Impact of pattern lines and technological features on the behaviour of vamp-over-quarter footwear type

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ARINA SEUL
MARIANA COSTEA
AURA MIHAI
RALUCA LUPU
ADRIANA CHIRILĂ
MANUELA-LACRAMIOARA AVĂDANEI
ANTONELA CURTEZA

ABSTRACT – REZUMAT

Impact of pattern lines and technological features on the behaviour of vamp-over-quarter footwear type

This article aims to demonstrate how the positioning of the seam line between the vamp and quarter and the number of stitches affect the joint strength and overall performance of the product during walking. The configuration of analysis conditions and constraints was conducted using ANSYSTM. The gait biomechanics were considered to establish the load model, including the distribution of forces, their magnitudes, and constraints. The analysis focused on the three phases of gait: heel strike, mid-stance, and push-off, evaluating three key parameters: directional displacement, Von Mises stress, and elastic deformation. The study emphasises how directional displacement, stress distribution, and elastic deformation change based on the gait phase and the materials used in the construction of the selected footwear type. Using a two-stitch seam to join the components promotes directional displacements and reduces stress/tension compared to a single-stitch seam. Positioning the seam line between the vamp and quarters along the toe line increases stress/tension in the front section of the shoe. The analysis was validated by comparing simulation results with average plantar pressures obtained from a biomechanical assessment of plantar pressure distribution.

Keywords: *gait biomechanics, directional displacement, von mises stress, elastic deformation, plantar pressure distribution*

Impactul liniilor de model și al caracteristicilor tehnologice asupra comportamentului încălțămintei de tip căpută peste carâmb

Acest articol își propune să demonstreze modul în care poziționarea liniei de cusătură dintre căpută și carâmb, împreună cu numărul de tigheluri, afectează rezistența îmbinării și performanța generală a produsului în timpul mersului. Configurarea condițiilor de analiză, precum și a constrângerilor a fost realizată utilizând ANSYSTM. Biomecanica mersului a fost luată în considerare pentru a stabili modelul de încărcare, inclusiv distribuția forțelor, magnitudinea acestora și constrângerile. Analiza s-a concentrat pe cele trei faze ale mersului: impact, reazem și propulsie, evaluând trei parametri cheie: deplasarea direcțională, tensiunea Von Mises și deformarea elastică. Studiul subliniază modul în care deplasarea direcțională, distribuția tensiunii și deformarea elastică se modifică în funcție de faza mersului și de materialele utilizate în construcția tipului de încălțăminte selectat. Utilizarea unui tighel dublu pentru a îmbina reperele, favorizează deplasările direcționale și reduce tensiunea în comparație cu un singur tighel. Poziționarea liniei de cusătură între căpută și carâmbi de-a lungul liniei degetelor crește tensiunea în zona anterioară a încălțămintei. Analiza a fost validată prin compararea rezultatelor simulării cu cele ale presiunilor plantare medii obținute din evaluarea biomecanică a mersului.

Cuvinte-cheie*: biomecanica mersului, deplasare direcțională, tensiune von mises, deformare elastică, distribuția presiunii plantare*

INTRODUCTION

The constructive type of footwear, vamp-over-quarter, called Oxford, involves seaming the entire length of the anterior contour of the quarter. This ensures a more uniform stretching during space forming in both longitudinal and transversal directions, and the displacement of the pieces in the longitudinal direction is smaller than in the case of the quarter-over-vamp construction. Taking into account the deformability of the prefabricated in spatial forming, the opening point of the cap should be displaced towards the instep. The joint area between the toe cap and the quarters is subject to high stresses during walking. For this reason, it is recommended to add a reinforcing notch to increase the strength of the joint in the area of repeated bending [1–3].

