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Study of Customized Plastic High Heels Footwear

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Abstract: *The high heels footwear industry is permantly evolving due to the increasing attention given to combine confort and elegance. The purpose of footwear has changed with the evolution in the fashion industry and it is no longer limited only to protect the feet. This paper represents a first step to develop customized shoes outer sole, taking into consideration the unicity of each individual anatomy. Another important aspect is the manufacturing of these outer soles using plastic materials. The additive manufacturing presents itself as a viable option in obtaing a working prototype. Based on previous research, an analysis has been performed in order to optimise the design and its functionality. The study validation has been done using FEA and Topology Opimisation.*

Keywords*: shoe outer sole, plastic materials, FEA, shape optimisation*

1. Introduction

High heels footwear as the name suggests is a type of footwear in which the heels are maintained at a higher position than the toes. These footwears are not just comfortable and fashionable but also makes the wearer appear taller. However, continuous usage of high heels footwear can lead to injury and pain. The market for high heels footwear is expected to increase during the forecast period because of changing lifestyles and rise in disposable income [1, 2].

The footwear industry developed as the society evolved. Across time, shoes had different purposes like a symbol of elegance for women, horse-riding for men, hide different defects, ranking in society. Until the 19th century, there were no difference between the design for right and left shoe.

A variety of high heel types have been developed over time, like wedge platform, block heel, stacked heel, conic heel, stiletto heel, kitten heel, continental heel and cuban heel (Figure 1). In the 90s, the most popular footwear outer sole was the wedge heels. This type has withstood the test of time, by maintaining a top position in customers preferences. The wedge platform, known also as orthopedic heel, is the most comfortable due to its specific structure, which gives more support to the foot paw.

This study focuses on finding the suitable heel heigh for a certain individual. This can be achieved by taking into account the anatomic parameters that describe a walking cycle. There are eight type of forces that act in a human body: body weight, soil reaction, joint reaction force, muscle strength, intra-abdominal pressure, fluid resistance, elastic force and force of inertia. The ratio between the vectors of these forces ensures the stability, balance, and correct, physiological movement of the human body [3, 4]. The center of gravity depends on the position of the body segments and can sometimes protrude from the body contour (Table 1). In motion, the body mass is redistributed, causing the center of gravity to change position. Its identification is possible through a process called "segmental analysis" in which the center of gravity for each segment of the body is assessed. Subsequently, based on this method, the center of gravity of the whole body is determined [3].

For this study, the wedge platform was chosen due its popularity.

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Figure 1. Type of high heels: a) wedge platform; b) block heel; c) stacked heel; d) conic heel; e) stiletto heel; f) kitten heel; g) continental heel; h) cuban heel

Table 1. Localisation of center of gravity (CG) [3]

Segment	Center of Gravity (N)	Localization of CG in the total length of the segment, starting from its proximal end (%)
Head	0.032 * body total weight + 18.70	66.3
Torso	0.532 * body total weight+ 6.93	52.2
Arm	0.022 * body total weight + 4.73	50.7
Forearm	0.013 * body total weight + 2.41	41.7
Hand	0.005 * body total weight + 0.75	51.5
Thigh	0.127 * body total weight + 14.82	39.8
Shank	0.044 * body total weight + 1.75	41.3
Leg	0.009 * body total weight + 2.48	40

A gait cycle has two main phases: support and swing. The support phase represents 60% of the gait cycle. A gait cycle is comprised of the following stages (Figure 2):

1) Loading response - initial contact (heel strike);
2) Mid-stance- includes flat foot;
3) Pre-swing phase - includes toe off;
4) Swing phase - includes initial, mid and terminal stage.

Related to the gait cycle, the soil reaction is an important parameter. It appears in response to the force of gravity according to the principle of action and reaction. Walking (or running) speed causes changes in the action of body segments, reflected by the soil reaction. For example, if the speed is increased from 3 to 5 m/s, the standing support time decreases (on average) from 270 to 190 m/s, and the peak reaction force increases from 2.51 * body weight to 2.83 * body weight. Thus, while walking or running, the soil reaction appears in the support phase of the foot on the ground and has a higher value than the body weight at the beginning of this phase. The point of application of the resultant of the reaction forces of the soil is called the "center of pressure"[5].

