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Definition and evaluation of plantar mechanical comfort for the support of footwear design

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ABSTRACT
Footwear is one of the most widely and intensively used human centric products. Evaluating and optimizing footwear performance is of outmost importance for human comfort. This paper presents a definition of foot plantar mechanical comfort along with a detailed approach for evaluating it through finite element analysis. An extensive review of biomechanical and shoe mechanical aspects related to human comfort is presented providing ample justification for the selection of the comfort characteristics which are addressed in this paper. A foot biomodel has been developed which is combined with solid shoe structures in order to evaluate plantar pressures distribution and shock absorption. In addition, bending and torsional behavior of shoe structures is also taken into account and, therefore, appropriate finite element models have been developed and tested. All experiments are analytically presented and discussed, while the related results illustrate the potential of the proposed approach to support footwear design optimization under an integrated biomechanics-enabled framework.

KEYWORDS
Plantar mechanical comfort; footwear design; foot biomodel; finite element method

1. Introduction

Footwear is one of the most widely and intensively used human-centric product categories influencing human comfort. Footwear use is both leisure and occupational. It has also medical implications in podiatry, thus attracting significant interest in the field of biomechanical research. Today, increased understanding of foot mechanical comfort issues has led to improvements in design and material selection in footwear development.

This paper deals with the evaluation of footwear performance in terms of plantar mechanical comfort. The purpose of this work is to provide a unified framework which is based on analytical finite element models (FEM) of shoe structures combined with a detailed biomodel of the human lower foot. The contribution of this paper is twofold: first, a thorough definition of foot plantar mechanical comfort is presented along with an extensive review of the associated literature. Second, a set of simulation tools is presented based on finite element analysis (FEA) for assessing plantar comfort parameters as defined in this work.

The concept of plantar mechanical comfort is first introduced in Section 2, followed by a review of relevant assessment practices and the definition of the adopted plantar mechanical comfort in Section 3. The application of the finite element method for the evaluation of mechanical comfort is demonstrated in Section 4 using indicative examples. Finally, Section 5 discusses the derived results and concludes this paper with some hints for future work.

2. The concept and aspects of foot plantar mechanical comfort

Comfort is “lack of pain” and “a feeling of health and wellbeing”. It is also situational (reaction to a situation) consisting of physiological, psychological and physical aspects [3], [16], [48]. The skeletal part of the foot defines basic form and provides the foundation for other softer tissues. The foot is enclosed by the skin which supports local small scale mechanics that constitute the field of haptics and tactile comfort. On the other hand, form and skeletal structure provide for gross mechanics which involves the foot and the higher body and delimits the field of foot mechanical comfort.

The foot is the receiving body end for significant loads. Excessive foot loading can be the cause of discomfort, pain and actual injury in lower local or other higher parts of the body. Interaction with the ground is either direct or through the use of footwear consisting of a sole and

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an upper. The sole is subject to significant forces through its interaction with the plantar foot side and the ground. In contrast, the shoe upper is mainly subject to restrictive or touch forces, that are much smaller compared to plantar loads, limiting dorsal mechanics to fitting and stability [17]. Thus, mechanical comfort can be divided into plantar mechanical comfort, concerning the interaction of the foot plantar side with the sole and the ground, and dorsal mechanical comfort, limited to the dorsal side of the foot and its interaction with the upper surface of footwear. Plantar mechanics of the upright stance and gait are of utmost importance to gross mechanics of the body and it is addressed in several works [28], [31], [53].

The most important issue in plantar mechanics is ground reaction forces to the action of body weight [19], [29], [53]. The normal (to the plantar foot surface) vectors of these forces are markedly greater than transverse and longitudinal vectors (Fig. 1). Additionally to actual measurements, the estimation or calculation of normal plantar forces has been subject to extensive modeling, including the use of Finite Element Analysis [15], [20], [43]. The effects of normal plantar forces on discomfort, pain and injury rates are significant while those of the shear vectors on gross mechanics are limited, although they cause superficial tissue damages [7], [18].

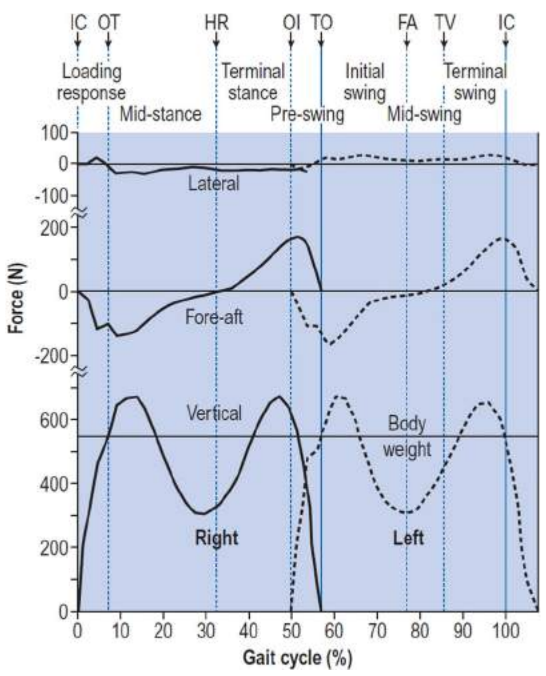

Figure 1. Forces during gait (normalized to body weight) [51].