Finite element modelling has emerged as a powerful tool for gaining a deeper understanding of foot and footwear biomechanics, as well as for optimising footwear designs. In recent years, several researchers have identified key challenges and research gaps that must be addressed to develop more realistic and precise models for both clinical and industrial purposes [4]. While most existing foot-shoe FE analyses have been conducted with certain simplifications and assumptions, they have significantly contributed to understanding the mechanical behaviour of the foot in both casual and athletic footwear. However, further simulations continue to face multiple obstacles, including obtaining reliable data for geometric reconstruction, balancing detailed accuracy with computational efficiency, accurately representing material properties, applying realistic boundary and loading conditions, and ensuring comprehensive model validation [5–8]. Given the current research gaps in areas related to footwear design, the authors of this study have aimed to validate the FE model both internally and externally.

Biomechanical assessments of how footwear characteristics affect foot parameters and the interaction between the foot and shoe can be valuable for preventing injuries and optimising footwear design [9, 10]. Laboratory-based methods like 3D motion capture analysis and in-shoe plantar pressure monitoring can provide useful insights. However, due to technological limitations, precise mechanical changes, such as the distribution of internal stress and strain within foot structures and joint contact pressures, remain unmeasurable. In response to this challenge, researchers have increasingly turned to computational approaches, such as finite element (FE) analysis, for more detailed investigations. FE analysis allows for the modelling of complex geometries, varied material properties, and intricate boundary and loading conditions [11–13].

METHODOLOGY

To evaluate how the line position and the number of stitches influence the gait behaviour of the footwear, a classic vamp-over-quarter type of footwear was chosen, whose upper assembly includes the following components: vamp, quarters, tongue and counter.

The shoe was modelled in the DELCAMTM Shoe Maker application, using the last designed based on the average representative foot specific to the group of subjects analysed in a previous anthropometric study undertaken by the authors [14].

To obtain the virtual model, the following steps were performed:

- import the last previously obtained;
- drawing the baselines, checking the position of the toe line (point C), determining the height of the quarter at the back, drawing the upper line of the quarter, marking the point of the instep and drawing the auxiliary line of the instep;
- drawing the pattern lines according to the rules for the design of Oxford-type shoes;
- creating the components (vamp, tongue, quarters, counter), adding the details (stitching, laces) and the sole.

Three variations of the Oxford shoe were designed by changing the position of the separation line between the upper and the toe: the topline positioned on the toe line; the line of the vamp positioned 10 mm towards the tip; the vamp line positioned at 10 mm towards the instep (figure 1).

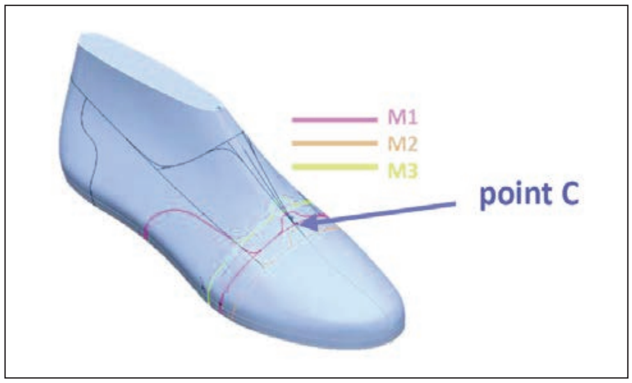


Fig. 1. Variations of the Oxford shoe

For each model, two other model variants were developed, with one and two stitches. The width of the overlap area between the vamp and the quarters and the quarters and the counter is 8 mm. The distance between the eyelets is 8 mm. To recognise the geometrical elements and perform the finite element analysis, each geometrical feature was processed individually using the tools provided by the Space Claim program integrated in the ***ANSYSTM*** suite. The foot was reconstructed based on the imported last in *.stl format. The upper set imported in *.iges format and opened in the Space Claim application is presented as a set of surfaces. Each part consists of four surfaces. To avoid errors during simulation and to simplify the model, surfaces that do not influence the structure of the upper assembly have been removed. The remaining surfaces were assigned a thickness of 2 mm. The original model was provided with laces, but it was decided to remove them because of the errors that can be introduced by them. The sole, the structure of which the insole is integrated, also imported in *.iges format, was transformed into a solid using the tools in the Repair menu.

The whole foot and sole assembly has been positioned on a parallelepiped support built directly in the Space Claim application.

The result of this step is a highly accurate model consisting of three solids – simplified foot, sole and support, and a group of surfaces, representing the component parts of the upper assembly (figure 2).

