Experimental strain field distribution in ankle-foot orthosis (AFO)

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Abstract: Medical dictionaries define the ankle-foot orthosis (AFO) as follows: a brace (usually plastic) worn on the lower leg and foot to support the ankle, hold the foot and ankle in the correct position, and correct foot-drop. People, who suffer from a foot-drop, or the inability to raise the foot, often wear an ankle-foot orthosis to assist in clearing the toes during walking. Most of these orthoses are made of special plastics by thermoforming. One of the most used materials for this orthosis is Polyethylene PE-HWV. This paper shows an experimental study on the behavior of an AFO in two different cases: in the first case, the AFO is subjected to a tensile test and the heel part of the orthosis is constrained so that it cannot move in vertical direction; in the second case, the heel part is free to move in vertical direction. In both cases, the orthosis was stressed using an Instrin 5587 machine. For capturing the strain field in the AFO in real time, the authors used an Aramis system, which is a non-contact optical 3D deformation measuring system.

Key-Words: ankle-foot orthosis (AFO), Aramis system, photogrammetric methods, strain field distribution.

1 Introduction

Computer and video technologies in the form of motion analysis systems are used extensively in assessing the complex configurations of walking, they supplying directly valuable information on the joints' movement, muscle activity as well as on the generation of forces. The objective quantification of the walking configuration allows prosthetics specialists to evaluate the performance of designed devices and the benefits they bring to patients.

Ortheses specialists describe three periods in the walking phase (figure 1): heel-strike, mid-stance and push-off. Because of their importance, these three periods are used by specialists in the field of prosthetics and orthoses when evaluating the walking configuration.)

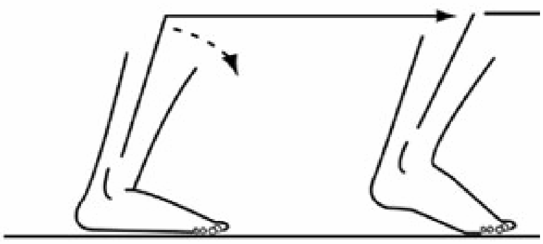


Fig. 1 Mid-stance phase

The heel-strike is defined as the time interval from the attack with the heel until reaching the ground with the whole foot sole. At this moment, the leg begins to gain in stability.

The mid-stance is defined as the time interval from the ground contact with the whole foot sole until the heel's detachment from the ground (heel-off). During this period, the force vector moves before the ankle and behind the knee and hip and would need to provide an optimal stability in the device [1].

Orthoses are defined as being external devices applied to a body segment in order to prevent or correct the disfunctionality of that segment (mobility limitation, correction or prevention of vicious positions or deformations, reduction of the axial load).

All orthoses apply forces on the body. The therapeutic benefit of applying a force may be to oppose or assist the movement, to transfer power or to protect a part of the body. From a constructive point of view there are three types of orthoses: rigid orthoses, soft orthoses and semi-rigid orthoses.

Rigid orthoses are used primarily for walking or standing and are usually made of plastics or other similar resilient materials. The device is usually made from a type of structure which takes the form of the patient's leg and comprises the entire foot sole.

Soft orthoses are used to restore balance, to absorb shocks and to diminish pain in certain inflamed areas. A soft orthose is made from a soft material that is foldable and easily adaptable to different situations. This type of orthose is often used by those suffering from diabetes or by those suffering from a foot malformation [3].

Semi-rigid orthoses are used primarily by those who practice sports. These orthoses are made of a soft material and a part of plastic material and are placed in the area most stressed by the athlete. For athletes, this type of orthoses helps the tendons to work efficiently during the time of effort [3].

The aim of this paper is to determine and as much as possible to also eliminate the possible causes leading to the fracture of ankle-foot orthosis (AFO), a type of rigid orthosis, after a certain period of use. A first assumption regarding the cause for these failures could be accidental overloads during their usage. For this reason, the autors intend to analyse the stresses and strains in the AFO in the two steps of the mid-stance phase.

2 Preliminary determination

For the experimental tests, the authors used an AFO for a right foot, made of PE-HWV. For the best possible assessment of the AFO's behavior, in a first stage the authors determined the mechanical and elastic characteristics of the PE-HWV material. These studies were conducted using the universal machine for tensile, compression and buckling testing Instron 5587 and a set of three test samples of 2 mm thickness (Figure 2).