Insole shape conformance to the foot affects their resulting contact areas [51] while outsole design determines the contact between the outsole and the floor, thus, affecting plantar pressure distribution. Insole fitting has attracted significant attention. Trials conducted on patients with plantar fasciitis support claims that insole geometry affects comfort perception [52]. Along with footbed geometry, material effects analyses have been part of insole comfort studies. Besides insole shape, special arrangements such as ordinary and reverse heeling, wedged soles and rocker complicate force transfer characteristics [45]. The effects of sole geometry and materials on comfort aspects are well documented [11], [15], [25], [34], [41], [50].

Another major issue in plantar mechanics is cushioning. In biomechanics, it is the ability of a material to reduce forces that have the potential to cause injury (shock absorption). In particular, the relation between maximum values of plantar forces and areas of discomfort or pain is the subject of the works [7], [26]. Maximum force values are therefore a simple yet sufficient measure for evaluating shock absorption. In contrast to biomechanics, in ergonomics, interest shifts onto material hardness or compression characteristics related to fatigue and discomfort. Goonetilleke [19] reviewed cushioning and proposed relevant metrics based on hardness, material compression, deceleration on impact, rebound resilience and percentage energy lost.

Bending and torsional deformation characteristics of footwear are also mechanical comfort aspects arising due to the very use of sole structures and their interaction with the ground. The influence of longitudinal bending characteristics on push-off forces during the gait cycle has been demonstrated in [13] and so have the relationships between longitudinal rotation and lateral rotation along the toe break line with comfort [23].

3. Previous work on plantar mechanical comfort assessment and the proposed approach

3.1. Previous work

Most researchers and foot health practitioners focus on specific comfort aspects (e.g. plantar loading, conformity, shock absorption) and make use of proven measurement arrangements that have been in existence for several decades [6], [14], [16], [22], [30], [39], [51]. In addition, proprietary testing arrangements for bending and torsion characteristics of sole assemblies have been developed (e.g. the CTC flexometer and the TNO – IND/MPO Torsion Tester). Moreover, biomechanical researchers have identified cause-effect relationships and developed analytic, differential and finite element models for plantar mechanics, though most are limited to individual mechanical aspects. Until recently, specialists lacked an integrated approach to mechanical comfort assessment. An integrated set of design specifications and testing guidelines for footwear comfort was first developed in 2002 in Brazil [46]. These specifications considered mass, plantar pressure distribution, cushioning, balance, fitting and thermal aspects but were limited to design guidelines and late or post-developmental testing.

Given the recent advances in IT and virtual engineering, the emphasis shifted towards mechanical comfort assessment tools prior to physical prototyping. Mechanics simulation evolved from simple analytical [27] to rheological models [2] and more recently to finite element analysis (FEA) based tools [5]. Taking into account such advances and the need for an integrated pre-prototyping aid to comfort design, an interesting multi-aspect testing tool was developed during the European CEC-MADE-SHOE project under the name Virtual Shoe Test Bed [4]. In this approach, comfort is described in terms of the following aspects: normal plantar pressure, cushioning, shock absorption, bending, torsion, friction, stability, footwear weight and thermal aspects of footwear. Extensive use of simplified analytical and rheological differential models was made along with a detailed and specialized material library to support a virtual comfort engineering tool. More recently the project OptShoes [40] has moved to the use of FEA to evaluate plantar loading, shock absorption (through maximum force values), bending and torsional characteristics of the sole. Geometric plantar and dorsal conformity are also addressed. The OptShoes approach is built on the concept of mechanical comfort as established by both the VSTB virtual engineering tool and the Brazilian specifications.

FEA has been applied in biomechanics for the calculation of stress-strain relationships within tissues due to interaction with the environment. In foot biomechanics, early research [8], [27], [34], [38] resulted in simple though adequate 2D and 3D models. Such early models were used for material sensitivity studies [11], [33] and for investigating the effects of insole geometry on plantar pressure distribution [9]. Advances in FEA and IT led to the development of improved models [10], [47] followed by more advanced simulation cases [1], [11], [21], [25], [56], [7]. Some assumptions are often made, e.g. cartilage is treated as extension of osseus tissue and tarsal bones are considered as one large solid in order to reduce the complexity of the produced model [8], [12] and facilitate FE modeling.

Most of the above mentioned works deal with individual biomechanics aspects of lower foot without offering a consistent approach to the development of human-centric products like footwear. On the other hand, a main goal of this work is to integrate various foot biomechanics aspects in order to allow for the derivation of a recommendation for the design or the functional improvement of footwear.