Determining the properties of materials

The values for the Young's modulus and Poisson's ratio specific for the foot, upper assembly (overlap zone, lacing zone), bottom assembly and support are given in table 1.

In the case of the foot, a basic structure has been chosen, for which the properties of the muscular and skeletal system, cartilages and joints are neglected. For the characterisation of the sole, a material with properties and characteristics specific to rubber was chosen [15, 16]. Textile materials play a crucial role in footwear, serving as key components in uppers, linings,

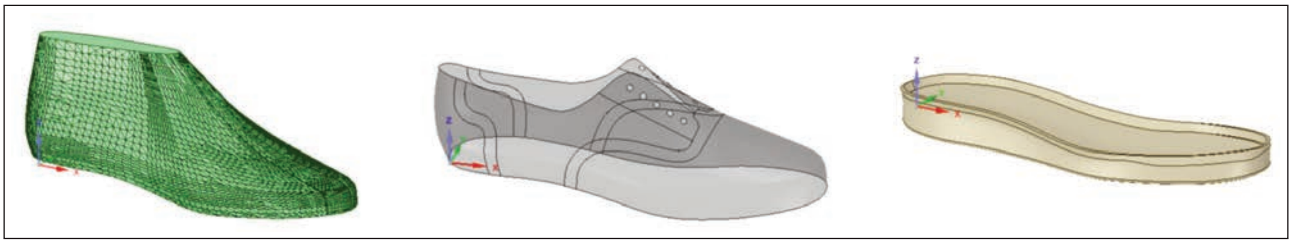


Fig. 2. Editing and preparing 3D components for simulation

Table 1

PROPERTIES OF THE MATERIALS USED IN THE ANALYSIS			
	Young's modulus (MPa)	Poisson's ratio	Thickness (mm)
Foot	4.47	0.45	-
Knitted + cowhide lining (uppers)	55.9	1.10	1.9
Knitted + cowhide lining, 8 mm overlap, single stitch (uppers)	11.2	1.01	2.4
Knitted + cowhide lining, 8 mm overlap, double stitch (uppers)	14.5	1.00	2.4
Knitted + cowhide lining, perforation spacing of 8 mm, with staples (uppers)	55.9	0.46	1.9
Rubber (sole)	1000	0.42	-
Concrete (support)	90000	0.18	-

and insoles. They offer breathability, flexibility, and comfort while incorporating advanced options such as mesh, canvas, and engineered fabrics to optimise performance and aesthetics [17]. Their lightweight and sustainable nature further enhances functionality and design versatility [18–20], making them indispensable in modern footwear engineering. In contemporary footwear production, the integration of textile materials with leather has become increasingly prevalent. This study focuses on a simplified model combining knitted material with cowhide leather for analysis and evaluation. The upper assembly was defined as bovine leather on the outside and Belgian overknit on the inside. The overlap areas joined by stitching and the lacing areas with perforations were described according to the data obtained from the study of the mechanical behaviour of the materials. The entire shoe-foot assembly stands on a concrete support.

Setting up the analysis conditions. Making connections and setting model loading conditions

The behaviour of the three model variants was analysed in the Static Structural module. To perform the finite element analysis, each geometric entity was assigned materials with properties defined in the previous step. Model discretisation was performed using the The traedrons method. The line grid was created using a coarse finite element size and with an average adjustment of the node positions, resulting in a grid with 133214 nodes and 78408 elements (figure 3). A direct connection was created between all elements with a tolerance of 0.91 mm.

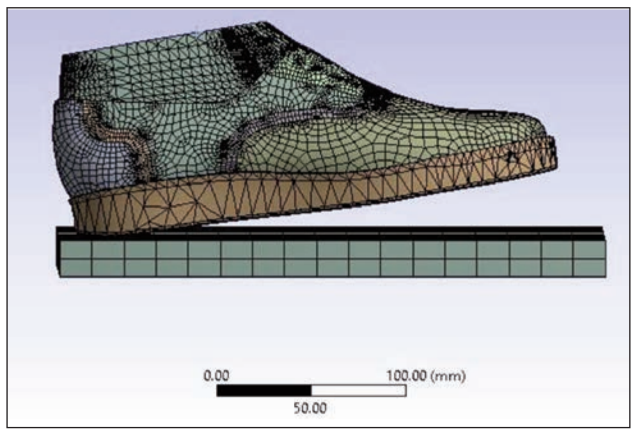


Fig. 3. Defining a line grid on the surface of the 3D model (mesh)

To define the loading model, the distribution of forces and their values, the restrictions imposed by gait biomechanics were taken into account.

