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Improving comfort of shoe sole through experiments based on CAD-FEM modeling

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ABSTRACT

It was reported that next to style, comfort is the second key aspect in purchasing footwear. One of the most important components of footwear is the shoe sole, whose design is based on many factors such as foot shape/size, perceived comfort and materials. The present paper focuses on the parametric analysis of a shoe sole to improve the perceived comfort. The sensitivity of geometric and material design factors on comfort degree was investigated by combining real experimental tests and CAD-FEM simulations. The correlation between perceived comfort and physical responses, such as plantar pressures, was estimated by conducting real tests. Four different conditions were analyzed: subjects wearing three commercially available shoes and in a barefoot condition. For each condition, subjects expressed their perceived comfort score. By adopting plantar sensors, the plantar pressures were also monitored. Once given such a correlation, a parametric FEM model of the footwear was developed. In order to better simulate contact at the plantar surface, a detailed FEM model of the foot was also generated from CT scan images. Lastly, a fractional factorial design array was applied to study the sensitivity of different sets of design factors on comfort degree. The findings of this research showed that the sole thickness and its material highly influence perceived comfort. In particular, softer materials and thicker soles contribute to increasing the degree of comfort.

1. Introduction

Comfort assessment is a crucial element in product design. This is especially true for certain categories of products characterized by repeated and prolonged usage, such footwear. Serving as an interface between the foot and the ground, footwear is expected to protect the foot from undesirable pressure stimuli and facilitate it in performing its daily functions. However, foot deformation caused by ill-fitting footwear has been considered one of the most important factors influencing perceived comfort [1]. Next to style, comfort is the second key aspect in the purchase of footwear. The user's opinions may provide valuable information on whether or not a shoe is comfortable. However, this information is often limited to qualitative descriptions. Therefore, to "quantify" what may influence comfort, the relationship between the perceived sensations and objective parameters should be determined [2,3].

Over the last two decades, researchers in the medical and biomechanical fields have addressed their attention to comfort issues. Some studies were based mainly on questionnaires as an indication of user preferences [4–6]. However, little research has focused on evaluating the analytical correlation between subjective and objective responses. It was reported that physiological responses, such as plantar pressures [7–9], are strongly related to physical parameters such as materials and plantar shape.

A first valid scientific contribution to the analysis of correlation was offered by Jordan and Bartlett [1]. They attempted to correlate the subjective perceptions of users with dorsal and plantar pressure distribution of the foot through short-term dynamic tests. Perceived comfort was measured by using specific questionnaires, while pressure distribution was monitored through high-resolution insole sensors. The analysis of correlation was based on the results from three different shoes. The study showed a negative correlation between pressures and subjective comfort perception (high peak pressure corresponding to low perceived comfort). Moreover, the authors highlighted also the need to further investigate other objective responses that may affect the user perception (see, for example, shear and normal forces and heat transfer).

Witana et al. [10] researched the interactions between comfort and plantar shape. They found substantial differences between the subjective perceptions relating to the mid-foot for the different materials tested, thus confirming that comfort perception varies for different plantar areas.

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Table 1
Descriptive statistics for the twenty three subjects (13 males and 10 females).

	Mean	Maximum	Minimum	Standard Deviation
Age (years)	23.6	28.0	18.0	2.8
Weight (kg)	69.3	84.7	51.6	8.6
Height (cm)	170.2	180.0	160.0	6.2
Foot size (EU size)	40.8	42.0	39.0	0.8
Arch length/foot length (%)	25.6	32.2	16.5	4.2

The use of virtual simulations and parametric models may be a valid support wherever the large number of design factors makes it extremely difficult and expensive to identify the optimal design through experimental tests carried out on different product designs.

Recently, computational methods based on finite element method (FEM) modeling have been adopted to give a valuable support to experimental investigations. FEM models of the human foot have been developed applying certain simplifications and assumptions such as: (i) simplified or partial foot shape, (ii) assumptions of non-linear, hyper-elastic material laws, (iii) ligaments and plantar fascia modeled as equivalent forces or elastic beams/bars, (iv) no friction or thermal effect at the plantar–foot interface accounted for (see for example [11–14]). Moreover, Cheung et al. [11] combined FEM and the Taguchi method to identify the sensitivity of five design factors (arch type, insole and mid-sole thickness, insole and mid-sole stiffness) of footwear on peak plantar pressure. From the FEM results, the most important design factors in reducing peak plantar pressure were identified: the custom molded shape and the insole stiffness.