3.2. The proposed approach

Foot structures are often combined with structures resembling soles and floor surfaces. Such multi-layered multi-material assemblies, have been designed, meshed and simulated by several researchers in the past [12], [34]. Similarly, in this work, complex sole structures have been developed with the aid of parametric CAD software.

With regard to bending and torsion analysis of soles, it is assumed that the sole assembly is flexible enough to bend and follow the foot motion through forces developed due to the presence of the footwear fastening system. It is also assumed that foot supination-pronation and varus-valgus angles are 0°. In flexible structures, the strain energy required for bending the sole and conforming to rotation around the metatarsophalangeal articulations is much lower than in rigid ones. For walking and some track athletics, flexible footwear are considered more comfortable than rigid ones [54]. The use of energy measures is preferred to forces or moments, as is the case in some laboratory equipment. Energy (or work) is a true indication of human effort to bend the sole structure. Given wide variations in sizes, geometry and material arrangements in footwear soles, strain energy can be normalized to strain energy density (strain energy per unit volume) and, given the interest in changes of bending characteristics along the structure, to strain energy per unit volume and unit length. Maximum principal stresses and their exact location within the sole assembly can also be calculated for identifying areas of stress concentration. Sole flexibility is an intrinsic property to the footwear structure, depending on footwear geometry, material arrangements and the assembly technology used between sole and upper. Therefore, bending and torsion analysis does not require the use of a foot biomodel.

Maximum bending occurs during the push-off phase of gait. It takes place around the metatarsophalangeal articulations and the bending angle, for the joints concerned, is of the order of 55°. The position of these joints is estimated at 26% of the foot length, measured from the end of the big toe. Therefore, during the push-off phase, the part of the sole to the front of the metatarsophalangeal articulations is, practically, fixed to the ground and the rear part is bent upwards to 55°.

In additionto bending, the ability of the structure to "twist" is critical to comfort. Published research on the effects of longitudinal torsion rigidity on mechanical comfort is limited; however, there is consensus on the fact that increased resistance to torsion leads to increased heel pronation, thus increasing discomfort, pain and injury rates [35], [36], [42], [45]. Practically, any sole assembly may be subject to torsion due to natural pronation or supination, as well as uneven ground. Most torsion related published research on footwear refers to mid and long distance running activities and forefoot landing. This is not the case with gait, where the heel strikes the ground first and forefoot contact with the floor follows later. However, it is known that, during gait, there is a natural tendency for pronation during heel strike and supination during pushing-off. Therefore, torsion applies both to the front and the rear parts of footwear, though at different instances of the gait cycle. Thus, it makes sense to study torsion effects on comfort on each end of footwear. Due to lack of symmetry (e.g. flared sole designs), analyses shall account for both clockwise and anticlockwise rotations. As in the case of bending, maximum principal stresses, strain energy, strain energy per unit volume and strain energy per unit volume and unit length can be calculated and the use of forces or torque avoided. Maximum ankle mobility allows for rotation up to 15°, so angles of sole torsional deformation are not expected to exceed this value.

Additionally, the simulation of the forces applied to sole structure and the reactions applied to human foot can be evidently examined by computing the corresponding plantar pressures distribution. This is achieved by using an adequate foot biomodel and appropriate material properties of the soft/hard tissues. Strain energy density is selected as a measurement of shock absorption which describes the capacity of the selected material to absorb shock energy during human upright position and gait.

Concluding, the proposed plantar mechanical comfort approach with respect to footwear design-optimization consists of the estimation of the following comfort-related aspects/parameters:

- Sole structure bending and torsion
- Foot planar pressures distribution (incl. shock absorption)

A unique characteristic of the proposed method is that all aforementioned comfort parameters are evaluated under a unified environment offering to the designer the means to assess the performance a footwear product. In the next section, we demonstrate how these comfort parameters can be evaluated using analytic FE models of shoe structures combined with a detailed biomodel of the foot.

4. Evaluation of plantar mechanical comfort using finite element analysis

4.1. Calculation of bending and torsion parameters

A 3D sole model is reconstructed that resembles an asymmetric flat sole (Fig. 2(a)). The maximum length of the structure is 290 mm, the maximum width 120 mm and depth 10 mm. A corresponding FE model of the sole has been developed which consists of 4747 tetrahedral elements with maximum size of 10 mm (Fig. 2(b)). Structures consisting of an outer sole and a mid sole were also developed in order to simulate a typical poly-urethane (PU) sole system of the market (Fig. 2(c)) with 5 mm thickness for the outer sole, and 10 mm for the midsole.

Four of the most usual footwear sole elastomer materials were selected for the analyses (Tab. 1) and linear mechanical properties were assumed for each trial.

4.1.1. Calculation of bending

The structure is fixed on its lower front side (forward of the 26% of the total length of the structure) and the back part of the structure is bent upwards. This involves the

Table 1. Materials used for the bending and torsion analyses.