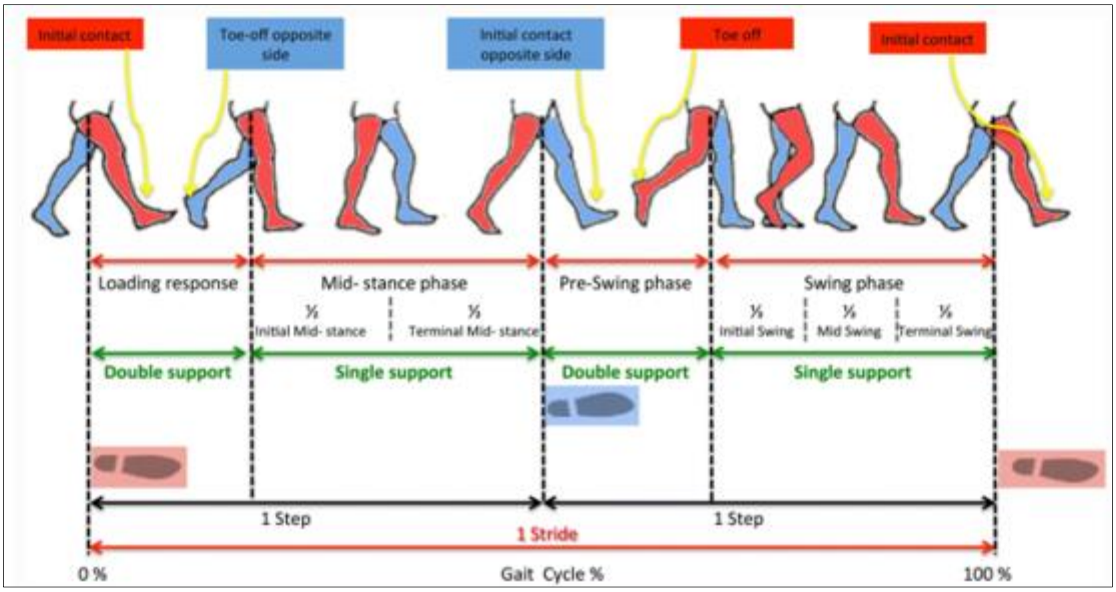

Figure 2. Gait cycle phases [6]

Each type of high heel footwear influences the center of gravity and the center of pressure, by producing visible changes in a gait cycle. The footwear sole of a person wearing high heels withstands a load increased with 15% of its body weight. Maintaining the normal balance when wearing high heels footwear, puts an additional pressure on the body. Complications, like muscle overloading, joint wear, back and leg pain, are frequently reported.

This paper aims to analyze the gait cycle wearing footwear with no heels, wedge platform and block heels. The results obtained led to a design optimization for wedge platform, which was analyzed with a FEA software. The last step of this study was the use of generative shape design to obtain the suitable internal structure of the wedge platform.

2. Influence of heels height on gait cycle

The study was made using Kinovea software, considering three situations: walking on a flat surface, walking on a surface tilt at 8° and climbing stairs. Three types of shoes were used (illustrated in Figure 3): no heels, wedge platform with 6.5 cm height and block heels with 9 cm height. The analysis was done for each gait cycle phase and consists in measuring the angle between leg and foot at ankle level.

a b c

Figure 3. Types of shoes: a) no heels; b) wedge platform with 6.5 cm height; c) block heels with 9 cm height

The minimum and maximum angle values for walking on a flat surface is illustrated in Figure 4a and b, for walking on tilt surface in Figure 4c and d, and for climbing stairs in Figure 4e and f. In the cases of flat and tilt surface, the minimum angles values were recorded in the terminal mid-stance phase of the gait cycle. For climbing the stairs, the minimum angle value was recorded in the initial mid-stance phase. The maximum angles values for flat and tilt surface were recorded in loading response stage. And the ones for climbing the stairs were recorded in pre-swing phase. All recorded data are centralized in Table 3.

In Figure 4g, h and i, the angle variation for walking one meter is illustrated for all types of surfaces and heels. In all cases the higher values are registered for the block heels. This can be related to other studies, where a plausible explication can be the fact that decreasing the contact surface between the sole and ground can lead to a higher pressure. Increasing the heel height can expand the support phase and contract the swing phase [7].

