# MATERIAL MODELING OF ORTHOPEDIC INSOLES

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**Summary:**

An experimental setup is presented for the material characterization of rubber-like sensomotoric insoles. This setup consists of local hardness measurements, quasi-static compression tests and dynamic testing using the 4a Impetus II pendulum test system [1]. A correlation between the measure of shore hardness and the stress strain relation of rubber-like materials is presented and verified in order to consider the inhomogeneous properties of insoles due to milling work of the manufacturing process. The dynamic response of the material is modeled by MAT_SIMPLIFIED_RUBBER/FOAM (material no. 181) in LS-DYNA [2] and MAT_SIMPLIFIED_RUBBER_WITH_DAMAGE respectively. The presented modeling technique is capable to describe the entire process chain from milling of the insole up to its usage.

A further experimental setup is presented for converting the inlay and the human foot to a finite element model. By means of the Streifenlichttopometrie (SLT) [3] it is possible to record the complete surface of the object in a practically photorealistic fashion, i.e. three-dimensionally. In comparison with the classic method of photogrammetry, Streifenlichttopometrie is remarkably faster (10,000 points/s instead of 1 point/s). In this paper we present a modification of this method towards the measurement of dynamic processes.

**Keywords:**

Biomechanics, Insoles, Dynamic Testing, Rubber-like Foams, MAT_SIMPLIFIED_RUBBER

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# 1 Introduction

Insoles are employed to improve the gait of patients and to avoid further damages of the joint structures of the patients. In orthopaedics there are different concepts to build up insoles. The concept of the sensomotoric insole is to change directly the muscle length and for this reason the stimulation pattern of the gait. With this concept many patients could improve their gait without an operation of their musculo-skeletal system. During the therapy the task of the orthopaedic shoe specialist is the recognition of the pathologies, the choice of the shore hardness of the material, the creation of the surface of the insole and the adaption of the insole to the patient.

In this complex procedure the behavior of the material must be well known to provide the patients with well-designed insoles. The state of the art is that the properties of the used materials are dependent of the charge and the loading conditions during wearing the insoles. For this reason the aim of the project is to investigate the properties of the materials, the creation and the adaption of the insoles and beyond it the change of the properties during wearing the insoles.

# 2 Methodology

In our investigation we use a three-dimensional gait analysis system and a three-dimensional surface measuring method (dynamic SLT) to document the gait of the patient and the deformation of the feet. To analyze the vertical ground reaction forces on the feet we use a Zebris pressure platform. With the data of the above described measuring methods the insoles are created and adapted by the orthopaedic shoe experts. For the measurement of the dynamic behavior of the insoles, the testing system Impetus II is used that was developed by 4a engineering GmbH in Traboch, Austria.

## 2.1 Experimental Setup

### *2.1.1 Surface Measuring Method*

The gait of the patients is documented by means of a gait analysis system, which was developed at the Biomechanics Lab in Giessen. The deformation of the feet is measured by a surface measuring method. SLT is a method for the optical 3D measurement. A recent development, the dynamic SLT, makes it possible to investigate the dynamic behavior of surfaces by the 3D documentation and measurement of objects in motion, see [4] and [6].