The technical literature on footwear and insole design focuses on specific clinical pathologies [15], such as diabetic diseases, in researching the best combination of material and geometric shape to reduce foot pains, but no contribution takes into account shoe design parameterization in relation to perceived comfort. Moreover, one of the most important components of the footwear is the shoe sole [16–18], whose design is based on many different features such as the shape/size of the foot, the materials used and perceived comfort. The present investigation focuses on the parametric analysis of the shoe sole to identify the factors that influence comfort. The final aim of the analysis was to define the best sole design to maximize perceived comfort.

2. Methodology overview

Fig. 1 shows the general methodology adopted. The aim of the research was to correlate subjective perceived comfort to physical and measurable responses, such as those from contact pressure maps. By comparing the rate of perceived comfort to the measured pressure maps, a comfort function relating to the peak pressure was established. The Taguchi method [19] was used to study the sensitivity of different design settings on plantar peak pressure and then on the comfort score. The study was conducted on the soles of commercially available footwear (by SAFE WAY srl, Italy).

A 3D FEM model of the footwear was developed for this purpose. In order to simulate as closely as possible the contact between the plantar surface and the foot, an anatomical detailed FEM human foot model – with soft tissue, bones and cartilages – was generated from computer tomography (CT) scans. A design of experiments (DOE) study [19], with a fractional factorial design, was then carried out to develop the best virtual prototype of the footwear, through the combinations of design factors (materials and geometrical parameters). By statistically analyzing plantar pressure maps, the most prominent design factors were identified.

3. Materials and methods

3.1. Subjects

Subjects were selected among students of the School of Engineering at the University of Naples, Federico II. Subjects who had a foot pathology were excluded. Twenty-three subjects (13 males and 10 females) aged between 18 and 28 years were selected. Written consent was obtained from each before the experiments. Table 1 shows the data relating to the right foot.

3.2. Equipment

Plantar pressure maps were recorded using a high-resolution plantar sensor (LORAN Engineering, Italy). The device adopted has the following features: sensor size – 0.5 cm × 0.7 cm; number of sensors – 512; insole size – 39–41; 0–500 kPa measure range. The insole sensor provides a limited set of values, that is, pressures are read on 512 × 4 points (every sensor provides four pressure values).

The plantar surface was sub-divided into three areas, as also suggested in [20]. Fig. 2 shows the proposed foot division: rear-foot, mid-foot and fore-foot.

Four configurations were tested for each subject (see Table 2). With respect to the bare-foot test (configuration D), pressure maps were measured by putting the plantar sensor on a hard flat surface on which the subject could stand.

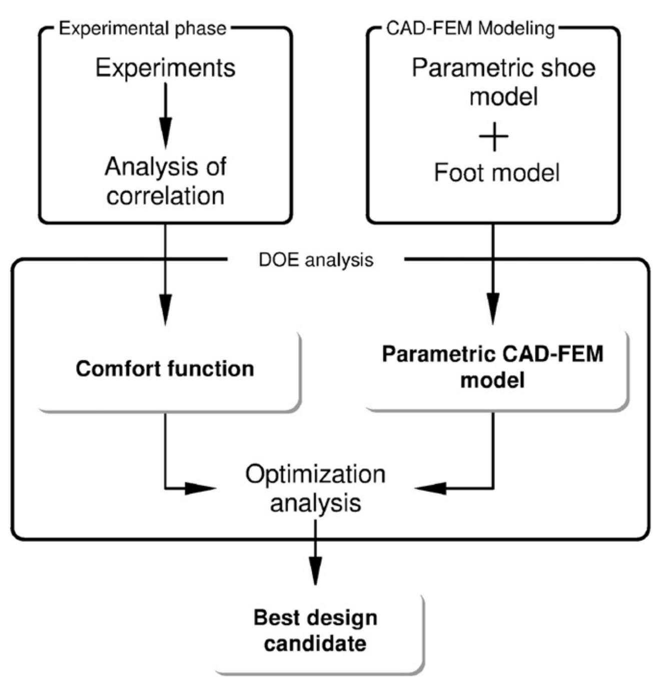

Fig. 1. General work-flow methodology.