Three gait phases were analysed: heel strike, mid-stance and push-off. In the mid-stance phase, the foot is in contact with the ground plane over the entire plantar surface. In the heel strike and push-off phases, the foot touches the ground plane partially and is inclined to the ground plane by –7 and 7 degrees, respectively (figure 4).

It was considered that in the heel strike and push-off phases, the body acts with a force equal to 1.2*G. Taking into account that the average body mass specific to the group of subjects obtained from the biomechanical study conducted by the authors [14] is 52 kg, a force of 612 N was applied. Since the

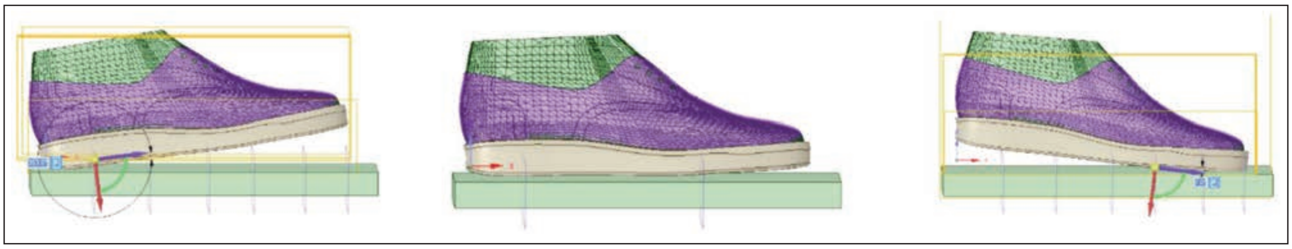


Fig. 4. Representation of foot positions in heel strike, support and push-off phases

analysis is performed on one leg, the distributed weight is equal to G/2, i.e. the applied force is 255 N. The forces were applied to the dorsal surface of the foot in a vertical downward direction. Displacement of the footwear-foot assembly was allowed in the Z-direction, while the support was considered fixed. The analysis time was limited to one second.

Configuring analysis parameters

Directional deformation of Z-directional component, stress distribution, and elastic deformation were evaluated to examine the behaviour of three previously modelled variants. The changes occurring in the footwear during the three gait phases for one second under the influence of the weight force were recorded and analysed.

The directional deflection highlights the displacements of the model under the influence of the determined forces. The Von Mises stresses help to determine the efficiency of the materials under analysis and the distribution of pressures in them, while the elastic deformation is intended to define the limit to which the model returns to its original shape after load removal.

RESULTS

Solving the finite element model. Analysis results

Once the displacements and directional deformations have been calculated, the application displays the values of the tensions and moments acting on the footwear due to the interaction with the foot and the support surface.

The results for the directional deformation field, stress field distribution and elastic deformation obtained from the analysis were centralised, 54 representations being obtained. The authors have selected 3 relevant examples for the propulsion phase and presented them in figure 5.