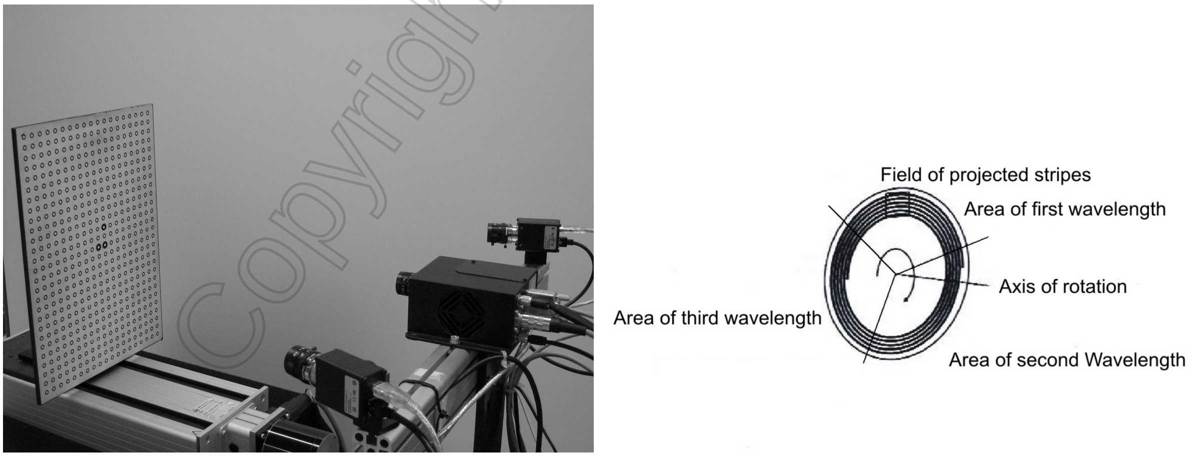


*Figure 1: Left hand side: Dynamic SLT equipment; projector Minirot® and two video cameras. Right hand side: Rotating slide of the Minirot® Projector.*

The SLT method consists of two working steps, the measurement and the analysis. SLT is an optical measurement method based on the projection, recording and analysis of coded sets of stripes of light on the object to be measured. Physical principles of the method are the triangulation and the light sectioning, see [7] and [8].
There are a new element of the measurement process which is called the multiple wavelength phase shift and new algorithms for the “unwrapping” of the data sets [7]. These replace the Graycode sequence and the phase shift in the measurement of stationary objects.

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For this kind of measurement we use a new type of projector developed by ABW GmbH, Frickenhausen, Germany which is called the “MiniRot”®.
The projector is equipped with a special rotating slide. On this slide there are three different grid patterns, representing the three wavelengths. The projector can be synchronized to different types of cameras.
The result of the measurement process is a 3D film showing the deformation of the object. In the data procedure a choice of significant stages of the movement is submitted to the actual data analysis.

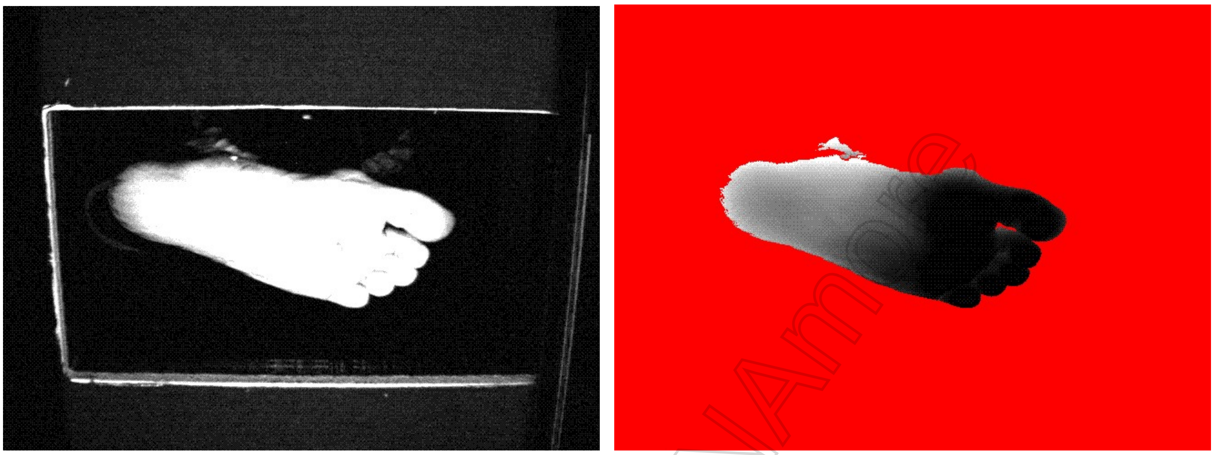

*Figure 2: Left hand side: Recording of the changing surface of the foot; frame 32 of the video sequence of the dynamic SLT. Right hand side: Recording of the changing surface of the foot; frame 32 of the 3D-film of the dynamic SLT; deepness z grey coded.*

### *2.1.2 Pressure Distribution*

To obtain the vertical ground reaction force a pressure platform of Zebris is used (FDM 1.5 platform; dimensions 158 x 60.5 x 2.5 cm (L x W x H); sensor area 149 x 54 cm; Number of sensors 11264; sampling rate 100 Hz).

