FOOT MODEL USING FEM ANALYSIS

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SUMMARY

Using a recent developed process to build tridimensional anatomical structures, this work presents finite element analysis simulating different gait stages using ground reaction force (GRF) experimental data, from a sensor specifically developed to measure the three force components under 1st/2nd metatarsal heads. In this study it was obtain internal stress, strain, shear stress and plantar pressure distributions and maximum peaks for three stages of stance phase of the gait cycle. The objective of this analysis is to validate a methodology based on real local measurements to design individual foot orthoses, especially for patients suffering from obesity or diabetes. Also, in a broader application this methodology and its results may be used in foot biomechanical studies.

INTRODUCTION

Foot forces have been extensively measured using force platforms, pressure insoles as well as a large variety of sensors. One of purposes of this type of measurements is to establish plantar force influence or pattern in several locomotion conditions, or in patients with abnormal gait, or suffering from pathologies, eg, diabetes, obesity, etc., since it represents the body response to contact to ground. When analyzing gait, a variety of factors have to be accounted for due to alteration on gait pattern or plantar forces (GRF or plantar pressures)[1], like body weight and height, gait characteristics, foot geometry and deformities, patient tissues physiological conditions, pathologies and others. In the case of diabetic patients, one can predict the areas where ulcers will most probably be developed. It is known that shear forces act as enablers in the weakening of plantar surface tissues, being more critical during heel contact and during stance final phase, namely right before toe-off, than during midstance. Since GRF horizontal in-plane component is greater in these time instants, the corresponding contact areas, namely under the calcaneous and under the metatarsal heads, are regions of major ulceration for a patient with diabetes. On the other hand, geometry is also a key factor, when studying stresses and plantar shear forces. With availability of new tools and technologies, it has become recent practice to use CT images to obtain 3D computer body models. These models lead to more realistic simulation results when associated with experimental values. Therefore, one possible application of this methodology is to determine the body internal stresses and strains and predict its influence in the comfort of the individual, namely by designing foot orthoses for that purpose.

METHODS

From computed tomography (CT) medical images (DICOM files) of an individual with body mass of 51 kg, it was obtained a single file with the corresponding mesh clouds, using Mimics® v9.1 [2,3]. By using different masks, according to its tissue density, one could obtain mesh clouds of two groups: bone structure (that includes bones and cartilage) and soft tissue (ligaments, muscles, skin, tendons, fat pad). These mesh cloud were exported as STL files to Solidworks® 2009 (CAD software), where they were edited and improved to generate a solid part for each 3D object. As bone structure is a complex object and it is difficult to generate surfaces along all the structure, bone structure was anatomically divided into five pieces: tibia and fibula; calcaneous and talus; cuboid, cuneiforms and navicular; all the metatarsals and all the phalanges; then solid parts for all objects were generated. Finally they were combined, resulting in a unified bone structure, which was assembled with the soft tissue and a rigid support was added to simulate the ground (Figure 1).

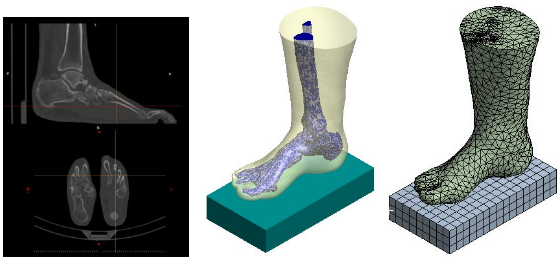

Figure 1: CT scan of individual foot (left), 3D foot model after being process in Solidworks® (center) and mesh for Ansys® (right).