Fig. 2 Test sample

These tests were done using a constant loading speed for all test samples (10 mm/min) and following characteristics were determined: tensile yield stress, maximum tensile stress, strain at maximum tensile stress, Poisson's coefficient and elastic modulus. The most important results are shown in Table 1.

Table 1 Characteristics of the PE-HWV material

No. of test sample	Tensile stress at fracture [MPa]	Elastic modulus [GPa]	Maximum tensile stress [MPa]	Tensile strain at maximum stress [%]
1	14.52	0.418	21.39	12.35
2	13.17	0.407	21.19	12.56
3	14.28	0.411	21.47	12.12

Figure 3 presents the tensile stress–strain curve for all three tested material samples. It can be noticed that all these results are within the range specified in the standards in effect for this material.

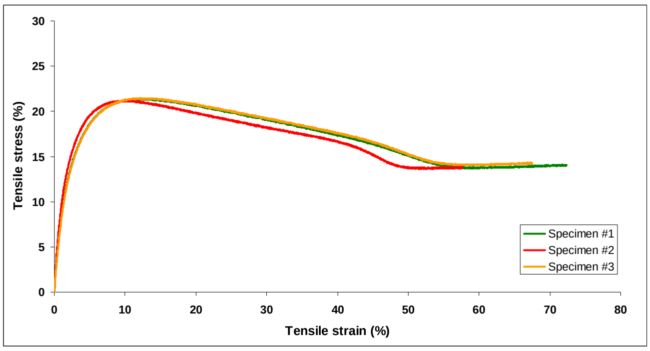


Fig. 3 Stress-strain curves for the PE-HWV material

3 Optical determination

An overview of the system used for this experimental determination is shown in Figure 4.

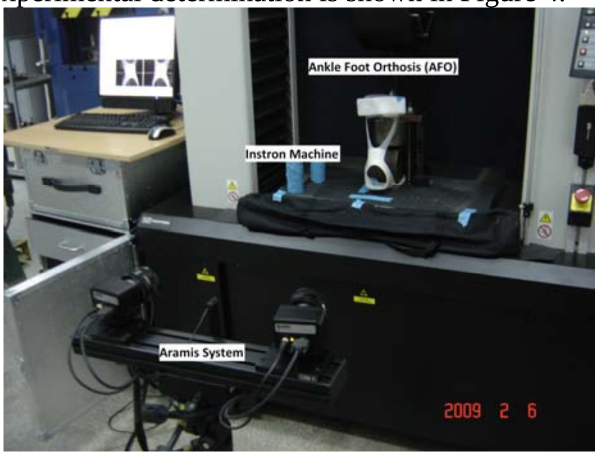
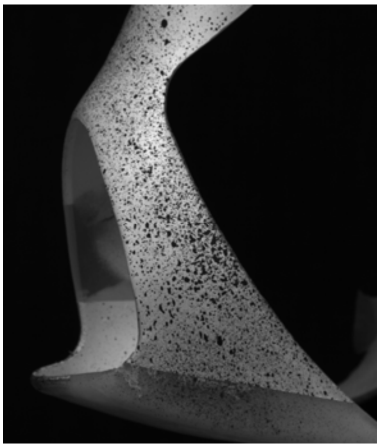


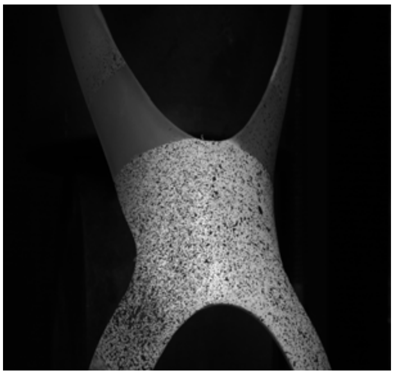
Fig. 4 Overview of the experimental installation

ARAMIS is particularly suitable for three-dimensional deformation measurements under static and dynamic load in order to analyze deformations and strains of real components. The system determines the 2D coordinates of the facets from the corner points of the green facets and the resulting centers [5]. Using photogrammetric methods, the 2D coordinates of a facet, observed from the left camera and the 2D coordinates of the same facet, observed from the right camera, lead to a common 3D coordinate. After a successful computation, the data must undergo a post-processing procedure in order to e.g. reduce measuring noise or suppress other local perturbations. After this conversion, the measuring result is available as a 3D view.