In the next step the orthopaedic shoe specialist designs the surface of the insole by means of the measured data of the gait analysis. He must recognize the pathologies of the anatomy of the feet and the sensible area where the sensomotoric insoles should actuate the feet. In this adapting process the material of the insole must have the appropriate properties.

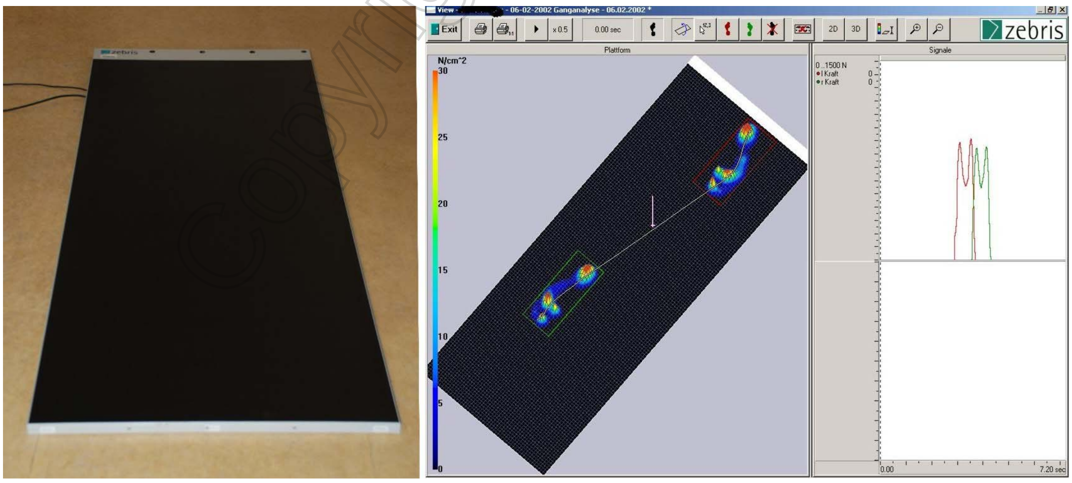


*Figure 3: Zebris FDM 1.5 pressure platform.*

### *2.1.3 Dynamic Behavior of the Insole*

In order to measure the dynamic behavior of the insole’s material, the 4a Impetus II pendulum test system is used, see Figure 4. Impetus II represents a fast and efficient experimental setup for dynamic

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testing of foam-like materials. The corresponding software package allows for the validation and verification of the obtained test data with material laws in LS-DYNA using the optimization package LS-OPT.


*Figure 4: 4a Impetus II pendulum test system.*

For the material testing, cube-like specimens of 30x30x30mm have been used. A maximum compression of 50% for an impact velocity of 4m/s has been reached. Some selected results of the obtained engineering stress-strain relation of the insole material for impact velocities of 1m/s, 2.5m/s and 4m/s are shown in Figure 5. The stress values are normalized for confidentiality reasons. The material shows the typical behavior of rubber-like foams. Apart from the expected visco-elastic response, the material also exhibits a small amount of permanent deformation.