With Ansys® v.11, three gait cycle stages from stance phase were simulated: heel contact (HC), midstance (MS) and toe off (TO). It was defined that bone structure and soft tissue were bonded in the corresponding contact surfaces and edges, and five springs were added to bone structure simulating more important tendons in the plantar fascia. For all simulations, the ground was vertically recessed, with no longitudinal expansion and rigid, and tibia and fibula were fixed. Bone structure, soft tissue and tendons were considered linearly elastic, isotropic and homogeneous [4]. For bone, Young's modulus and Poisson's ratio, were calculated by weighting cortical and trabecular bone, resulting in a value of 7300MPa and 0.3, respectively; for soft tissue were used 0.15MPa and 0.45, respectively, and for the plantar fascia the Young's modulus is 350MPa [5]. Applied loads were obtained by experimental measurements with a sensor located under the $1^{st}/2^{nd}$ metatarsal heads [6], for the three stages.

RESULTS AND DISCUSSION

In MS stage displacement, internal stress, strain and pressure are distributed in majority in metatarsal heads zone and in calcaneous zone. Maximum peak internal stress is on the contact between tibia and fibula, but evaluating plantar stress, its maximum peak is 16.296MPa and is on metatarsals zone. For plantar pressure, maximum peak is 0.15563MPa and it is on calcaneous zone and for maximum peak strain, located near fourth and fifth metatarsal, the value is 0.49907.

During HC stage (Figure 2), internal stress, strain and pressure are distributed more in calcaneous area and during TO stage (Figure 3) are distributed more in metatarsal heads and toes, as it was expected, since foot support is mostly on calcaneous during HC stage and on metatarsals and toes during TO stage. Maximum peaks results (Table 1) are located on calcaneous area for HC, and on metatarsals heads for TO and for MS. Internal stress values are lower for HC comparatively with the other two stages, possibly due to geometric conditions of the foot ground assembly. Shear stress values are higher on HC due to joint ankle-foot inclination and in MS has the lowest value because plantar force is mainly vertical (horizontal component is negligible).

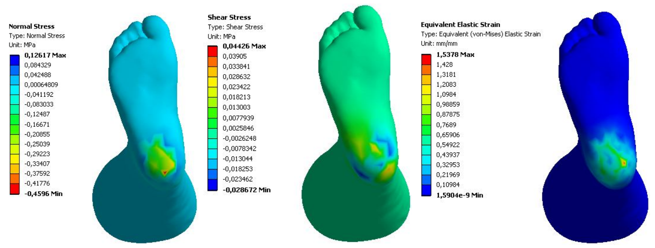

Figure 2: Strain, shear stress distribution and plantar pressure during HC.

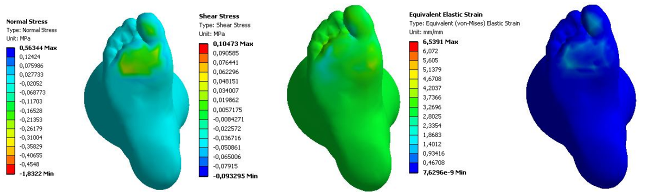

Figure 3: Strain, shear stress distribution and plantar pressure during TO.

CONCLUSIONS

To get accurate simulation results, foot geometry and foot-ground contact have to be very well defined, which is difficult to achieve, due to foot alignment and its position in the CT scan and geometrical separation of the foot with the ground. In HC stage internal stress analysis, having maximum peaks lower than the other to stages, but still higher in calcaneous than in metatarsal heads. In the three studied stages, individual's plantar pressure distribution shows regions representative of hyper pressures, enabling the search for the best orthosis for each disease, since these pressures peaks are very well localized in the plantar surface of the foot. Like plantar pressure, shear stress values and distribution are well defined for each stage, leading to knowledge of critical areas and to the search for solutions to protect them.

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Table 1: Results for 3 gait phases for maximum peak internal stress, maximum peak strain, maximum peak shear stress and maximum peak plantar pressure.

Gait Cycle stages	Maximum Peak Internal Stress (MPa)		Maximum Peak Strain	Maximum Peak Shear Stress (kPa)	Maximum Peak Plantar Pressure (kPa)
	Metatarsals	Calcaneous			
Heel Contact	1.8743	2.1651	1.4212	31.019	459.16
Midstance	16.296	8.0275	0.49907	21.094	155.63
Toe off	13.695	8.5468	1.2439	33.253	281.49