Material	Young Modulus (Typical Range) MPa	Young Modulus (Selected Value) MPa	Poisson Ratio
Poly-isoprene	2–4	2	0.499
Poly-butadiene	4–6	5	0.485
Double Density polu-urethane (PU)	4–12	8	0.3
Single Density poly-urethane (PU)	2	2	0.28

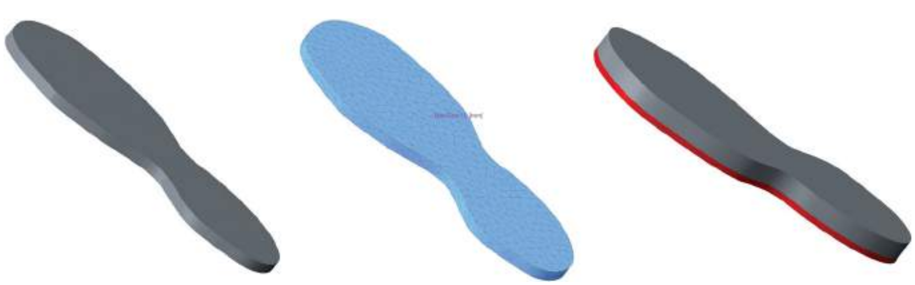

Figure 2. Models of the sole (from left to right): (a) 3D model of a single-layer sole, (b) the finite element mesh of the same sole, (c) 3D model of a double-layer sole.

lifting of a reference line section by 150 mm (Fig. 3). The produced deformation corresponds to angles of bend of approximately 55° (maximum expected angle of bend at pushing-off). Table 2 presents the results of the analyses for the four material combinations selected.

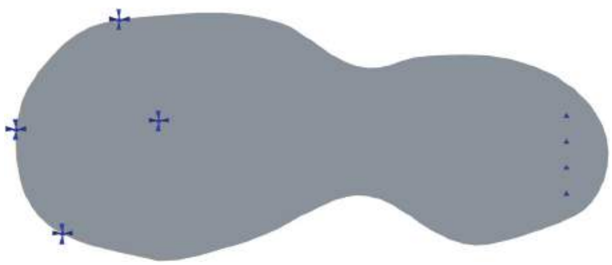

Figure 3. Setting initial conditions for bending analysis.

Calculated values for both maximum principal stress and strain energy are higher for increased Young's modulus of the sole material, indicating a realistic approach to assessing bending deformation characteristics of footwear components.

Graphical illustrations (fringe diagrams) for maximum principal stress and strain energy per unit volume distribution within the sole structure, for polyboutadiene elastomer are provided on Fig. 4(a) and Fig. 4(b) respectively. In particular, the calculated and illustrated strain energy distribution, on the middle area of the sole is as expected for such a practical upwards oriented bending of the sole with the front part firmly secured. Such graphical presentation of distribution for either stresses or energy quantities allows for problematic areas within the structure to be identified and sole design to be improved.

4.1.2. Calculation of torsion

The presented trials are restricted to the heel area and anticlockwise rotational deformation of the structure but a similar approach can be applied for the forepart area of the sole structure, as well as clockwise rotational deformation.

The structure is fixed as for the bending analyses (Fig. 5). Torsion effect is simulated by translating two points located at the ends of a straight line section on the lower part at opposite directions. Table 3 presents the results of the analyses for the four material combinations selected.

High values for principal stresses are due to boundary conditions that force Cartesian translation of points rather than rotational movement. However, total strain energy, as proposed in this work, appears to be a true and accurate measure for the structure, material properties and deformation concerned. Calculated values for

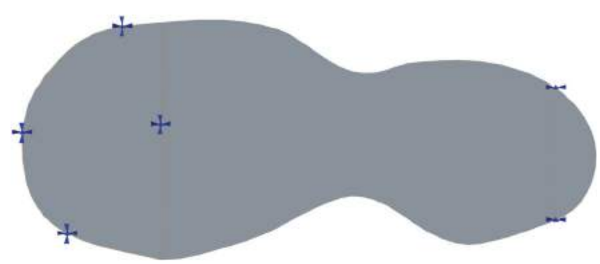

Figure 5. Setting initial conditions for torsion analysis.

Table 2. Bending Analysis Results.

Material	Maximum Principal Stress MPa (N mm^{-2})	Total Strain Energy mJ (N mm)	Strain Energy per unit volume mJ mm^{-3}	Strain Energy per unit volume and unit length mJ mm^{-4}
Poly-isoprene	0.4747	82.6338	3.2001×10^{-4}	1.1035×10^{-6}
Poly-butadiene	0.7503	164.3751	6.3656×10^{-4}	2.1950×10^{-6}
Double Density PU	1.1412	248.8644	9.6375×10^{-4}	3.3233×10^{-6}
Double & Single Density PU system	2.0638	805.2205	20.7887×10^{-4}	7.1685×10^{-6}