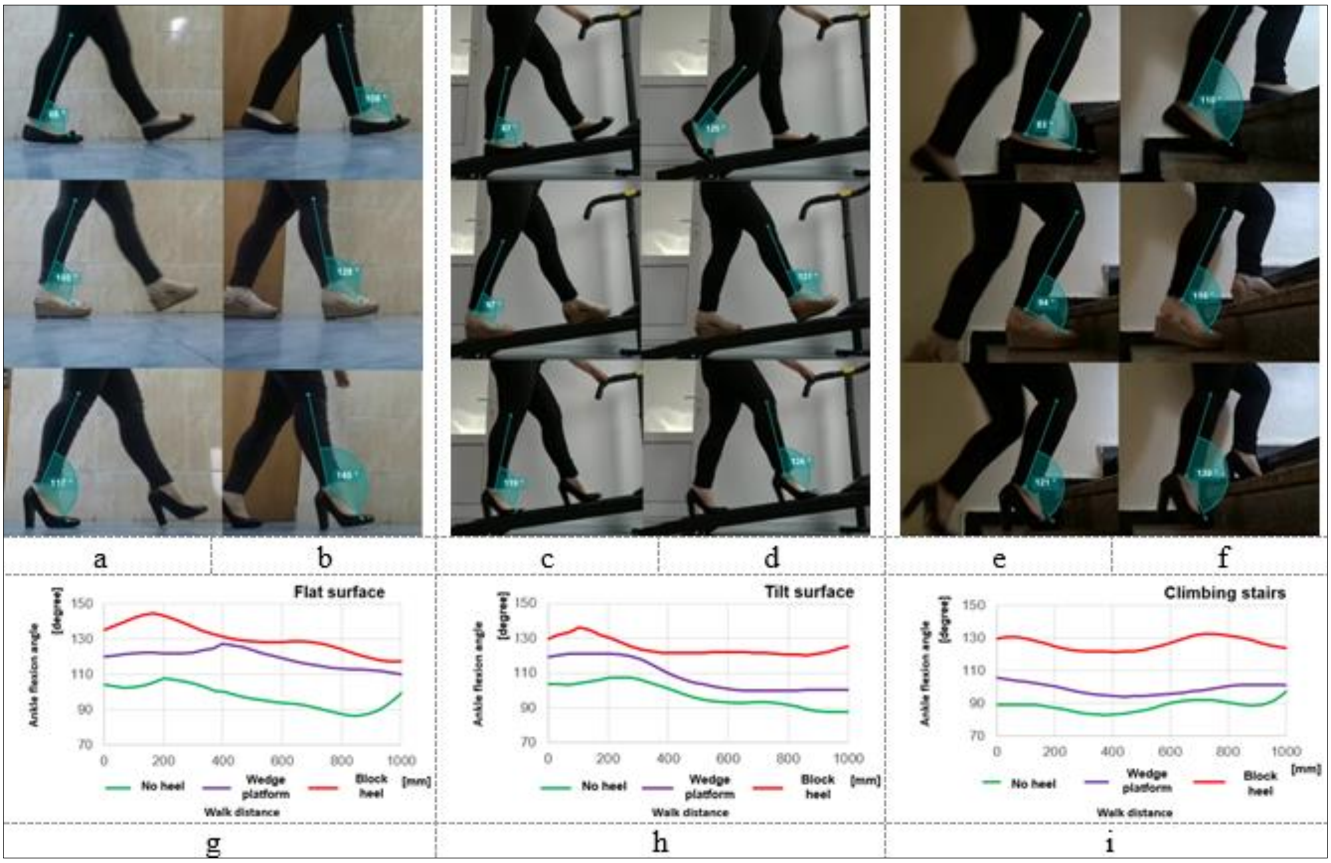

Figure 4. a) Minimum angle - flat surface; b) Maximum angle - flat surface; c) Minimum angle - tilt surface; d) Maximum angle - tilt surface; e) Minimum angle - ascending stairs; f) Maximum angle - ascending stairs; g) Angle variation for a gait cycle - flat surface; h) Angle variation for a gait cycle - tilt surface; i) Angle variation for a gait cycle - ascending stairs

Table 2. Ankle joint angle

	Flat surface			Tilt surface			Climbing stairs		
type of heels	no	platform	block	no	platform	block	no	platform	block
minimum angle	86^0	105^0	117^0	87^0	97^0	119^0	83^0	94^0	121^0
maximum angle	108^0	128^0	145^0	120^0	121^0	136^0	110^0	115^0	139^0

To relieve the leg and foot pain, the angle at ankle level must have minimal reference value. In the next part of this article a design of wedge platform was optimized to maximize comfort. In literature can be found methods to calculate the suitable value of the heel height in function of individual anatomical parameters [8].