The AFO's preparation consisted in covering it with a layer of antireflexive paint, followed by the deposition of a grid made of fine graphite powder in order to determine the specific strains that appear in it.



(a)



(b)

Fig. 5 Preparation of the AFO in the area of interest

The results of the research were focused on the main strains and the total displacement for the two stressing stages in two distinct areas of the AFO: the connection area between the outer foot-sidewall and the foot sole and the intersection area between inner and outer walls, respectively (Figure 5 a, and b).

Table 2 Experimental results

	View type	u_{total} [mm]	ε_1 [%]	ε_2 [%]	ε_{VM} [%]
First case	side	19.40	1.662	-0.105	2.120
	back	23.00	1.730	-0.130	2.200
Second case	side	34.02	0.762	-0.055	1.276
	back	33.90	5.010	-0.074	6.788

These areas were chosen because in practice it was found that the AFO fails occurs most often in these areas. Also, in Table 2 are presented the experimental value of total displacement (u_{total}), principal strain (ε_1, ε_2) and equivalent von Mises strain (ε_{VM}) for both case studied.

4 Test Results

The orthose's testing was done through the materialization on the Instron machine of the human leg movement, namely a flexion of the AFO's fastening area on the shank by 60 mm on a direction parallel to the foot sole. This was achieved by means of a pulley and an inextensible thread.

The tests results for AFO are shown in the following figures. Thus, figures 6...9 present experimental results obtained in the connection area between the outer foot-sidewall and the foot sole of the AFOR (side view of the AFO).

Figures 10 ... 13 present the experimental results for the intersection area between inner and outer walls (back view of the AFO).

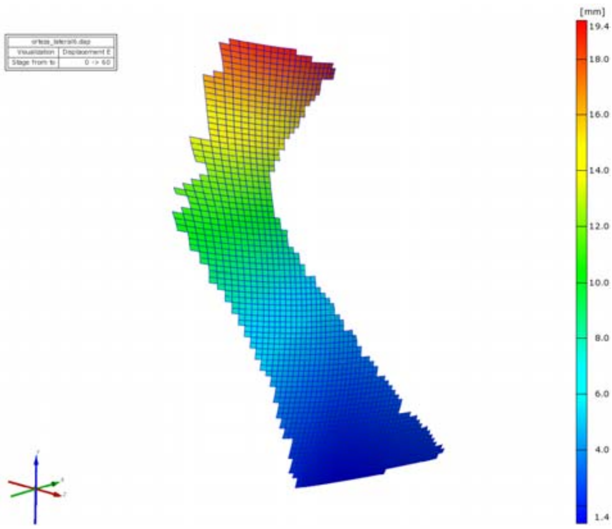


Figure 6 Total displacement for the first stage of the mid-stance phase (side view of the AFO)

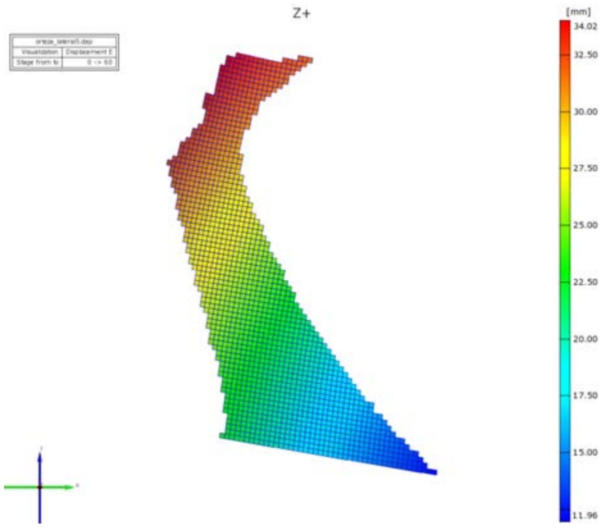


Figure 7 Total displacement for the second stage of the mid-stance phase (side view of the AFO)

