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Mechanical behaviour of the heel pad: experimental and numerical approach

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***Abstract* – The aim of the present work was to investigate the stress relaxation phenomena of the heel pad region under different loading conditions. A 31-year-old healthy female was enrolled in this study and her left foot underwent both MRI and experimental compression tests. Experimental results were compared with those obtained from finite element analysis performed on numerical 3D subject-specific heel pad model built on the basis of MRI. The calcaneal fat pad tissue was described with a visco-hyperelastic model, while a fiber-reinforced hyperelastic model was formulated for the skin. The reliability and accuracy of the investigation performed was confirmed by comparing results obtained from experimental data and numerical analysis. Specifically, the mean absolute percentage error was found to be less than 1%. The evaluation of viscous phenomena can be useful for understanding the mechanical response during daily activities.**

***Keywords*—Compression test, heel pad mechanics, constitutive model, numerical model.**

I. INTRODUCTION

THE human heel pad acts as an efficient shock absorber, smoothing the effects of impact forces during gait. The heel pad exhibits non-linear visco-elastic behavior as characteristic of soft biological tissues. Due to the visco-elastic nature, when a loading/unloading cycle is applied a load-deformation curve is obtained showing a hysteretic behavior. The compressibility of the heel pad depends on how the load is applied, i.e. depends on the strain rate and time. The non-linear, visco-elastic behavior is described by the stress relaxation that interprets the condition of a constant deformation applied [1]. To determine the mechanical properties of the heel pad, a compression device can be used [2], [3]. The aim of the present study was to interpret the local biomechanical response of heel pad region, depending on indentation technique, and in particular to investigate the stress relaxation phenomena by comparing experimental with finite element analysis. The correlation of experimental tests with the results of computational models allows an accurate interpretation of the phenomenon in terms of deformation and stress [4].

II. MATERIALS AND METHODS

A. Experimental tests

A 31-year-old healthy female was enrolled. Her left foot underwent both MRI and compression tests. A detailed description of the compression device (Figure 1 (a)) and procedure used for experimental tests can be found in [4]. In the present study loading/unloading cycles were applied on the heel pad by using a piston and a spherical indenter both with diameter of 40 mm (Figure 1(b)).

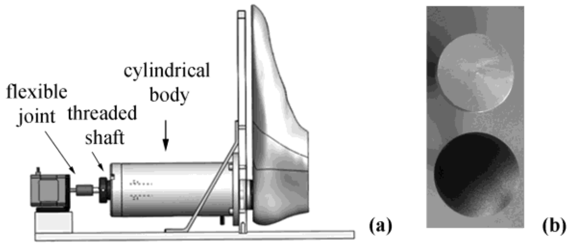

Fig. 1. (a) The compression device. (b) The piston and spherical indenter.

The compression test was repeated five times (for both piston and indenter) by using a strain rate of 1.73 mm/s with 1-minute-break between each trial. The upper limit of the displacement was fixed at 9 mm, while the maximum value of the load was set to 40 N [5]. Furthermore, in order to investigate the stress relaxation characteristics of the heel pad, compression tests were repeated with both piston and sphere adding a pause of 40 s once the displacement reached its maximum limit. During the pause the piston was still in contact with the heel pad, so that it was possible to visualize the decrease in load with time at constant deformation. Then, after the pause, the decompression started until the piston reached the initial position. Six Velcro straps were used to stabilize the foot. In order to quantify the involuntary movements of the ankle (the most critical part) during the entire duration of the test, a fiducial marker was attached on the skin of the ankle bone with a transparent tape. Videos of the fiducial marker movements were recorded during all trials. This marker-video-procedure allowed calculating the movement of the ankle in order to correct both the hysteresis and stress relaxation characteristics obtained from the compression test.

B. Numerical analyses

A 3D model of the heel region was built on the basis of 3D MRI. The DICOM images were processed using Simpleware, imaging density segmentation software that allows obtaining 3D CAD solid model by applying density segmentation techniques. The 3D CAD solid model of the heel region, composed of calcaneus, muscles and plantar fascia, fat pad and skin (Figure 2(a)), was meshed by 4-node tetrahedral elements. Figure 2(b) shows the numerical models of heel region and the initial position of the piston. A linear elastic anisotropic model was adopted to describe the mechanical properties of the bone, while the muscles and plantar fascia were described using a hyperelastic model. A specific visco-hyperelastic constitutive model accounting for the typical stress-strain behavior of the fat pad tissues was formulated. The constitutive model describes the material and geometric non-linearity typical for soft tissues, as well as the almost incompressible behavior and time dependent response. The heel skin tissue mechanical response was characterized by a strong non-linearity, almost incompressible behavior and anisotropic characteristics induced by the organization of the collagen fibers. A fiber-reinforced hyperelastic model was considered to describe the heel skin tissue. The evaluation of the constitutive parameters followed a procedure reported in detail in [4], [5].