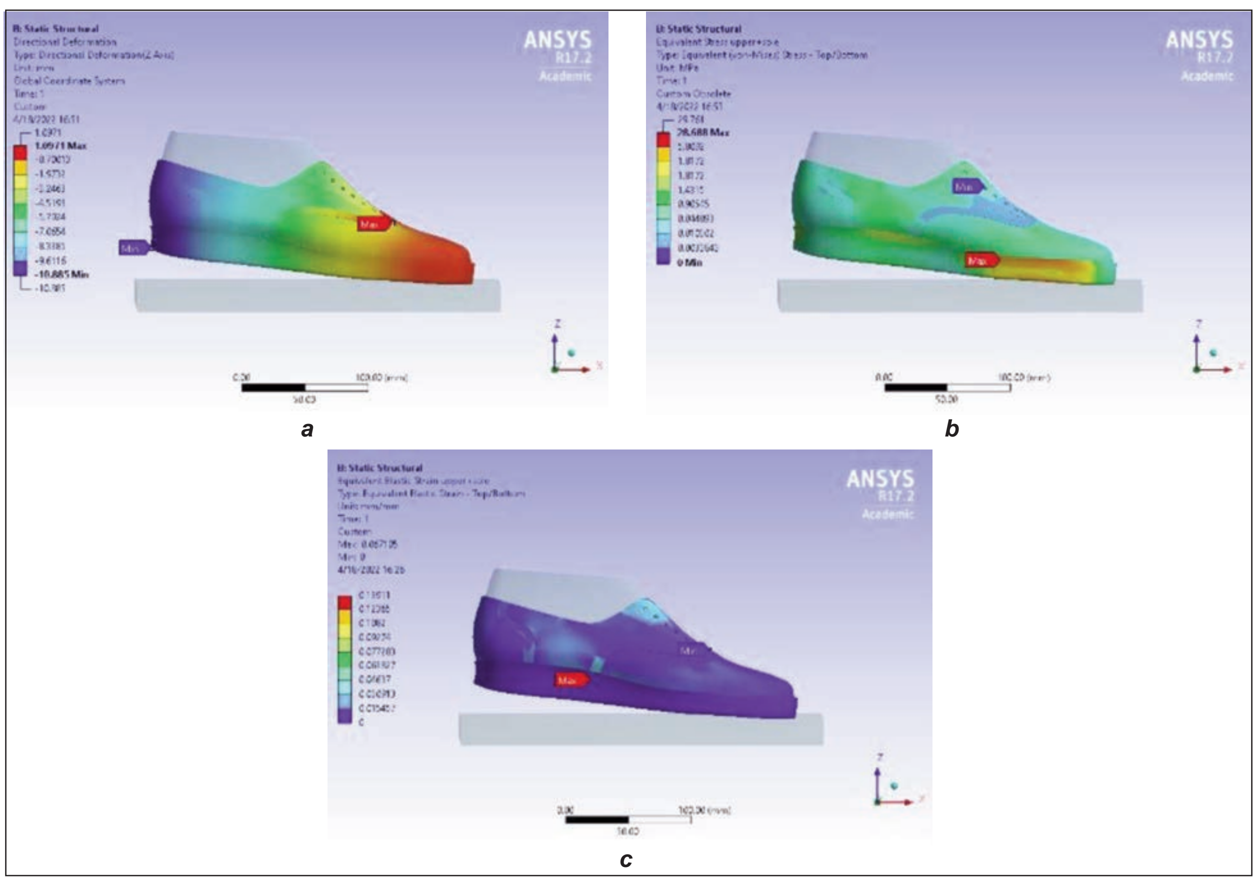


Fig. 5. Representation of: *a* – the directional deformation field; *b* – stress field distribution; *c* – elastic deformation obtained in propulsion phase

