DESIGN, TEST AND MANUFACTURE OF A SYNTHETIC HEEL PAD

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ABSTRACT

The compressive mechanical properties of a human cadaver heel pad have been obtained by a range of experiments. The mechanical properties were evaluated from force displacement data and include stiffness and shock absorbency. Two failure levels were discovered from the testing and relate to the separate fat layers in the heel pad. Manipulation of this data has contributed to a material selection through common engineering criteria such as Youngs modulus. A manufacturing process has been pursued with the use of a MRI scan to obtain an accurate representation of a heel pad. This data is to be used in a rapid prototyping process to enable molds of the heel pad to be created and subsequent synthetic pads to be produced for testing.

KEYWORDS: Heel Pad, Human Surrogate Program (HSP), Frangible Surrogate Leg (FSL), Shock Absorbency, Stiffness.

1.0. INTRODUCTION

The natural gait associated with a human walking requires the hind of the foot to be the first part of the body to come into contact with the ground. Hence, when stepping on a landmine with the leg straight, all the body weight rests through this direct line of the bones. This results in a large percentage of the explosive force directly transmitted into the heel pad, through the calcaneus, up through the ankle and the lower leg section into the remaining skeleton. As a consequence, the foot and ankle are completely destroyed and in most cases the only form of medical treatment available is to amputate the limb.

The purpose of this project is to design, manufacture and test a synthetic heel pad that will closely model the behavior of a human heel pad from a fit, young and healthy male between the ages of 19 - 39 years that is typified by the average foot soldier. The synthetic heel pad will be incorporated in a current model of the lower leg that is being developed for the testing of anti land mine footwear. The heel pad is recognised to be a unique structure in the body and it has significant shock absorbing characteristics, consequently it is important for the validity of the model that the heel pad is accurately represented.

2.0. BACKGROUND

2.1. The Human Surrogate Program

The human surrogate program (HSP) is a joint project between the Defence Science and Technology Organisation (DSTO) and the Royal Adelaide Hospital (RAH) and is aiming to create a totally synthetic body that has a close correlation to human characteristics. This will enable a range of testing and modelling to be performed giving reliable and accurate data with regards to how shock is attenuated throughout the body. The project has advanced to a position where the leg model, the frangible surrogate leg (FSL) is currently being used in testing the performance of anti land mine footwear.

The FSL skeletal structure utilises a material specifically developed for the project and is a composition of resin, hardener, hydroxyapatites and radio contrast agent. This material mimics the structure and composition of human bones and importantly behaves similarly under CT imaging, which aids in the diagnostics of the testing procedures. The muscles and tissue located on the leg are simulated by molten ballistic gelatine.

2.2 Heel Pad

Currently the ballistic gelatine that is used to simulate the muscles and tissues in the leg is modeling the heel pad region of the foot. It is accepted that the heel pad has a unique construction that aids in adsorbing shock that is transmitted through the body from impacts such as walking or running. Hence in the context of the HSP it is essential to have an accurate representation of these shock-absorbing qualities of the heel pad region for the accuracy of the model.

3.0. LITERATURE REVIEW

3.1. Structure Of The Heel Pad (Anatomy)

The human heel pad has an average cross sectional thickness of 18 mm, with a range from 12 mm to 22 mm. The biggest value is measured on the posterior part of the tissue, where the pressure developed in gait is at its greatest (K. Sarrafian, 1989 [1]). The skin acts as a protective layer against mechanical and electrical injury for the underlying tissues and, as found by F.H. Silver, 1987 [2], it is composed of two components: the external epidermis whose thickness on the heel varies from 0.7 - 1.2 mm and the internal dermis, which contains cells and glands that is 1.0 – 2.0 mm thick. Above the skin, connected to the dermis and the bone is a special fat pad called Superficial Fascia that is divided in micro-chambers as an outer layer and an inner layer (Figure 1). They are held together by a dense system of irregular septa, which are rich in collagen and elastic fibers giving it internal strength. The septa are designed to avoid any outflow of fat from the single compartments and hence, they are resistive to compressive loads (C.W.J. Oomens et al., 1987 [3]).