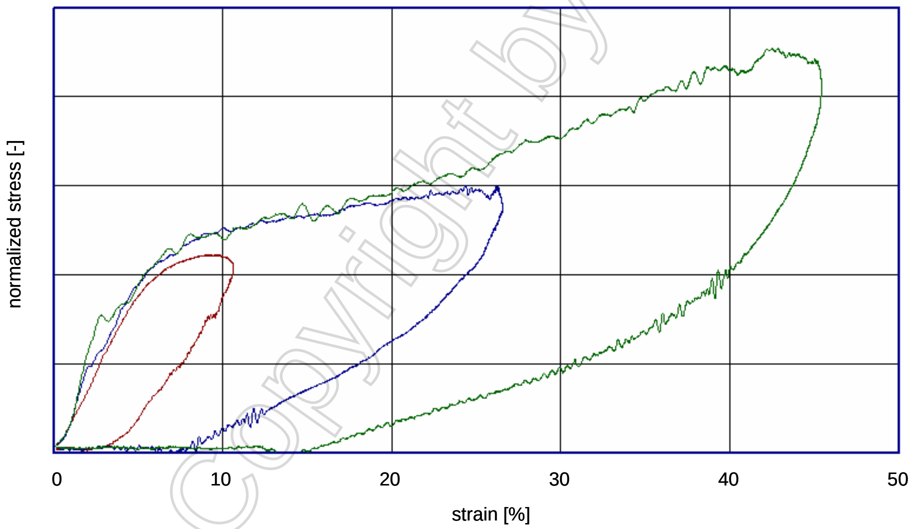


*Figure 5: Stress-strain relation of the insole material for 1m/s, 2.5m/s and 4m/s.*

In Figure 6, the true strain-rate is depicted over engineering strain for different impact velocities. As can be seen a wide range of strain rates up to 150/s are realized. This range of strain rates can be used very efficiently for the validation and verification of the test data by the including Impetus II Software.

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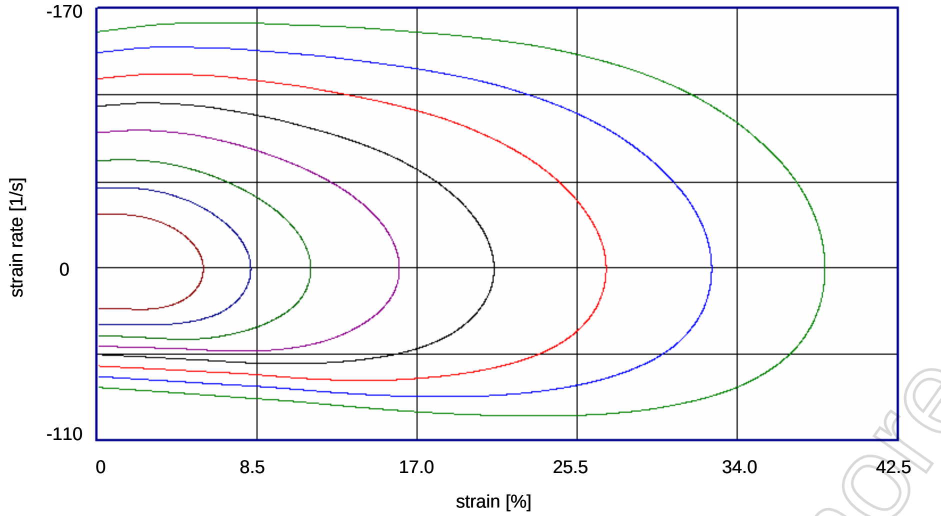


*Figure 6: Strain-rate over strain for different impact velocities.*

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## 2.2 Validation of the Material Data with LS-DYNA

The insole material consists of rubber-like foam. The experimental results described above show the following phenomena:

- Poisson's ratio 0.25
- non-linear elastic behavior during loading
- nonlinear unloading / viscosity
- strain rate dependency / viscosity
- (small) permanent deformation

For modeling these phenomena with LS-DYNA the permanent deformations are neglected and a bunch of material laws are thus available. In the following the material is modeled by the most popular hyper-elastic laws in LS-DYNA. Using MAT_SIMPLIFIED_RUBBER/FOAM the Poisson effect and the strain rate dependency can be taken into account. However the unloading behavior can not be modeled properly with this law. Therefore we use MAT_SIMPLIFIED_RUBBER_WITH_DAMAGE as a second alternative. The unloading behavior may then be modeled by elastic damage in a pretty good way though the strain rate dependency is neglected and the material is considered to be incompressible.

