

Evaluation and optimization of footwear comfort parameters using finite element analysis and a discrete optimization algorithm

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Abstract. Footwear is subject to bending and torsion deformations that affect comfort perception. Following review of Finite Element Analysis studies of sole rigidity and comfort, a three-dimensional, linear multi-material finite element sole model for quasi-static bending and torsion simulation, overcoming boundary and optimisation limitations, is described. Common footwear materials properties and boundary conditions from gait biomechanics are used. The use of normalised strain energy for product benchmarking is demonstrated along with comfort level determination through strain energy density stratification. Sensitivity of strain energy against material thickness is greater for bending than for torsion, with results of both deformations showing positive correlation. Optimization for a targeted performance level and given layer thickness is demonstrated with bending simulations sufficing for overall comfort assessment. An algorithm for comfort optimization w.r.t. bending is presented, based on a discrete approach with thickness values set in line with practical manufacturing accuracy. This work illustrates the potential of the developed finite element analysis applications to offer viable and proven aids to modern footwear sole design assessment and optimization.

1. Introduction

In gait, the foot interacts with the footwear and the ground. High loads lead to discomfort and pain [1], while, for ordinary fastened shoes, excessive work to make the sole conform to the plantar side of the foot increases fatigue and imposes high stress on tendons. Plantar mechanical comfort has several objective aspects: normal and shear plantar loading, shock absorption, cushioning, friction, stability, sole bending and torsion characteristics [2,3]. The actual experience of comfort, though, is the combined result of physical, physiological and psychological processes [4].

Sole geometry and material properties affect sole deformation characteristics. The influence of longitudinal bending and torsion characteristics of sole structures on gait biomechanics and comfort has been demonstrated in [4-10]. In ordinary gait, reduced sole rigidity can favor comfort. Though testing equipment for bending and torsional characteristics of soles exists (e.g. CTC flexometer, TNO-IND/MPO Torsion Tester), modeling approaches to the study of these deformations are by far few and limited. A comfort related multi-aspect approach proposed by the Virtual Shoe Test Bed project [2] incorporated longitudinal bending and torsion simulation based on simplified differential and



analytical models. Current trends are moving away from analytical models towards iterative simulation techniques, such as Finite Element Analysis (FEA), well suited to multi-material structures with complex geometries, loading and boundary conditions. The OptShoes project [4] demonstrated the use of FEA for longitudinal bending and torsion simulation of multi-material sole structures, though subject to slow converge and simplifications for complex rotational analyses. In addition, multi-material optimization based on continuous functions could not converge in reasonable timescales. Optimization analyses often do not converge quickly enough or fail altogether unless improved algorithms reduce the amount of iterations required or overcome divergence problems.

In this work, three key issues are addressed utilizing the FEA software ANSYS. The first is the simulation of bending and torsional deformations of modern multi-layer sole structures, applying realistic boundary conditions. The second is the establishment of comfort levels relating objective mechanical measurements to subjective perceptions, thus providing practical comfort evaluation at design stage. The third issue is to optimize sole structures by defining optimum material arrangements for given layer thickness values and targeted comfort levels.

2. Bending and Torsion Simulation

Deformations of sole structures in gait, their relation to mechanical comfort and a review of relevant simulation studies were described in [3,4]. Longitudinal bending, at the push-off phase of gait applies to the rear of the metatarsophalangeal axis while the front section of the structure remains fixed. Longitudinal torsion takes place alternatively at the front and rear parts of the sole due to natural walking pronation and supination, with one end being fixed under loading and the other end conforming to foot motion. Clockwise and counter-clockwise deformations are observed due to left-right sole flare arrangements. For assessing rigidity, strain energy is preferred to forces or moments [6], since it is a true indicator of work required to make the structure conform to foot motion. Normalization of strain energy to volume allows for comparison of dissimilar structures and sizes. The actual flexibility of the sole is intrinsic property, not requiring the use of biomodels for simulation, and it depends solely on sole geometry, material arrangements and manufacturing assembly options.