One method is to consider the ratio between the foot length and number 7 (Figure 5a). The second method (Figure 5b) is determined using the following calculus formula:

$$h_h = \left(\frac{h}{l} - 1.61\right) * 10 \quad (1)$$

where: h_h - heel height; h-individual height; l- leg length. The third method consists in measuring the distance between the heel end and foot mount (Figure 5c) [7].

As a study case, was chosen a person with a height of 1.48m and a leg length of 0.65m. Applying the three methods, described above, the determined values are as it follows: 3.21cm, 6.67 cm and 9.5 cm. For the next step of this study, the wedge platform was chosen due to its larger contact surface with the ground. Therefore, the pressure felt on the sole is lower (both in the contact phase of the heel and in the support phase on the sole). Based on applying the three methods described above, it was chosen for a wedge platform footwear, a heel height of 8 cm (the approximate average between the values obtained by methods 2 and 3), and a height of 4.5 cm for the front side of the sole (this foot inclination is in optimal parameters for daily wear). This choice should prevent the occurrence of significant changes in the angle corresponding to the ankle (aspect confirmed in the experimental analysis of the platform heel made in Kinovea).

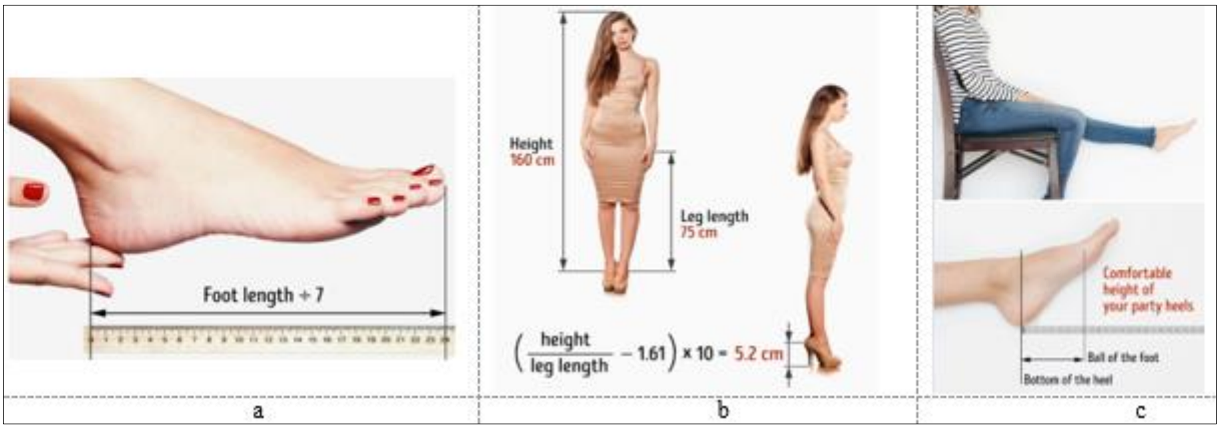

Figure 5. Methods to calculate individual high heels height

3. Wedge platform design and FEA analysis

The 3D model of the wedge platform was obtained using Autodesk Fusion 360 software (Figure 6) and imported in Ansys software for FEA analysis and topology optimization.