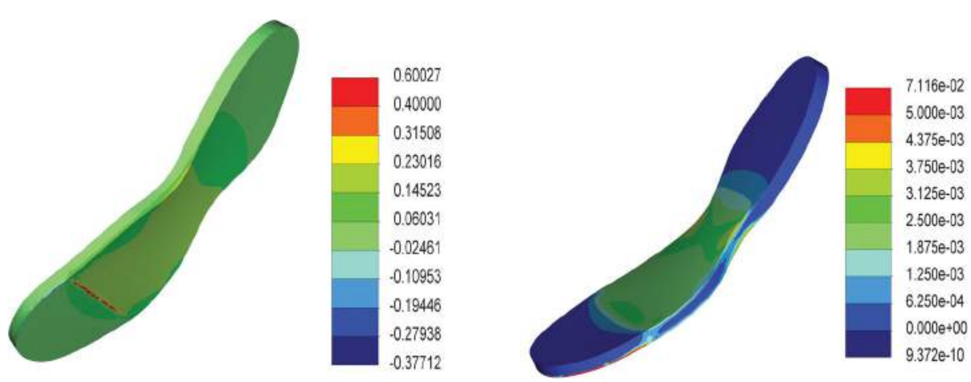

Figure 4. FEA distribution fringe diagrams (from left to right): (a) Maximum principal stresses on bending, (b) Strain energy per unit volume on bending.

Table 3. Torsion Analysis Results.

Material	Maximum Principal Stress MPa (N mm^{-2})	Total Strain Energy mJ (N mm)	Strain Energy per unit volume mJ mm^{-3}	Strain Energy per unit volume and unit length mJ mm^{-4}
Poly-isoprene	4.7194	15.6129	0.6046×10^{-4}	0.2085×10^{-6}
Poly-butadiene	4.3262	33.2739	1.2886×10^{-4}	0.4433×10^{-6}
Double Density PU	12.1621	54.5362	2.1120×10^{-4}	0.7283×10^{-6}
Double & Single Density PU system	28.1788	123.2040	3.1808×10^{-4}	1.0968×10^{-6}

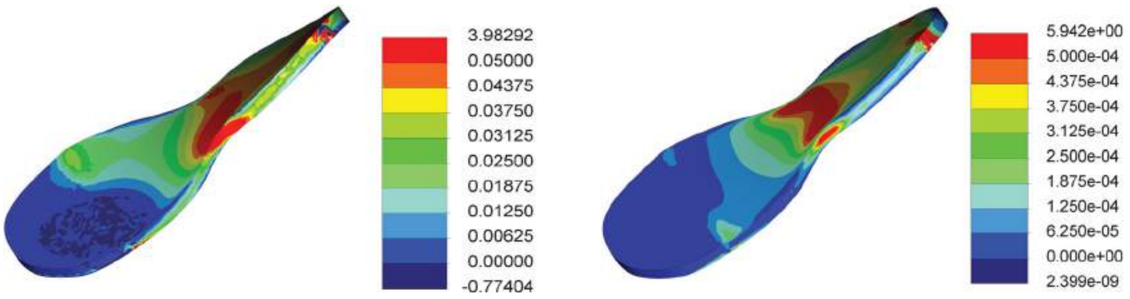

Figure 6. FEA distribution fringe diagrams (from left to right): (a) Maximum principal stresses on torsion, (b) Strain energy per unit volume on torsion.

both maximum principal stress and strain energy are higher for increased Young's modulus of the sole material, indicating a realistic approach to assessing torsion deformation characteristics of footwear components.

Fringe diagrams for maximum principal stress and strain energy per unit volume distribution within the sole structure for poly-boutadiene elastomer are provided on Fig. 6(a) and Fig. 6(b) respectively. In particular, the calculated and illustrated strain energy distribution, on the "shank" area of the sole is in line with practical scenarios that exhibit such a "twisting" of the sole with the front part firmly secured on the floor.

4.2. Plantar pressures and shock absorption analysis

A biomodel of the foot consisting of soft tissue and an inner structure resembling the bone structure is developed. The geometry of the model is derived from a complete reconstruction from dense CT scans and a Reverse Engineering (RE) methodology where a point-cloud is extracted from the CT sections. The model consisting of the soft tissue and an embedded bone structure is assumed to rest on sole solid models (Fig. 7). Because of the large difference of stiffness between bones and soft tissue, bone structure was assumed rigid and cavities in the soft tissue model were fixed. Linear material properties were considered for the soft tissue with a Young's modulus of 1.15 MPa. Contact elements were developed between the soft tissue and the sole and the model was loaded with a step-wise normal displacement of the lower part of the sole. The reaction force, evaluated from the solution, was considered to be the force applied to the foot. For the analysis, ANSYS software code was implemented.