The recorded values are accompanied by images containing a set of colours ranging from blue (low values) to red (high values). This colour coding, accompanied by the numerical values obtained, highlights areas of high pressure and deformation in the patterns, which affect both the footwear and the foot during gait.
The analysis parameter with Z-axis directional deformation has the highest values in the push-off and heel strike phases, when the foot is subjected to significant forces. This distribution is similar for all models analysed.
The chromaticity maps suggest that the maximum deformation values in the Z-direction for all models are found in the upper assembly, and their distribution varies with the phase of walking. In the heel strike phase, the deformations are higher in the heel area (quarter and counter) and decrease in the vamp area. The overlap area between the vamp and the quarters shows an average deformation for all the model variants analysed. In the mid-stance phase, according to the colour maps, the magnitude of the deformation is smaller and its distribution on the shoe surface is more uniform. In the push-off phase, when the efforts are transferred to the toe area, both the vamp and the overlap between the vamp and the quarters are exposed to larger deformations.
Figure 6 graphically shows the maximum values of the directional deformation fields, Von Mises equivalent efforts and elastic deformations for the three model variants in each gait phase.
In the heel strike phase, the differences from one model to another are larger, and the maximum deformation in the Z-axis direction is shown by model M2 (0.2858, 0.2697 mm), followed by M1 (0.2460, 0.2321 mm) and M3 (0.2210, 0.2210 mm). In the support phase, the maximum value is the model M3 (0.0195, 0.0193 mm), followed by M2 (0.0194, 0.0193 mm) and M1 (0.0193, 0.0192 mm), the differences between the values being almost insignificant. The maximum value in the push-off phase is M2 (1.0971, 1.0764 mm), followed by M1 (0.4541, 0.4548 mm) and M3 (0.3493, 0.3496 mm), respectively. The versions of the model joined by a double stitch show less deformation compared to the single stitch pattern versions.
Analysis of the stress field reveals that higher pressures occur in the footwear product in the push-off phase (29.761, 29.759, 28.688, 28.684, 28.528, 28.525 MPa), followed by the heel strike phase, with a reduction of about 80% (5.974, 5.951, 6.559, 6.538, 5.475, 5.461 MPa), and the support phase, respectively, with a 94% decrease compared to the push-off phase (1.903, 1.902, 2.028, 2.029, 2.251, 2.249 MPa). Such a distribution is due to the high deformation of the footwear occurring in the area of repeated bending in the metatarsophalangeal joint of the foot in the push-off phase, respectively, a more uniform distribution in the mid-stance phase, a situation