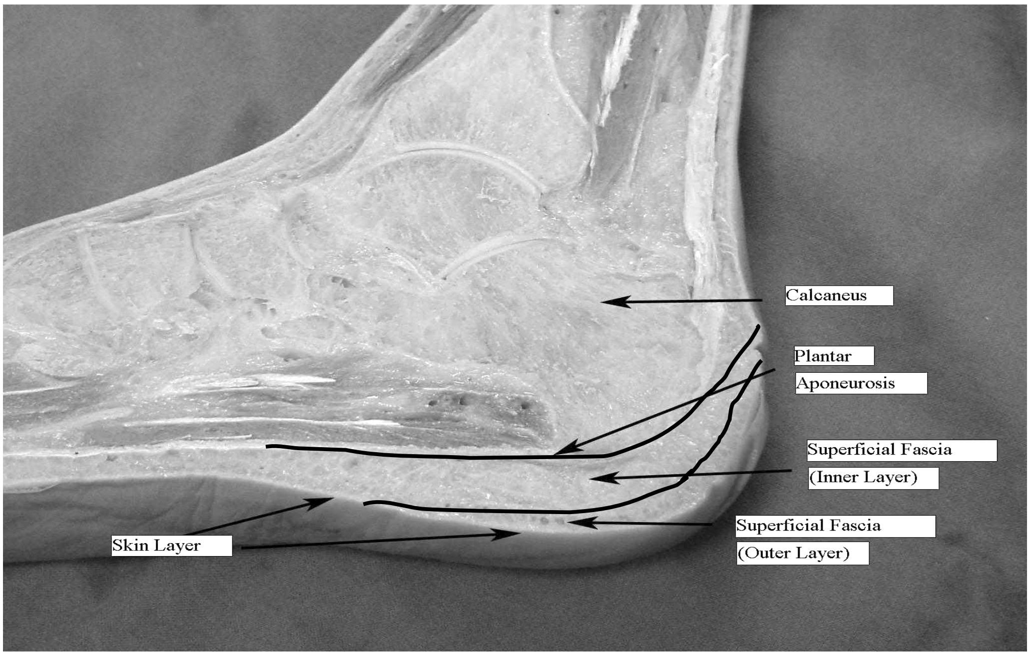

Figure 1. Anatomy of heel pad cross section.

3.2. Previous Studies On The Heel Pad

A large number of people suffer from heel pain and other problems that are due to the defective shock absorption of the heel. Fat pads tend to soften and loose elasticity and become thinner in aging, hence normal walking can already overload the calcaneus. To minimize or avoid these kinds of pain, there has been much research into this particular medical field, and several different testing methods have been devised to determine the mechanical properties of heel pads.

3.3 Testing Methods

Jorgensen and Bojson-Moller (1989) [4] examined the different behavior in shock absorption with a force-time relation. They performed drop tests with 10 human cadaver heel pads and compared the results to when using two artificial shock-absorbing materials. The materials used for these were a viscoelastic polymer Sorbothane and ethylvinylacetate (EVA). The collision time was higher with the heel pads (13.9 ms ± 0.2 ms) than with Sorbothane (5.5 ms ± 0.1 ms) and EVA (8.8 ms ± 0.1 ms) that is due to better energy dissipation, hence rise time and peak force were reduced. In previous studies, Jorgensen already showed a correlation between the shock absorption of the heel pad and the compressibility, comparing the pad thickness in weight bearing and non-weight bearing x-rays. A non-linear mechanical behavior is determined by the rapidly decreasing of compressibility as a function of load [4].

A simple clinically usable method to quantify the heel pad shock absorbency in patients (in vivo) is the Heel Pad Compressibility device (HPC) developed by Jorgensen et al. (1989) [5]. Through constant velocity compression and decompression of the stabilized heel, its force-deformation characteristics were examined and a force-deformation curve was determined during compression. When using the HPC-Device it was found that during compression some of the energy is lost as heat with the rest is stored as elastic energy in the walls of the septa and results in returning pressure to the piston during decompression. The magnitude of the energy loss during the compression of the heel is equivalent to the shock absorbency. This is simple to determine from the force/deformation plot, with the difference in area of the two graphs, compression and decompression being equal to the energy absorbed or the shock absorbency of the heel pad.