Earlier work has proven the potential of FEA in sole bending and torsion simulation [4]. Accuracy and convergence depend on the accuracy of the underlying solid models, the type and properties of finite elements, the meshing density, the accuracy and modeling of material properties and the accuracy of initial and boundary conditions along with relevant assumptions and simplifications. In this work, a 3D, linear multi-material finite element sole model for quasi-static bending and torsion simulation at maximum deformation is described along with improved sets of boundary conditions.

2.1. Finite Element Model

The geometric model used is this of an asymmetric sole, with inbound flare, 290mm long and 140mm wide. Figure 1 illustrates the model created using 22 control points and spline curves. The structure was meshed using solid, type 185, structural elements, with 8-nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions. These elements have plasticity, stress stiffening, large deflection, and large strain capabilities and, therefore, are appropriate for highly deflective soles. Maximum element edge length along the thickness direction was set to 2mm.

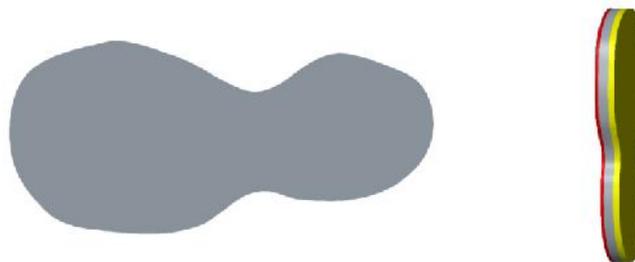


Figure 1. Sole structure layout (left) and pictorial view (right).

The model consists of 3 material layers. It is supported by material datasets (table 1) containing density, Young's modulus and Poisson's ratio values for common footwear materials. Linear properties have been assumed, in line with current practices in studies of foot biomechanics [11].

Table 1. Mechanical properties of footwear materials.

Material	Density (g/cm ³)	Young's Modulus (MPa)	Poisson's Ratio
Sole leather naturally tanned	0.900	300.00	0.20
Leatherboard	0.900	100.00	0.30
Cork	0.150	25.00	0.01
EVA	0.965	25.00	0.48
Double Density Polyurethane	0.920	8.00	0.30
Single Density Polyurethane	0.600	2.00	0.28
Polyurethane foam	0.028	0.60	0.26
Poly-isoprene & Natural rubber	0.920	2.00	0.49
Silicon elastomer	1.550	13.00	0.48
Poly-butadiene elastomer	1.140	5.00	0.49
Polychloroprene (neopren)	1.240	1.30	0.49
ABS	1.015	2000.00	0.40
PVC	1.400	3100.00	0.42
Wood	0.950	23000.00	0.37
Stainless Steel	7.800	200000.00	0.27

2.2. Initial and Boundary Conditions

For simplified modeling foot varus-valgus angles are kept to 0°. Maximum bending behind the metatarsophalangeal joints is of the order of 55°; this being the angle between the back end of the sole, the position of the joints and the ground. The position of the articulations is placed at 26% of foot length, measured from the end of the big toe towards the heel [12]. The lower side of the forefoot sector is, practically, fixed to the ground, whereas the higher side is compressed by the forefoot fully restricting translational and rotational movement of the sole at this region. On setting the system to these conditions, maximum principal stresses and the strain energy density are calculated.

Maximum torsional deformations occur due to the natural foot pronation and supination, early and late in the ground contact phase of gait and, therefore, they are simulated on both ends of the sole structure. Torsion simulation requires one end of the structure to be fixed while the other is held by a second torsional gripping element. Given that the forefoot and heel plantar areas do not differ significantly when compared to the whole plantar area of the foot, the 26% length rule used for fixing the forefoot in bending simulation may also conveniently and reasonably apply to the fixed and held parts of the sole in torsion simulation. Clockwise and counter-clockwise deformations on each end allow for right and left foot arrangements, sole flare and uneven ground. Since maximum ankle and foot joints mobility allow for composite rotation of the hind or forefoot up to 15° prior to the onset of discomfort, maximum angles of deformation are set on this value [4]. Strain energy density is calculated on setting the structure to these deformations.