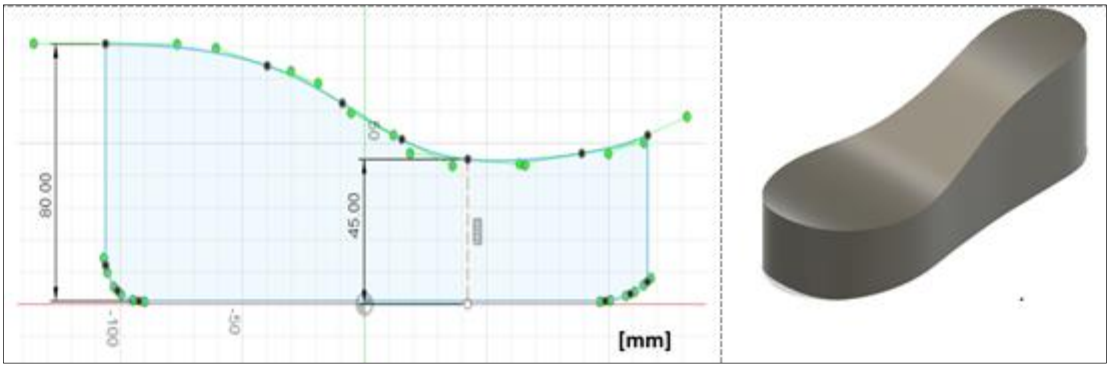

Figure 6. Wedge platform design: a) sketch; b) 3D model

For the FEA analysis, the force distribution was applied on the sole. The employed data was retrieved from a study performed by Albon [9]. In this study [9], ten force sensing resistors were sewed on the base of a nylon sock, which was worn inside different shoes of various heel heights. The force exerted on different areas of the foot, was measured while standing. The heel height did not consider any extra sole beneath the toe.

For the analysis, the sum of forces considered is equivalent for a person of 65 kg. This value was obtained by multiplying the values of the forces registered for a high heel of 8 cm (Figure 7a) in [9].

These forces were applied on the upper surface of the sole. This was divided to correspond with the position of the sensors from [9] (Figure 7b).

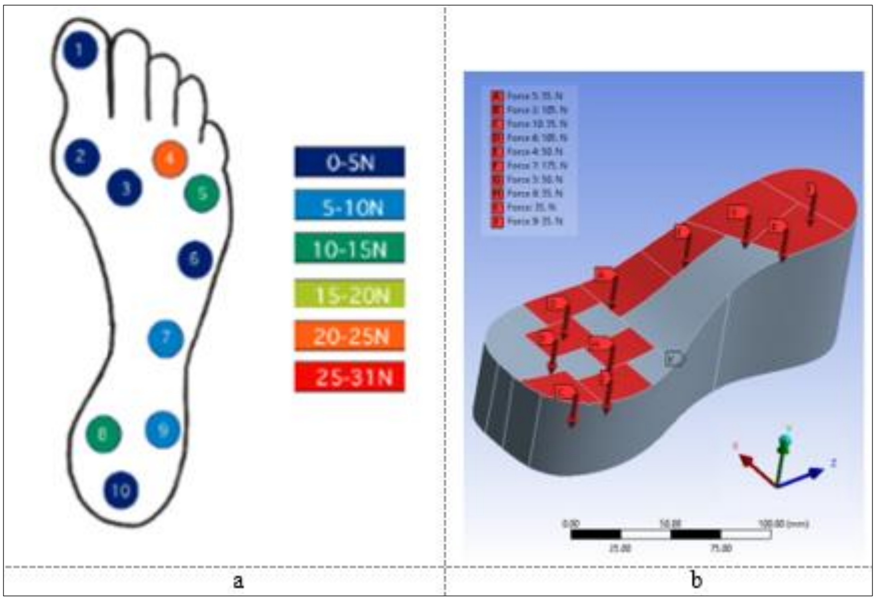

Figure 7. a) Force distribution at sole level for 8 cm heel height [27]; b) Sole segmentation of the sole for applying the forces

The mesh for model was obtained using tetrahedron elements. The size element used to mesh the regions where the forces were applied had 4 mm, and the for the rest of the model the size was 8 mm (Figure 8a). The bottom surface of the sole was considered to be fixed (Figure 8b).