3.4. Conclusions From Previous Studies

Considering these previous tests, there are many factors which influence the mechanical behavior of the heel pad such as size, location, thickness of the fat pad, the components of the fat which degenerate in aging [5] and the structure of the septa which is a major factor in the fluid flow between the fat layers [3]. The thickness of the heel pad is an important factor in sustaining the stress that occurs in the tissues. A thick layer exhibits lower peak stresses over a large area of contact, in contrast to a thin layer with higher peak stresses within a narrow region (M.H. Jahss et al., 1992 [6]).

Since the internal fat structure is less compressible, thicker and more fibrous than the external one, the walls between the fat compartments resist deformation even better under load. We conclude that the whole fat pad is acting as a buffer, whereby a lower viscosity of the fluid in the micro- and macro-chambers and the fat flow inside them lead to increase the shock absorption. That is suggested by Winter et al. (1991) [7] in their equation for the dissipation of energy (D), which is proportional to the viscosity constant (q_1):

$$D = \frac{1}{2}\sigma_o^2 \left(\frac{q_1}{\frac{q_o^2}{\omega^2} + q_1^2} \right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \text{(Equation 1)}$$

σ_o as amplitude of the applied stress, q_o as elasticity constant and ω as frequency of the applied stress [7].

4.0 EXPERIMENTAL RESULTS

The focus of the experimental procedure was to characterize the properties of the heel pad so we were able to make a material selection that will behave similar to a heel pad under loading conditions. The mechanical testing was performed using the University of Adelaide's Houndsfield testing machine that has the ability to test in both tensile and compressive situations. The rate of loading can be specified up to a maximum rate of 1000 mm/s with the force and displacement data being recorded for post testing investigation. The loads applied and the rate of loading was varied to obtain different aspects of the heel pad properties. Two methods were used on this machine, ultimate failure loading and cyclic loading.

4.1 Ultimate Failure

This testing situation involved positioning a cadaver heel pad into the apparatus and compressing it until failure occurred. This was done to a number of specimens at a number of different loading rates. Importantly this revealed that the heel pad failed at two specific points that relate to the two different superficial fascia layers of fatty tissue in the heel pad as specified in figure 1. To verify this discovery a heel pad was sectioned in to the two separate layers and compressed independently and compared to a specimen that was complete when failed. Although the failure points did not exactly compare they were close enough to conclude that the assumption of the different layers of the heel pad failing at different loads was correct. Figure 2 illustrates the results discussed above. Note the failure points of the different sections of the heel pad and the close correlation to the failure levels of the complete specimen.