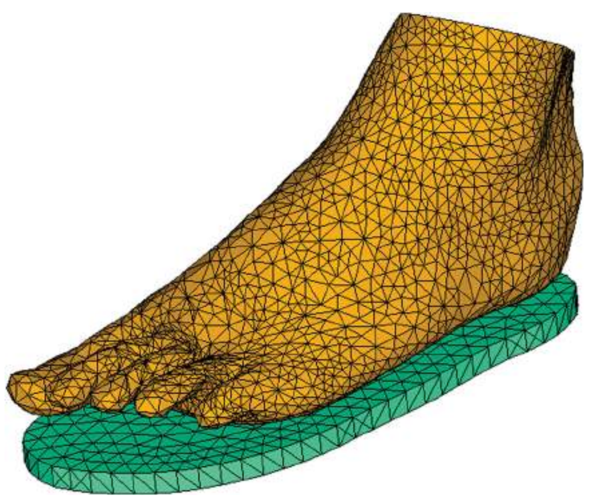

Figure 7. Foot/sole FE model.

The four materials for the single and double sole described in the previous section are used. The goal of this investigation is to evaluate the effect of sole material on the mechanical behavior of the system, including maximum plantar pressure and strain energy density. Typical distributions of the plantar pressure (minimum principal stress) for poly-isoprene and double density PU soles are shown in Fig. 8. The results show that the sole material has a small effect on both the distribution of the plantar pressure and its maximum value.

The force-displacement curves of the four models are shown in Fig. 9. No significant difference is observed.

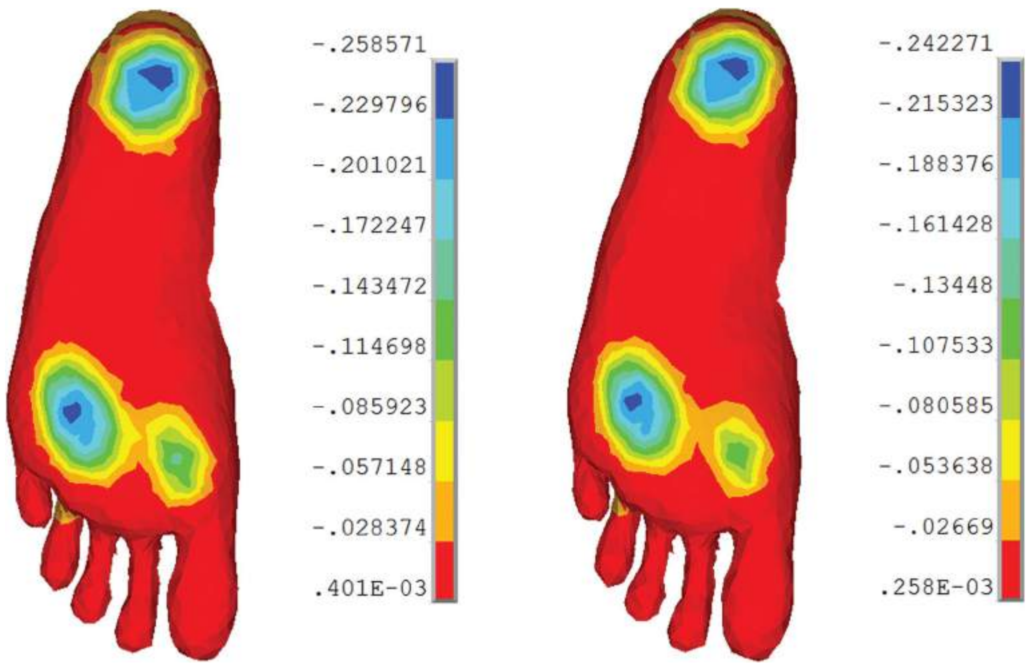

Figure 8. Distribution of plantar pressure for poly-isoprene and double density PU soles (at 350 N).

This may be attributed to the small contribution of the sole material to the stiffness of the whole model due to its small volume as compared to the volume of the soft tissue. The maximum plantar pressure with the applied load is presented in Fig. 10. In this case, the results for a single sole with a much higher stiffness (PVC with Young's modulus of 3 GPa) are also presented. No significant effect of the sole material is noticed. It should be noted that the maximum pressure depends on local contact behavior and the differences for the four materials are in the range of FE accuracy. However, for a significant stiffer material, higher values of contact pressure are clearly observed.

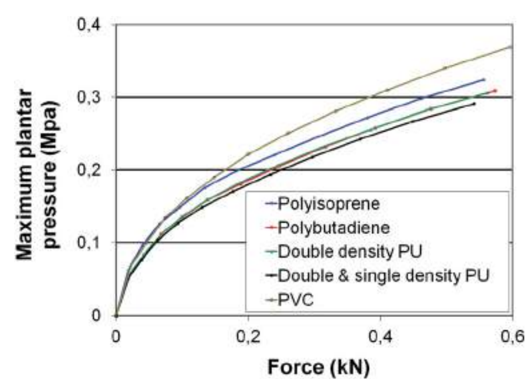

Figure 10. Maximum plantar pressure - applied force curves.