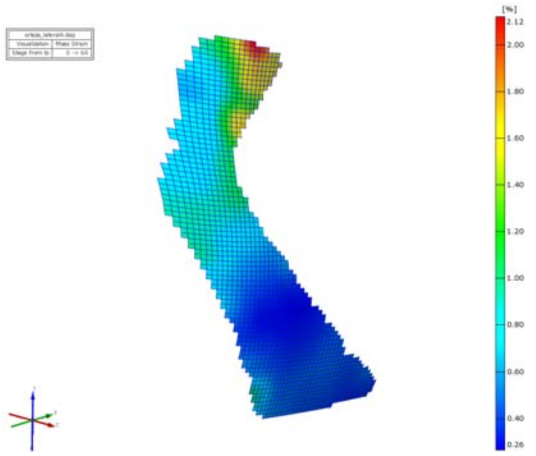


Figure 8 Distribution of von Mises strains for the first case of the mid-stance phase (side view of the AFO)

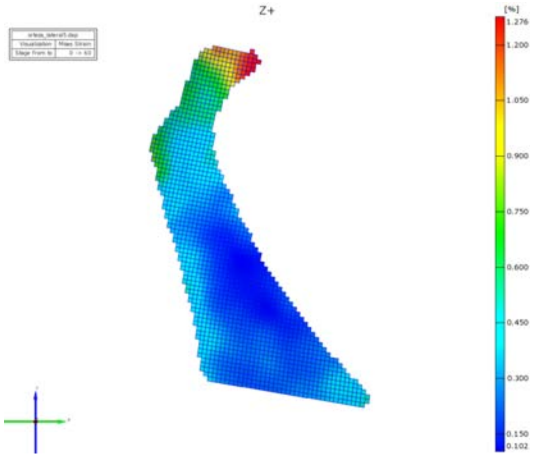


Figure 9 Distribution of von Mises strain for the second case of the mid-stance phase (side view of the AFO)

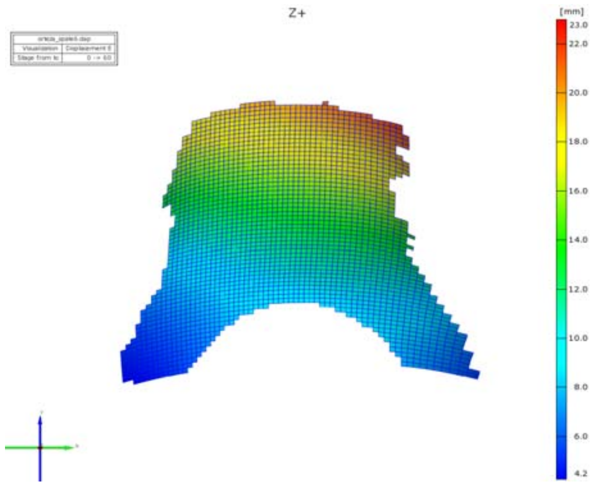


Figure 10 Total displacement for the first case of the mid-stance phase (back view of the AFO)

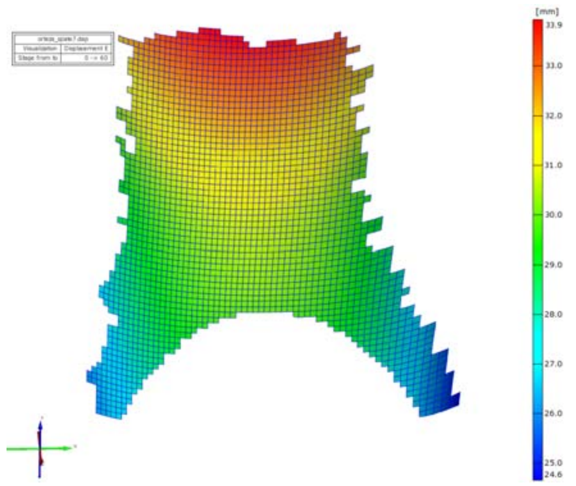


Figure 11 Total displacement for the second case of the mid-stance phase (back view of the AFO)