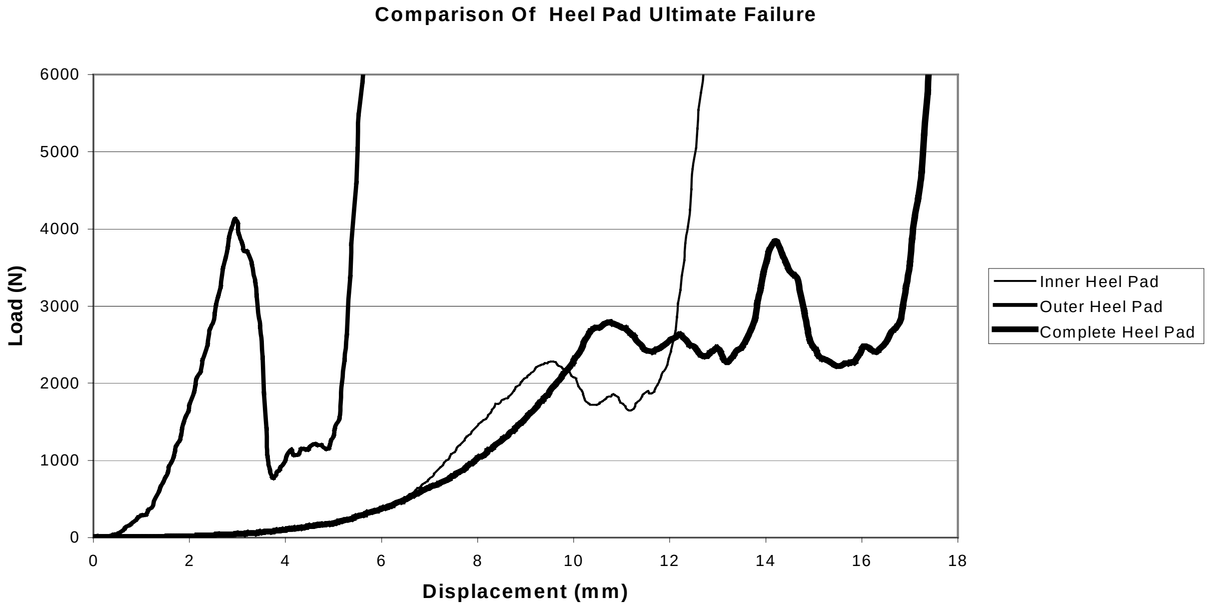

Figure 2: Ultimate failure loads of the heel pad.

From the force and displacement data during loading we were able to determine the stiffness of the heel pad material. This revealed that the stiffness showed no linear properties, the stiffness of the heel pad increased with load. Heel pad stiffness measured at a load approximating body weight was 7.5 kN/mm. Similarly from the data obtained during this test we were able to convert it into stress/strain measurements and subsequently Young modulus or the modulus of elasticity can be simply obtained from the slope of the stress/strain plot.

4.2 Cyclic Loading

The specimen was loaded in cyclic conditions to a maximum under the first failure point using the same apparatus to determine the percentage of energy absorbed using the HPC criteria as discussed above. It was found that during the first compression the heel pad absorbed approximately 25 % of the input energy, a result that is comparable to other research (Covey et al. [8]). From this we can concur that the heel pad behaves in a viscoelasitc manner with the graph having a hysteric appearance. Subsequent loading of the heel pads produced an almost elastic response with all energy inputted during the compression cycle of the test returned during the decompression phase of the cycle. This is most likely due to the damage of the individual fat cells comprising the heel pad and was indicated by the evidence of clear liquid on the specimen surface and hence limiting the shock absorbency of the heel pad. It appeared that the frequency of loading did not effect the results of the energy absorbed by the heel pad. So we can conclude that the individual fatty cells of the heel pad give the shock absorbance characteristic. The ability of the fat cell walls to deform under load and then return to the initial state enable the heel pad to absorb energy and when the cell structure is destroyed so is the shock absorbency of the heel pad.

5.0 DISCUSSION

We have been able to characterize the mechanical properties of the heel pad through compression testing and simple manipulation of the data. Youngs modulus (E), stiffness (k) and ultimate failure levels have defined the mechanical properties that we aim to replicate. This knowledge along with the constraints placed on the heel pad manufacture has narrowed down the list of probable materials.

Although all testing of heel pads have been *in vitro*, that is in artificial experimental situations it is suggested by Bennett et al (1990) [9] that these results are representative of the mechanical properties obtained from specimens that are *in vivo* condition. Hence we have not undertaken any experiments with specimens in *in vivo* situation where the risk of exposure to diseases is high.

A topic that needs to be explained is how we intend to relate the research and findings to the explosive blast as experienced by a land mine detonation. Obviously the land mine detonation has far greater energy than the experiments that we have undertaken. However the skeletal structure was designed under a loading rate of 500 mm/min, hence we used this rate as a benchmark for our experimental work.

6.0 FUTURE WORK

The next stage of the project will see the manufacturing of sample heel pads. We need to finalize the material selection from a range of polymers and complete the design of the manufacturing process. The manufacturing phase of the project has incurred some problems associated with the development of the molds of the heel pad. An MRI scan was performed to provide a 3 – Dimensional image of the heel pad. Due to the similar density of the other parts of the foot (tendons, cartilage) the shape output has required significant rework to accurately represent a heel pad. The format of the 3 – D image has also posed a problem, as the laser sintering software that we intend to use for the rapid prototyping of the pad does not recognize it. However these technical issues are currently being addressed and do not jeopardize the outcome of the project.

7.0 CONCLUSION

The heel pad provides a degree of cushioning from impact to the skeletal structure, the amount of cushioning is dependent on the size of the heel pad (thickness) and the degree of which the heel pad structure is remaining intact. We have seen that, when the structure of the fatty pads is destroyed, the heel pad shock absorbing characteristics are greatly reduced. We have characterized the mechanical properties of the heel pad through *in vitro* experiments and are close to achieving the aim of the project.

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