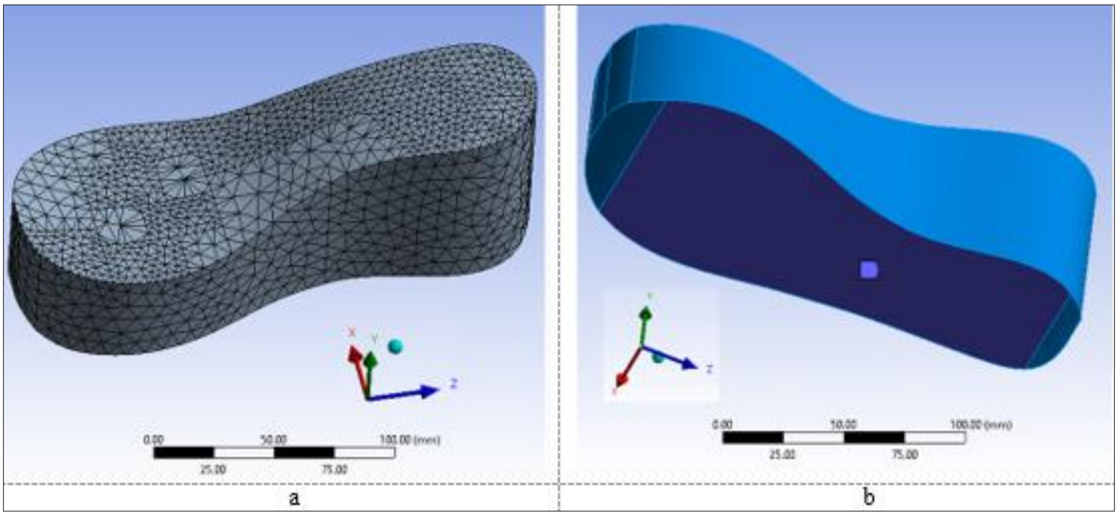

Figure 8. a) Mesh; b) Boundary condition (fixed support)

The main materials used to make heels and soles are wood, cork, rubber, leather. The shoes can be made by hand, using various machines, and more recently, 3D printers [9, 10]. Starting with the year 2012, additive manufacturing (AM) begins to be applied in this industry [11] by achieving the Cinderella's shoe in a futurist manner, using nylon filament. AM is also used to manufacture sport footwear, like "Zante Generate", "3D Runner" and "Architect" [12] using Thermoplastic Polyurethane (TPU). The sole for these models has a "lattice" structure, in which the material density varies in function of stress distribution transmitted during movement.

For the FEA analysis done in this paper, two plastic materials were considered: Acrylonitrile butadiene styrene (ABS) and Polyvinyl chloride (PVC). These materials were chosen because of their similar mechanical properties with TPU and can be used in additive manufacturing. ABS is highly durable with high impact strength. PVC is less durable, as it is designed to be flexible and softer than usual plastics. However, both plastics are resistant to chemical and water degradation.

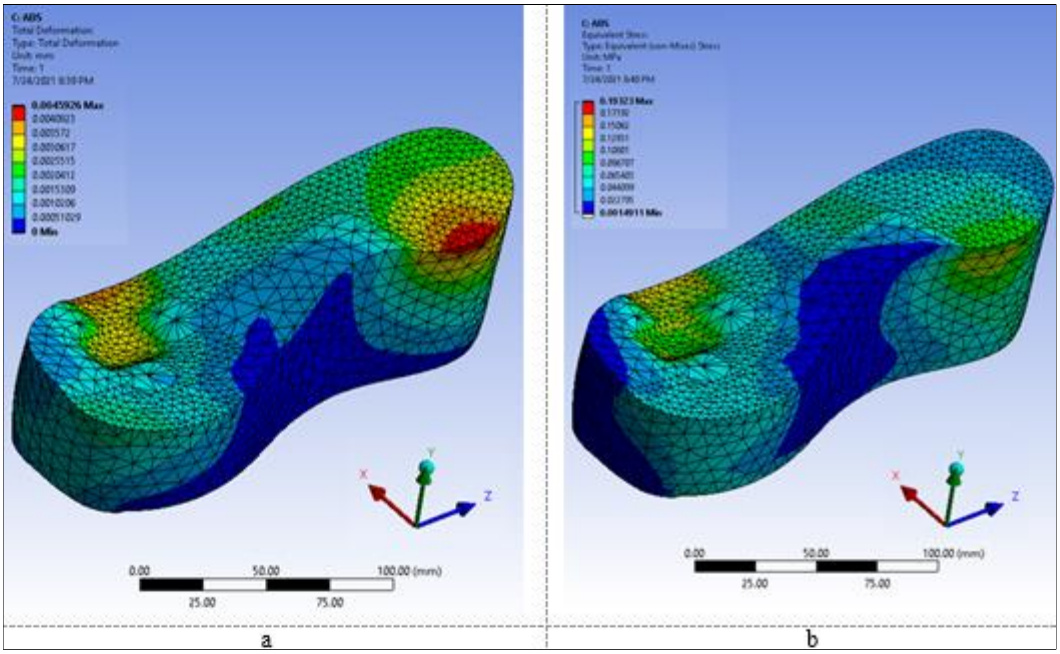

Figure 9. FEA results for ABS: a) Total deformation; b) Equivalent stress

The results of FEA analysis for the two materials are illustrated in Figure 9 and 10. The total deformation is twice smaller in the case of PVC, than for ABS. The equivalent stress has practically identical values for the two materials.