### *2.2.1 MAT_SIMPLIFIED_RUBBER/FOAM*

Starting point for this law is the energy per unit undeformed volume of the material as

$$W = \sum_{i=1}^{3}\sum_{j=1}^{m}\frac{\mu_j}{\alpha_j}\left(\lambda_i^{\alpha_j} - 1\right) + \frac{1}{n}\sum_{j=1}^{m}\frac{\mu_j}{\alpha_j}\left(J^{-n\alpha_j} - 1\right) \tag{1}$$

that is proposed by Hill [9]. In this equation *J* describes the relative volume, $\lambda_i$ are the principal stretches, $\alpha_j$, $\mu_j$ are material parameters whereby *n* determines the Poisson effect of the material. For the present insole rubber-like foam Poisson's ratio of 0.25 is used. The corresponding expression for the true stress is easily obtained by differentiation of the energy W with respect to the principal stretches:

$$\sigma_i = \frac{1}{\lambda_k\lambda_j}\frac{\partial W}{\partial \lambda_i} = \sum_{j=1}^{m}\frac{\mu_j}{J}\left[\lambda_i^{\alpha_j} - J^{-n\alpha_j}\right]. \tag{2}$$

In the implementation of Hill's law in MAT_SIMPLIFIED_RUBBER/FOAM, a tabulated approach is available for each strain rate.

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*2.2.2 MAT_SIMPLIFIED_RUBBER_WITH_DAMAGE*

The main drawback of MAT_SIMPLIFIED_RUBBER/FOAM is the unloading behavior (A phenomenon that is already known from MAT_FU_CHANG_FOAM up to version 9.70). A simple but effective way to avoid numerical instabilities during unloading is the incorporation of elastic damage (A way that now works also fine for MAT_FU_CHANG_FOAM). In the damage formulation the elastic stress $\sigma_0$ is reduced in the case of unloading by a factor $(1\text{-}d)$:

$$\sigma_{eff} = (1-d)\sigma_0 \,, \tag{3}$$

where $d$ is the damage parameter that can be expressed as a function of the current energy $W$ over the maximum energy $W_{\max}$ as a two-parameter function as

$$d\left(\frac{W}{W_{\max}}\right) = (1-HU)\left(1-\left(\frac{W}{W_{\max}}\right)^{SHAPE}\right). \tag{4}$$

Here, HU and SHAPE are shape parameters in the usual LS-DYNA notation.

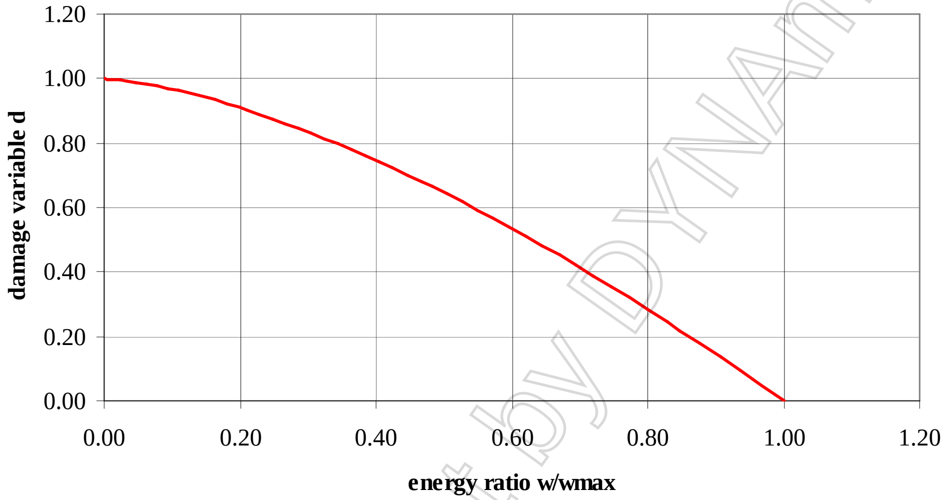


*Figure 7: Evolution of the damage variable for increasing energy.*

Setting HU=0.001 and SHAPE=1.5 (see Figure 7), the quasi-static stress-strain curve can be represented in a good approximation (Figure 8). Note that the formulation with the two-parameter function is necessary since the given test curve exhibits permanent deformation. This discontinuity can not be modeled by the tabulated approach.