2.3. Simulation results

Bending and torsion simulations for footwear materials in relation to sole thickness are illustrated in figure 2. Higher Young's modulus and increased thickness lead to higher rigidity as expected. Also, options for typical multi-layer and multi-material sole arrangements of the market have been investigated and the results are presented in table 2. The results correlate with expectations and working guidelines of the footwear industry.

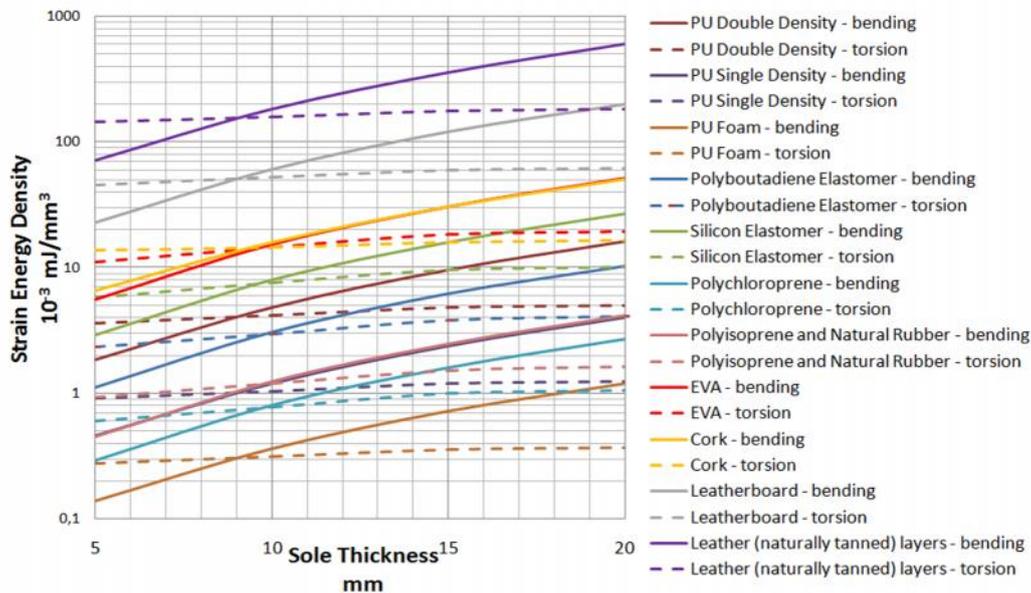


Figure 2. Strain Energy Density in relation to sole thickness and material.

Table 2. Strain Energy Density for bending and torsion of typical sole structures.

Sole design option	Strain Energy Density (10^{-3} mJ/mm ³)		
	Bending	Torsion (averaged values for clockwise and counterclockwise rotations)	
		Rear section fixed	Front section fixed
Leather outsole 8mm, EVA midsole 8mm	115.194	61.625	73.960
Polybutadiene outsole 10mm, EVA midsole 5mm	11.977	6.270	7.822
Polyisoprene or natural rubber outsole 10mm, EVA midsole 5mm	6.614	4.291	5.235
PU double density outsole 5mm, PU single density midsole 10mm, PU foam insole 5mm	4.422	1.487	1.812
Polybutadiene outsole 5mm, neopren midsole 10mm	2.835	1.443	1.721
PU single density sole 15mm	2.339	0.958	1.191

3. Determination of mechanical comfort levels

The results in figure 2 show clearly that increased Young's modulus and thickness lead to increased rigidity. It is also evident that there is clear distinction of strain energy density curves for typical materials used on the market. Industrial practice, dictates the use of certain materials over others to achieve desirable bending and 'twisting' characteristics that contribute to mechanical comfort level perception. These comfort levels can be objectively described by stratified strain energy density ranges. The results for bending and torsion simulation in Figure 2 can be allocated to five categories of comfort presented on table 3 and table 4 for bending and torsion respectively.