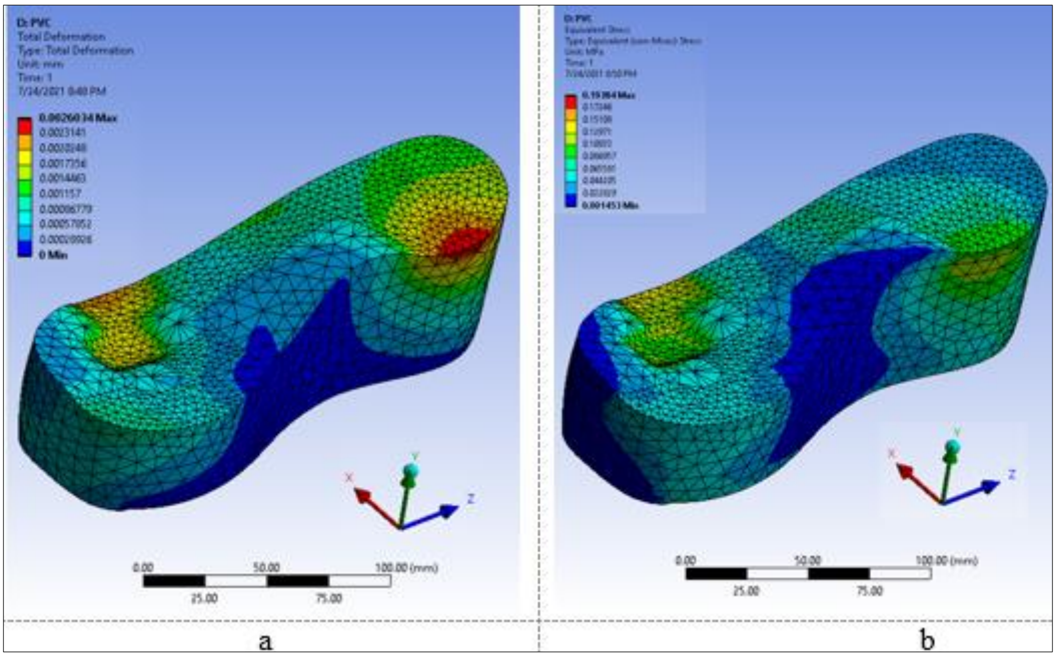

Figure 10. FEA results for PVC: a) Total deformation; b) Equivalent stress

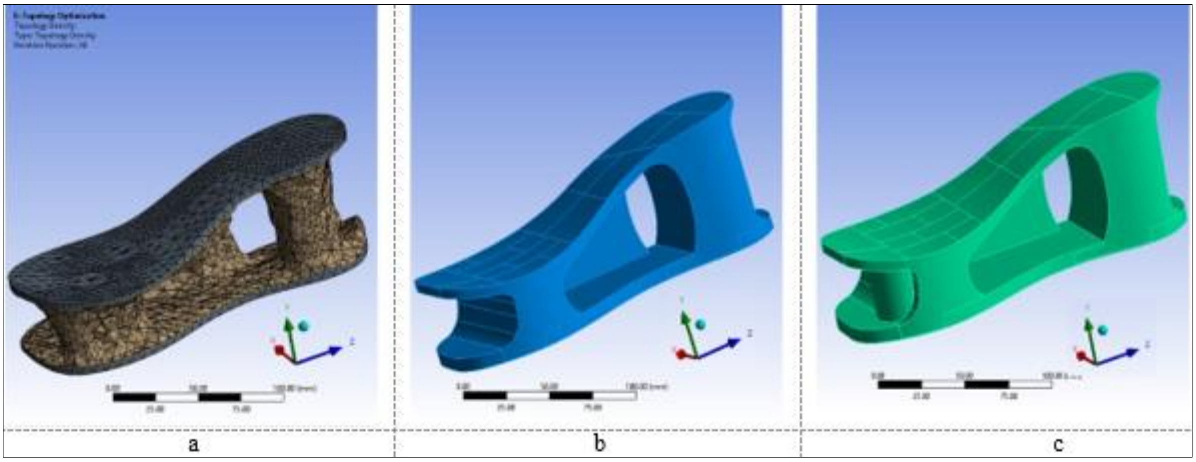

Figure 11. a)Topology optimisation; b) Shape adaptation 1; c) Shape adaptation 2

The topology optimization uses the physics of the problem combined with the finite element computational method to decide what the optimal shape is for a given design space and set of loads and constraints**.** In this study, a topology optimization was done using the module from ANSYS. The goal was to maximize stiffness while reducing weight by 50%. The shape obtained is illustrated in Figure 11 a. Based on this, two shape adaptations were obtained in order to be more easily manufactured using additive manufacturing.