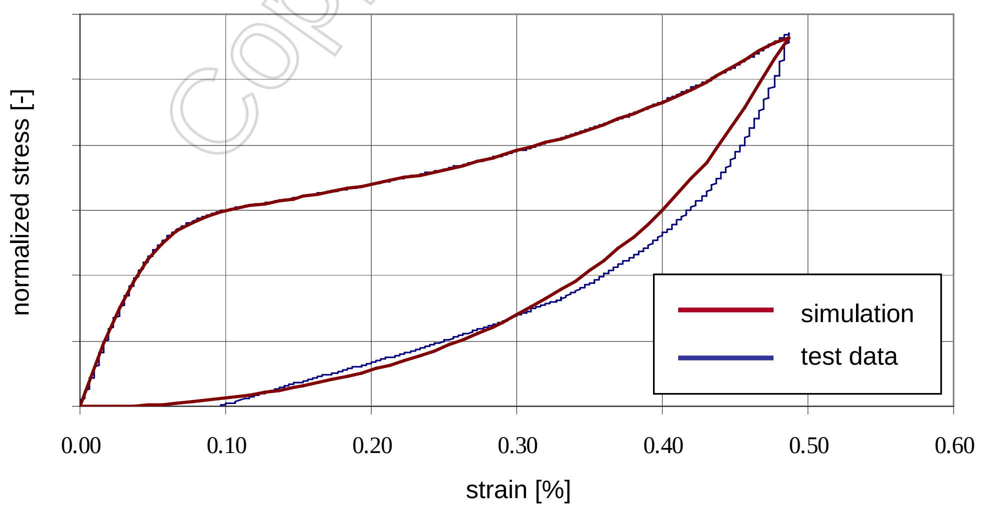


*Figure 8: Simulation vs. test data using MAT_SIMPLIFIED_RUBBER_WITH_DAMAGE.*

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### 2.2.3 Consideration of Shore Hardness Distribution

For the sufficiently small cube-like test specimens of 30 x 30 x 30 mm, the material can be considered as homogeneous. This is certainly not the case for the entire insole where the material stiffness varies from point to point due to the manufacturing process. In order to take this inhomogeneous behavior into account, the local shore hardness (A) has been measured and an empiric relationship between shore hardness and the local material tangent is formulated.

From more than 100 durometer measurements for a representative insole, we obtained the results given in Table 1.

| number of measurements | shore hardness (A) | | | variance |
|---|---|---|---|---|
| | Minimum | maximum | average value | |
| 126 | 41.9 | 50 | 46.8 | 2.9 |

*Table 1: Shore hardness measurements.*

Comparing the local shore hardness with corresponding quasi-static compression tests, a relation of the shore hardness and the initial modulus of elasticity can be expressed as an empiric function:

$$\left.\frac{\partial\sigma}{\partial\varepsilon}\right|_{\varepsilon=0} = \frac{\sigma_0}{2(1+\nu)} e^{b\cdot\mathrm{Shore}}, \quad (5)$$

where $\nu$ is Poisson's ratio, $\sigma_0$, $b$ are fitting parameters and Shore is the shore hardness (A) of the material. For rubber-like materials, the parameters are given as $\sigma_0$=0.074 MPa and $b$=0.045. It is now assumed that this relationship holds not only for initial modulus of elasticity but for the local material tangent of the stress-strain relation. The derivative of a stress-strain curve with known shore hardness is thus scaled by a scalar factor $\exp[b(\mathrm{Shore1}-\mathrm{Shore2})]$ to obtain the tangents for the new stress-strain curve:

$$\left(\frac{\partial\sigma}{\partial\varepsilon}\right)_{\mathrm{Shore2}} = e^{b\cdot(\mathrm{Shore2}\text{-}\mathrm{Shore1})} \cdot \left(\frac{\partial\sigma}{\partial\varepsilon}\right)_{\mathrm{Shore1}} . \quad (6)$$

Figure 9 shows a comparison between measurement and this approximation for a rubber-like material taken from [2]. From an engineering point of view, the formulation leads to a sufficient agreement.