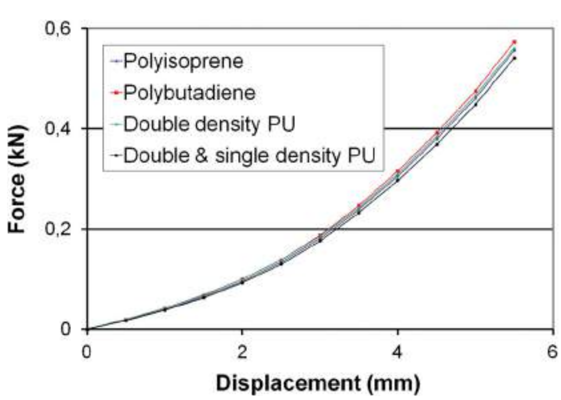

Figure 9. Force-displacement curves.

In this work, as described in the previous section, the parameter considered to represent the capacity for shock absorption is the strain energy density. In the bending and torsional loading of the sole, the same displacement for each material was used and the strain energy increased with stiffness. However, during the normal use of the sole, the displacement depends on the applied load, the stiffness of the sole and the contact area and pressure. In Fig. 11 and Fig. 12, the strain energy density of the sole evaluated for each load step is compared to the applied load and the maximum plantar pressure. Clearly, the increase in sole stiffness results in lower strain energy and, therefore, lower capacity for shock absorption. The results of Fig. 11 suggest that after, approximately, 20 kg of force, the relationship between load and strain energy density is linear, meaning that there is no significant change in the contact area. The same is observed for the relationship between strain energy density and maximum plantar pressure. This may provide a useful tool

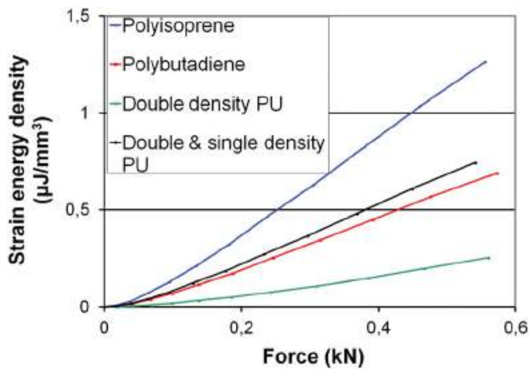

Figure 11. Strain energy density as a function of applied force.

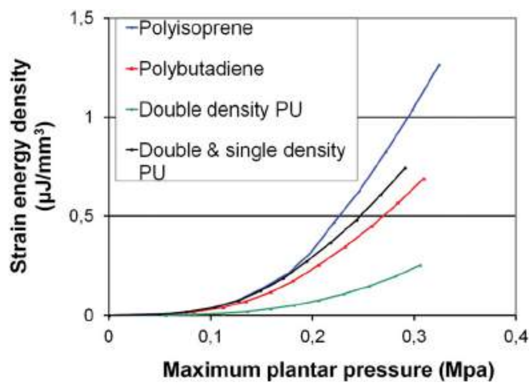

Figure 12. Relation between strain energy density and maximum plantar pressure.

for evaluating the strain energy density. Finally, Fig. 13 presents a comparison of the values of strain energy density at an applied load of 350 N and suggests an almost inverse proportionality between strain energy density and sole stiffness.

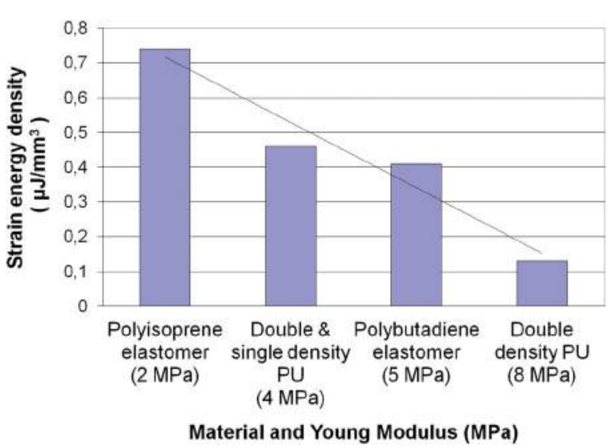

Figure 13. Strain energy density at 350 N (35 kg) for the materials used arranged in descending order of stiffness. Stiffness values have been obtained from Tab. 1.

5. Conclusions and future work

The finite element analysis of the system of the foot biomodel and the solid sole model produced accurate results for the foot plantar pressures distribution. In particular, it was observed that the sole material has a small effect on both the distribution of the plantar pressure and its maximum values. For the four material options considered, as well as the far more rigid PVC, the shapes of the force-displacement curves were similar as expected, though relatively higher values of contact pressures were registered for the much stiffer PVC.

The parameter that is considered to represent the capacity for shock absorption in the proposed approach is the strain energy density. The analyses revealed that increased stiffness of the sole leads to lower strain energy and, therefore, lower capacity for shock absorption. Thus, strain energy density may provide a useful aid to the study of shock absorption aspects.