Table 4. Results for FEA analysis

Mechanical analysis	ABS			PVC		
	Initial shape	Optimization 1	Optimization 2	Initial shape	Optimization 1	Optimization 2
Total deformation [mm]	0.004	0.12	0.02	0.002	0.068	0.011
Equivalent stress [MPa]	0.19	1.29	0.44	0.19	1.29	0.44

The total deformation, in case of initial shape, is six times greater than the case of optimized shape 2 for the two materials (ABS, PVC) (Table 4). The maximum stress value remains the same, for a particular shape and doesn't vary in function of the materials used. But between the initial shape and the optimized ones, the value for the maximum stress is different (double for optimized shape 2 and six time greater for optimized shape 1) (Figure 12).

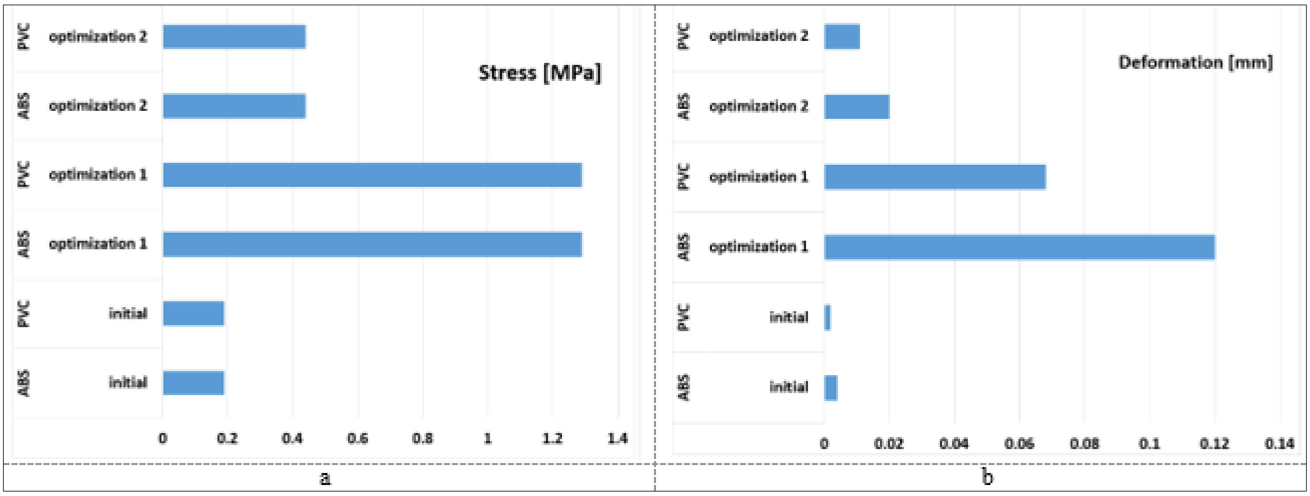

Figure 12. Comparative values a) stress; c) deformation

4. Conclusions

This paper represents a first step to develop customized shoes outer sole, taking into consideration the unicity of each individual anatomy. The results obtained by analysis of the gait cycle wearing footwear with no heels, wedge platform and block heels, led to a design optimization for wedge platform. A FEA analysis was performed on a generative shape design, for the wedge platform, to obtain the optimal shape. Two shape adaptation were presented, to show the effect of different levels of stiffness. The results regarding the maximum stress show that, for a particular shape, doesn't vary in function of the materials used. By increasing the stiffness (only in particular areas), a smaller value for the maximum stress was obtained. Same trend is observed for total deformation values.

This study shows that TPU type materials can be used to obtain customized shoes outer sole, by combining the comfort and elegance. A future study will be performed on 3D bone model, obtained from RMN/CT to predict plantar pressure and contact stress between the sole and different loading condition to which the leg is subjected. A future model must take into account, that some sole areas are more or less charged, and this be related to the design requirements.

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