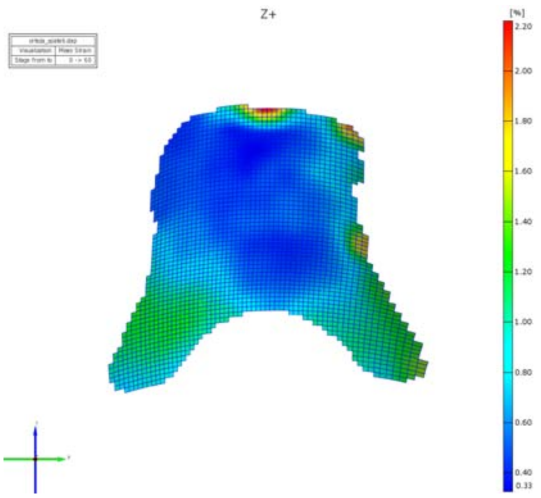


Figure 12 Distribution of the von Mises strain for the first case of the mid-stance phase (back view of AFO)

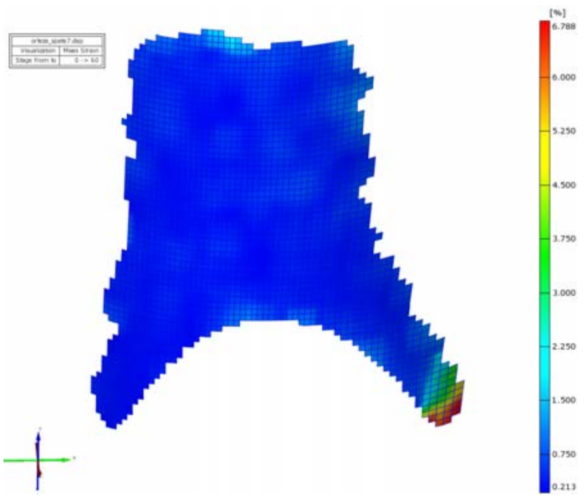


Figure 13 Distribution of the von Mises strain for the second case of the mid-stance phase (back view of the AFO)

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By analyzing these figures it can be noticed that the maximal strain on the direction of stepping is of 19.40 (23.00) mm for the first case and respectively 34.02 (33.9) mm for the second case of the mid-stance phase. Also, there can be noticed, from the equivalent strain (von Misses) distribution in the connection area between the outer side wall and foot soles of the AFO, a maximal loading in the second case of the mid-stance phase.

The maximum values of the equivalent strain are 2.120 (2.200) % for the first case and respectively 1.276 (6.788) % for the second case of the mid-stance phase. This analysis indicates that the maximum values of the equivalent von Misses strain are below the values corresponding to the elastic strain limit.

In figure 13 there can be noticed the presence of a maximal equivalent strain of 6.788 % in the connection area between the outer side wall and the foot sole of the AFO, because in this case the video camera field includes also a small portion from the inside of AFO.

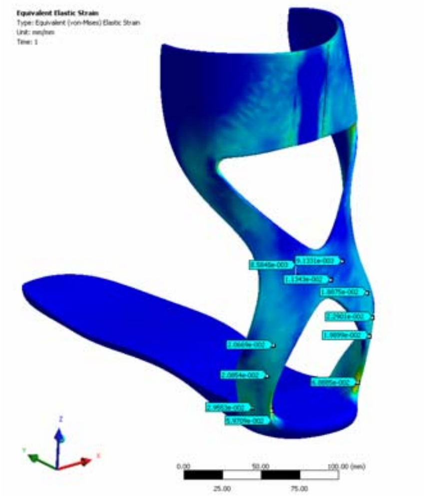

Fig. 14 Equivalent (von Misses) strain distribution in the AFO

The same point of maximum was observed in numerical simulation using a FEM method applied to this AFO (figure 14), and also in the case studies in which a failure of the AFO has been noticed in the same area.

5 Summary and conclusions

The results of the optical measurements show that the loading of the PE-HWV material is in the elastic domain, at specific strains and stresses that are far from reaching the material's tensile strength, so the only reason for a failure of the material can only be material fatigue. This was confirmed by the few fatigue tests performed on test samples made of the same material as the orthose. These results show that the material's failure occurs after several thousand loading cycles.

As a solution against these functional failures, there can be suggested the introduction of strengthening parts in the most stressed areas, namely in the connection area between the outer foot-sidewall and the foot sole and the intersection area between inner and outer walls of the AFO.

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