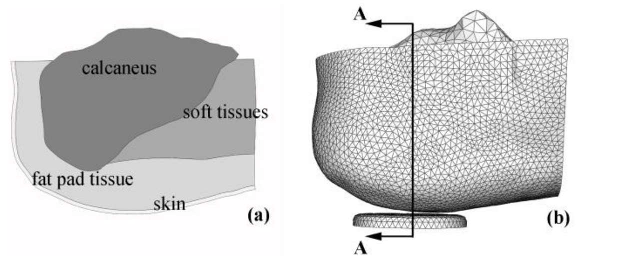

Fig. 2. (a) A section of the solid model of heel region and (b) the numerical model with indication of transversal section AA.

III. Results

Numerical results and experimental data are compared, considering loading-stress relaxation-unloading tests (Figures 3 and 4). The experimental force-displacement curves (Figures 3(a) and 4(a)) as well as normalized force-time curves (Figures 3(b) and 4(b)), obtained with the sphere and the piston are compared with those obtained by numerical analyses. The normalized forces were obtained dividing each curve by maximum force value.

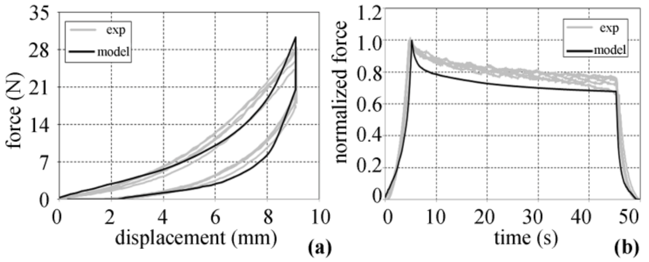

Fig. 3. Comparison of experimental and numerical results: stress relaxation tests done with a sphere of 40 mm diameter: (a) force vs. displacement and (b) normalized force vs. time.

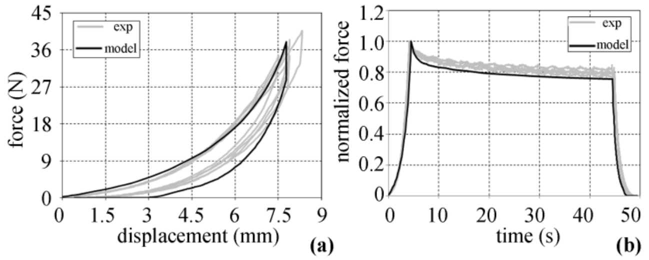

Fig. 4. Comparison of experimental and numerical results: stress relaxation tests done with a piston of 40 mm diameter: (a) force vs. displacement and (b) normalized force vs. time.

Deformed configurations of the heel region when interacting with the piston and the sphere of 40 mm in diameter are reported with regard to minimum principal stress (Figure 5(a-b)) after compression and after 40 s of the relaxation period (Figure 5(c-d)). All contours are reported over a transverse section of the fat pad (Figure 2(a)).

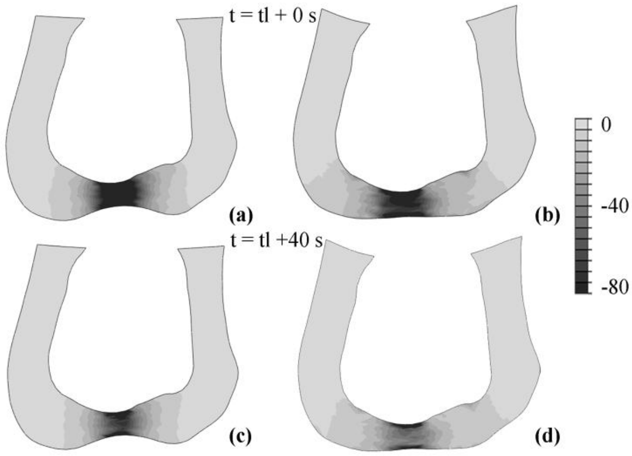

Fig. 5. Results from the numerical analysis with a sphere of 40 mm in diameter (a),(c) and piston of 40 mm in diameter (b),(d). Contours of minimum principal stress in the deformed configuration of heel pad structure after a loading: stress relaxation time $t=t_l+0$ s (a),(b) and $t=t_l+40$ s (c),(d) are reported over a transversal section AA of heel pad structure of Fig.2 (b).

IV. Conclusion

The reliability of the investigations performed is confirmed by the interpretation of the mechanical response of the heel tissues under the application of a piston as well as a spherical indenter at the same strain rate. The heel tissues showed a non-linear visco-elastic behavior exhibiting the characteristic stress relaxation response. Numerical analyses allow for a deeper evaluation of the stress relaxation phenomena within the tissues, showing the capability of the material to recover rapidly the stress induced. The compression device does not intend to reproduce the physiological conditions of walking or running, but rather to be used in a clinical setting involving diseased heel pads which cannot necessarily tolerate high loads. This analysis may be useful for diagnosis and prevention of pathologies, firstly for evaluating the mechanical properties of the heel pad tissues using experimental tests and successfully implementing a numerical model capable of interpreting the mechanical response of the tissues. The possibility to account for degenerative processes can be performed by means of specific damage models.

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