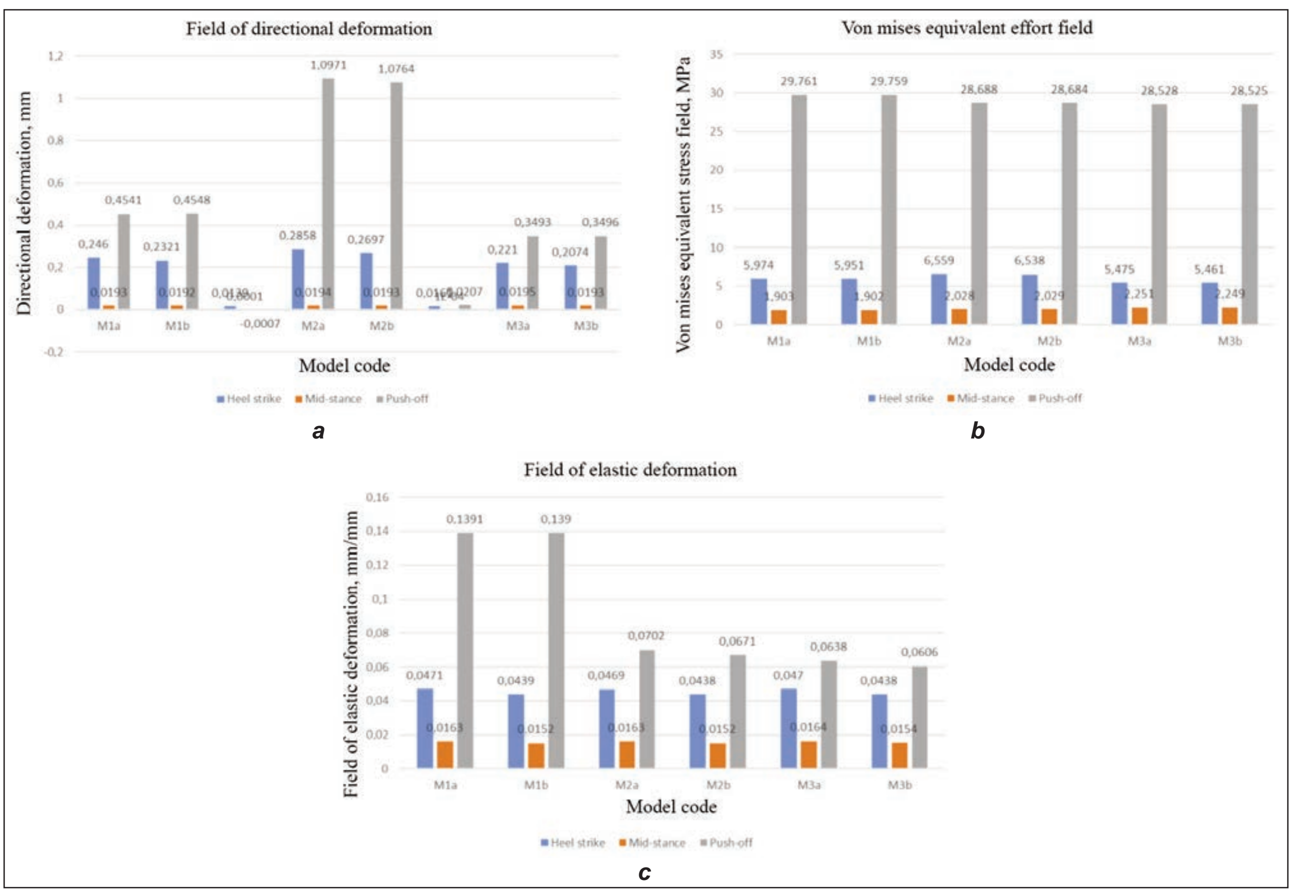


Fig. 6. Representation of: *a* – Z-axis directional deformation field for the vamp-over-quarter footwear; *b* – Von Mises equivalent force field for the vamp-over-quarter footwear; *c* – elastic deformation field for the vamp-over-quarter footwear

confirmed in the literature [19]. Analysing this parameter from the perspective of each model, higher values are observed for M1 in the push-off phase. This highlights that the positioning of the sectional line between the vamp and the quarter on the toe line leads to an increase in the pressures in the anterior area of the shoe. M2 and M3 show Von Mises stress values about 4% lower compared to M1.

The distribution of the elastic deformation varies in different areas depending on the phases of walking, model lines and technological particularities (in this case, the number of stitches). Maximum elastic deformation occurs in the push-off phase. In the heel strike and mid-stance phases, the values of this parameter decrease by about 66% and 88%, respectively. Similar to the distribution of values for the stress field parameter, also in the case of elastic deformation higher values occur in the M1 model (0.1391, 0.1390, 0.0163, 0. 0152, 0.0471, 0.0439 mm/mm), followed by model M2 (0.0702, 0.0671, 0.0163, 0.0152, 0.0469, 0.0438 mm/mm) and model M3 (0.0638, 0.0606, 0.0164, 0.0154, 0.047, 0.0438 mm/mm). Analysis of the chromaticity maps shows that the values of elastic deformation are very low in the joint area between the vamp and the quarter. Seam with two stitches leads to a decrease of about 5% of the elastic deformation compared to one stitch.

Validation of the load model

The validation of this analysis was carried out according to the methodology presented in a previous study [21], comparing the simulation values with the representative average plantar pressures obtained from the biomechanical study [22].

The maximum plantar surface pressure values and corresponding images for each zone are centralised in table 2.

By graphically showing the values in figure 7, a distribution model of the simulated maximum pressure values can be observed, which is very similar to the distribution of the experimentally obtained values.

The graphical representation of the values (figure 7) highlights that the results obtained to validate the data corresponding to the loading model (M2 being selected for this study) follow the same trend of plantar pressure distribution. Very close values were obtained in the case of First metatarsal (Z3), Second Metatarsal (Z4), Fourth Metatarsal (Z6), Lateral Heel (Z10). In the cases of First Toe (Z1), Third Metatarsal (Z5) and Fifth Metatarsal (Z6), the values obtained by simulation present larger differences compared to the experimental values. The registration of such differences is explained by the simplicity of the loading model, certain forces being ignored, as well as by the use of a simplified foot shape.

CONCLUSIONS

The objective of this study was to analyse how the model lines and the technological characteristics influence the behaviour of the Oxford-type shoe by simulating the biomechanical conditions of normal gait.