Table 3. Mechanical Comfort Levels for bending deformation of the sole.

Comfort Level	Strain Energy Density Range (10^{-3} mJ/mm ³)	Middle Point of Interval (10^{-3} mJ/mm ³)
Very Flexible	0 – 5	2.50
Relatively Flexible	5 – 15	10.00
Moderately flexible	15-200	107.50
Relatively Rigid	200 – 1000	600.00
Very Rigid	More than 1000	5000.00

Table 4. Mechanical Comfort Levels for torsional deformation of the sole.

Comfort Level	Strain Energy Density Range (10^{-3} mJ/mm ³)	Middle Point of Interval (10^{-3} mJ/mm ³)
Very twistable	0 – 1	0.50
Relatively twistable	1 – 5	2.50
Moderately twistable	5-20	12.50
Relatively difficult to twist	20 – 300	160.00
Very difficult to twist or rigid	More than 300	1000.00

4. Optimization

The mechanical comfort performance of prototypes can be objectively determined through strain energy density ranges depended on sole geometry and material properties. Geometry is, mainly, defined in early design stages and then becomes subject to costly restrictions (e.g. last type, assembly technologies), discouraging later changes. Thus, material selection with fixed geometry is highly likely. In this work, it is assumed that layer thickness values are predetermined and the problem becomes one of finding the best permutation of materials to achieve a targeted comfort level.

In optimization, a function of a property is either maximized or minimized. Algorithms exist for continuous or discrete problems; the most important being: screening, Lagrangian and multi-objective genetic algorithms. Optimization may not converge quickly enough or even fail altogether unless carefully selected algorithms either reduce the amount of iterations required or overcome divergence problems. Even then, it is not uncommon to simplify the finite element models, the material properties or the boundary conditions to facilitate convergence. In this work, linear material properties have been assumed and a sole structure optimization algorithm is proposed based on a discrete approach that is realistic for two reasons. First, material thickness values, which rarely, if ever, exceed 150mm, are set in line with practical manufacturing accuracy, which is of the order of 1mm. Second, the number of commercial footwear materials available for developing new footwear is limited. Thus, for defined topology, the comfort definition problem is not about calculating optimum values of Young's modulus and Poisson's ratio used as variables in a strain energy function, but rather one of finding the values of an existing material that best approximate the desired performance.

Comfort levels are strain energy density intervals. Values closer to the midpoints of the intervals are more desirable when a specific comfort level is targeted, whereas values near the endpoints are deviating significantly from desired performance. The highest categories of bending and torsional rigidity, practically, are not infinite; even when bending materials with very high Young's modulus, such as steel sheets and wood, strain energy density remains much lower than 10000 $\mu\text{J}/\text{mm}^3$.

Strain energy density sensitivity to thickness is higher for bending than for torsion (Figure 2). The clear demarcation of strain energy levels for bending makes optimization for a targeted strain energy density value and given layer thickness less susceptible to error than for torsion. Also, increases in bending rigidity positively correlate to increases in torsion rigidity. For reduced processing of overall bending and torsion behaviour, bending optimization may suffice and this view has been adopted here.

Given the limited number of material options the discrete algorithm proposed, is as follows. Let M_1 , M_2 and M_3 arrays for the material options for the first, second and third layer of the structure respectively and i , j and k the corresponding subscripts. Each material permutation can be noted as (i, j, k) with subscripts taking values to the maximum number of materials N_1 , N_2 and N_3 in each array. For each permutation (i, j, k) , the strain energy density for bending is calculated and stored to an array SED with general term $SED(i, j, k)$. A second array $SEDD$ stores the absolute difference of the terms $SED(i, j, k)$ from the targeted midpoint of comfort level of interest to the term $SEDD(i, j, k)$. The values of array $SEDD$ are then sorted. In this work, the three lowest distances are identified along with their corresponding material permutations, reasonably fast, typically between 32 and 34 minutes for problems involving 15x16x8 permutations of materials.