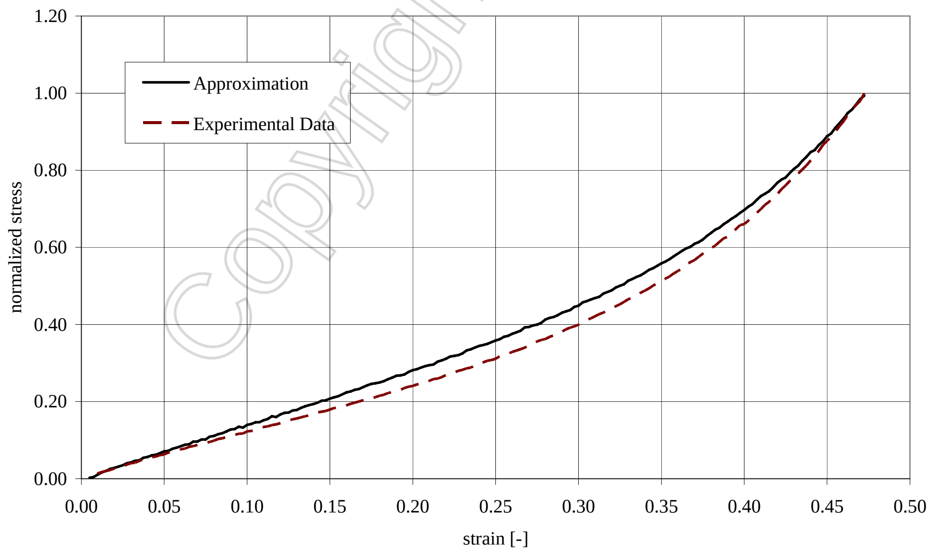


*Figure 9: Approximation vs. experimental results for two rubber-like materials with Shore 55 and Shore 70, see [2]. The stress-strain relation of the shore 55 material has been scaled by the empiric law (6) to approximate the stress-strain relation of the shore 70 material (dashed line).*

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With the empirical approximation given by Equation (6) it is very easy to assign the local material properties into the LS-DYNA material card. However, a proper mapping algorithm must be used to ensure a homogeneous distribution of the local hardness.

## 3 Summary and Outlook

First steps towards an optimization scheme for orthopedic insoles under dynamic loading are presented. A new SLT-technique for the measurement and digitalization of dynamic processes is presented. This can also be used for scanning human feet and for converting this data to a finite element model. In addition, pressure platforms are used to measure the vertical ground reaction forces. With these “ingredients” all required data is available for a proper validation and verification process of the foot-insole-interaction via finite element analysis.

As for dynamic material testing, Impetus II represents both an efficient experimental setup and a useful tool for the validation and verification of the obtained test data with material laws in LS-DYNA using LS-OPT. The insole material has been modeled by MAT_SIMPLIFIED_RUBBER/FOAM (material No. 181) and MAT_SIMPLIFIED_RUBBER_WITH_DAMAGE (material No. 183). At this point it has been turned out that a damage formulation in MAT_181 is absolutely necessary since MAT_183 neglects strain-rate effects and is available for incompressible materials only.

An empirical approximation of the stress strain curve by the shore hardness (A) has been suggested. Using this relation, it is very easy to assign the local material properties into the LS-DYNA material card. However, a suitable mapping algorithm must be used to ensure a homogeneous distribution of the local hardness. The influence of such kind of inhomogeneous hardness distribution is a topic of further investigation.

In the next step, the finite element modeling of the patient’s foot including the corresponding biomaterials will be performed and the foot-insole interaction will then be investigated in detail.

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