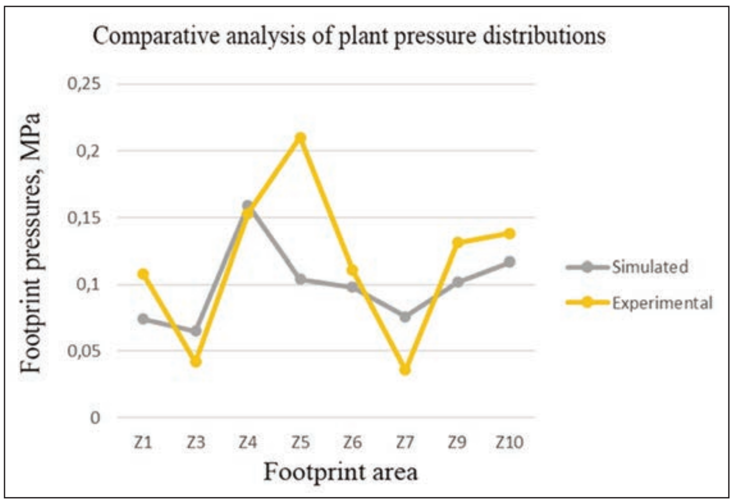
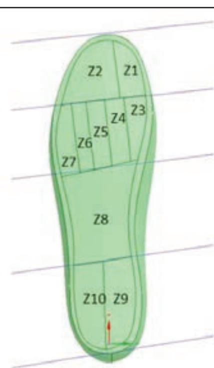


Fig. 7. Comparative analysis of simulated and experimental plantar pressure distributions

Table 2

SIMULATED AND EXPERIMENTAL MAXIMUM PLANTAR PRESSURES			
Area		**Plantar pressures (MPa)**	
		Simulated	**Experimental**
Z1 – First Toe		0.074	0.108
Z3 – First metatarsal		0.065	0.042
Z4 – Second Metatarsal		0.159	0.153
Z5 – Third Metatarsal		0.104	0.210
Z6 – Fourth Metatarsal		0.098	0.111
Z7 – Fifth Metatarsal		0.076	0.036
Z9 – Medial Heel		0.102	0.131
Z10 – Lateral Heel		0.117	0.138

The position of the sectioning line between the vamp and the quarters and the number of stitches that form the seam joint were chosen as the variables.

The footwear models were designed using the DELCAMTM Shoe Maker 3D application according to the specific design rules for the vamp-over-quarter construction. The simplified foot model was reconstructed using a last derived through modelling, based on the average dimensions of a representative sample from the subject group.

Using ***ANSYSTM,*** the material definition, 3D model editing for import into the simulation application, analysis conditions and constraints configuration were performed.

The gait biomechanics were taken into account to define the loading model, the distribution of forces, their values and constraints. The analysis considered the three phases of gait: heel strike, mid-stance and push-off, evaluating three analysis parameters, namely directional deformation, Von Mises forces and elastic deformation.

The study highlights how the directional deformation, the stress field and the elastic deformation vary depending on the gait phase and the types of materials used in the structure of the sports footwear. Joining the components with a two-stitch seam favours directional deformations and lower stresses/tensions compared to a single-stitch seam.

The positioning of the section line between the vamp and the quarters on the toe line leads to an increase in stresses/tensions in the anterior area of the shoe. Positioning the section line between the vamp and the quarter on the toe line leads to an increase in the efforts in the forefoot area. Shifting the line 10 mm towards the toe or instep results in a decrease in effort of approximately 4% compared to a shoe model with the section line between the vamp and the quarter positioned on the toe line.

The analysis was validated by comparing the simulation values with representative mean plantar pressures obtained from the biomechanical study of plantar pressure distribution.

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Authors:

ARINA SEUL, MARIANA COSTEA, AURA MIHAI, RALUCA LUPU, ADRIANA CHIRILĂ,
MANUELA-LACRAMIOARA AVADANEI, ANTONELA CURTEZA

”Gheorghe Asachi” Technical University of Iasi-Romania, Faculty of Industrial Design and Business Management,
29 Prof. D. Mangeron Blvd., 700050, Iasi, Romania

Corresponding author:

MARIANA COSTEA
e-mail: mariana.costea@academic.tuiasi.ro