5. Conclusions and Discussion

Figure 2 demonstrates that increases in Young's modulus and thickness lead to higher rigidity as expected. Also, table 2 demonstrates correlation of simulation results to established design practices. Therefore, the developed finite element model for the simulation of bending and torsional deformations of modern multi-layer sole structures in gait, applying realistic boundary conditions, is deemed acceptable for product option comparisons. The use of stratified strain energy density ranges (tables 3 and 4) to establish comfort levels relates objective mechanical measurements to subjective perceptions, thus, providing practical comfort evaluation at design stage. For the optimization option of material selection with fixed geometry to achieve targeted comfort levels, the discrete algorithm identifies ranked solutions within realistic timescales for typical material inventories in industry.

Figure 2 and table 2 provide means of assessing prototypes against standard structures, thus inferring performance levels for the geometry and material selection design options. Since minor changes in strain energy levels might not be noticeable by consumers, product comparisons based on comfort level attributes instead seem to be an acceptable alternative. However, bending strain energy density perception needs to be investigated through psychological scaling of psychophysics experiments.

With regard to optimization, the proposed discrete approach, based on the strain energy density distance from targeted performance function, offers a viable alternative to existing continuous function algorithms. Improved sorting and selection algorithms, utilizing relational operators, may supplement the presented principles, when large numbers of material sets are involved.

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References

- [1] Keller T S, Weisberger A M, Ray J L, Hasan S S, Shiavi R G and Spengler D M 1996 *Clinical Biomechanics* **11**(5) 1253-59
- [2] Azariadis P, Moulitanitis V, Alemany S, Olaso J, Jong D P, Zande V D M and Brands D 2007 *CAD and Applications* **4**(6) 741-50 <http://dx.doi.org/10.1080/16864360.2007.10738507>
- [3] Papagiannis P, Koutkalaki Z and Azariadis P 2014 *5th Int. Conf. on Advanced Materials and Systems* Oct. 23-25 Bucharest pp 349-54
- [4] Papagiannis P, Koutkalaki Z, Azariadis P and Papanikos P 2015 *Computer-Aided Design and Applications* <http://dx.doi.org/10.1080/16864360.2015.1084189>
- [5] Cikajlo I and Matjačić Z 2007 *Ergonomics* **50**(12) 2171-82
- [6] Hillstrom H, Song J, Heilman B and Richards C 2005 *7th Int. Symp on Footwear Biomechanics*, July 27-29 Cleveland OH
- [7] Xiang L W and Feng Q 2013 *China Sport Science* **12**
- [8] Michel F I, Kälin X, Metzger A, Westphal K, Schweizer F, Campe S and Segesser B 2009 *Sportverletz Sportschaden* **23**(4) 197-205.
- [9] Morio C, Lake M J, Gueguen N, Rao G and Baly L 2009 *Journal of Biomechanics*, **42**, 2081-2088. <http://dx.doi.org/10.1016/j.jbiomech.2009.06.015>.
- [10] Segesser B, Stüssi E, Von A, Stacoff M, Kälin X and Ackermann R 1989 *Sportverletz Sportschaden* **3**(4) 167-82
- [11] Cheung J T and Zhang M 2005 *Arch. Phys. Med. Rehab.* **86**, 353-58, <http://dx.doi.org/10.1016/j.apmr.2004.03.031>.
- [12] Xiong S, Rodrigo A S and Goonetilleke R S 2013 *Foot Characteristics and Related Empirical Models The Science of Footwear* ed. R S Goonetilleke (Boca Raton: CRC Press) p48