Furthermore, analyses of bending and torsion sole deformation, demonstrate the capacity of the proposed approach to investigate relevant characteristics of sole structures. In particular, strain energy per unit volume and strain energy per unit volume and unit length appear to have an excellent potential to be measures of the ability of the structures to bend or "twist" in motion. Fig. 14 and Fig. 15 illustrate the strain energy per unit volume for the bending and torsion analyses respectively. The results correlate with practical selection guidelines in the footwear industry (i.e., the use of isoprene based natural rubber is recommended for very flexible and "twistable" structures, compared to the use of polyurethanes).

All results are realistic, in accordance to footwear manufacturing practices and demonstrate that the proposed definition of foot plantar mechanical comfort has the capacity to supplement the footwear development process as an optimization aid. Future work will focus on improving the boundary and loading conditions on all comfort parameters in order to simulate with the highest possible accuracy the plantar mechanical comfort as it is defined in this work. In addition, although the results of the proposed approach are comparable with those in the literature, lab experiments are planned to be carried out in order to verify our approach with real testing data.

Another area of interest is related to investigating mechanical comfort characteristics with regard to footwear grading. Such grading related investigations are becoming easier to manage due to recent parameterization advances [32],[49]. The potential to integrate mechanical assessment, with grading and virtual footwear fitting and styling systems [55] may provide manufacturers with a powerful virtual engineering system supporting a full range of product development.

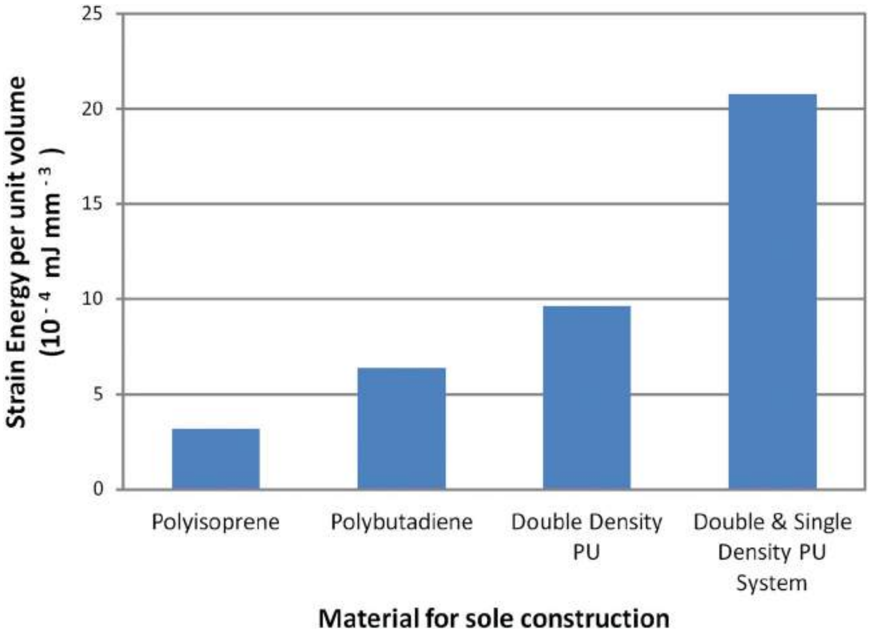

Figure 14. Strain Energy per unit volume for bending analysis.

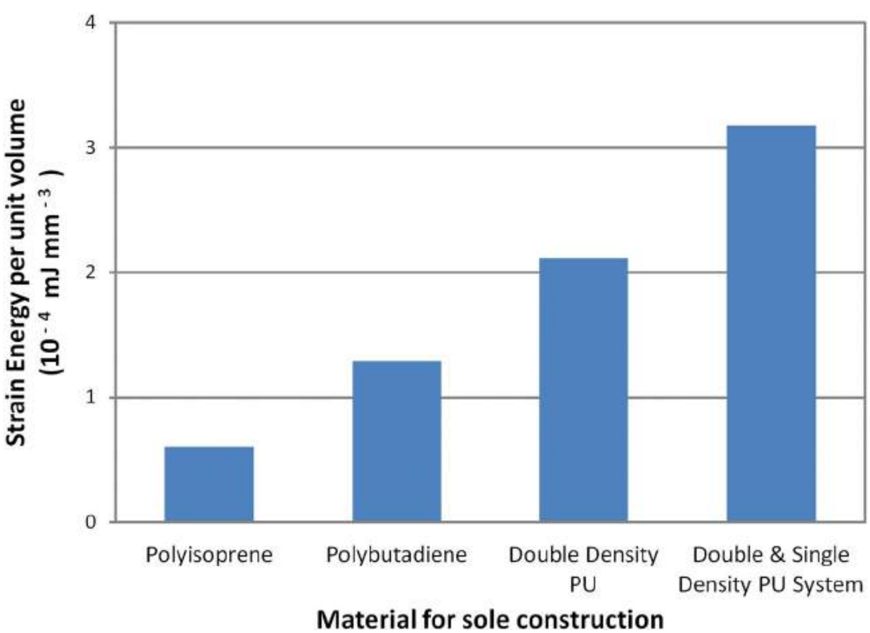

Figure 15. Strain Energy per unit volume for torsion analysis.

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