FOOTWEAR PLANTAR MECHANICAL COMFORT: PHYSICAL MEASURES AND MODERN APPROACHES TO THEIR APPROXIMATION

PANAGIOTIS PAPAGIANNIS, ZOI KOUTKALAKI, PHILIP AZARIADIS

University of the Aegean, Greece, papagiannis@aegean.gr, zoikout@aegean.gr, azar@aegean.gr

Comfort is a fairly complex subjective phenomenon consisting of physiological, psychological and physical aspects. Foot mechanical comfort is defined and two major groups are distinguished: dorsal and plantar. Plantar mechanical comfort is concerned with the interaction of the foot with the footwear sole and the ground. The most important mechanical phenomena and quantities related to plantar mechanical comfort and their relation to foot anatomy and physiology, footwear design and use activities are discussed. Though measurement and prediction tools for comfort aspects exist, there is limited evidence regarding integration of different approaches towards the complete measurement, calculation or approximation of plantar mechanical comfort aspects. The most appropriate measures for complete plantar mechanical comfort evaluation are proposed. Taking into account the modern trend towards applying computer simulation and optimization techniques, an account of attempts to evaluate mechanical plantar comfort for upright human standing and walking with the aid of Finite Element Analysis is given.

Keywords: footwear design, mechanical comfort, plantar comfort evaluation.

THE CASE FOR FOOT COMFORT

Comfort is “lack of pain”. Richards defined comfort as subjective wellbeing in reaction to a situation, whereas Slater as a pleasant state of physiological, psychological and physical harmony with the environment (Vink *et al.*, 2005; Fan, 2009a). Its perception is a cognitive process influenced by previous experiences with the product, the physiological and psychological state of the user and the environment. It includes physical, physiological and psychological aspects becoming apparent after the end of the use of goods. Comfort is now recognized as a subjective phenomenon, a reaction to the environment or a situation and that it has physical, physiological and psychological aspects, prior, during and after use. A product is never comfortable. It may provide the user with no discomfort experience under certain conditions (Vink *et al.*, 2005). Therefore, when referring to comfortable footwear, product effects on foot comfort shall be considered rather than product features.

Interest in foot comfort is strong. Impact mechanics have attracted the attention of sport shoes brands (Thompson *et al.*, 1999). In podiatry, solutions for patient pressure relief are well documented (Tyrrell and Carter, 2009). In addition, occupational health and safety research has attributed impaired cognitive and physical employee performance to low clothing permeability, whereas in military textiles investigations on the psycho-physiological comfort aspects are now established (Cardello, 2008).

PHYSICAL, PHYSIOLOGICAL AND PSYCHOLOGICAL ASPECTS

Luximon and Zhang (2006), Fan (2009a) and Kilinc-Balci (2011a) provide accounts of foot anatomy and physiology that are useful in understanding comfort. Skin supports cutaneous sensations: tactile (touch, pressure, vibration) and pain. Sensation is the awareness of changes (stimuli) in temperature, pressure, mechanical energy or chemical energy activating sensory neurons. When stimulus amplitude exceeds the ‘sensing’ threshold of a receptor, stimulus energy is converted to electrical impulses conducted through nervous pathways to the central nervous system and the cerebral cortex.

Establishing the thresholds is important in discomfort studies. For example, prickle (acute, localized, painful sensation) threshold is 75mN per $10cm^2$ and, recognizing this fact, fibre protrusion models referring to the rod buckling theory have been proposed to explain discomfort arising from fabric roughness (Fan J., 2009a).

Sensory mechanoreceptors are either free dendrite cells, associated with tickle and touch or encapsulated Merkel discs, Meissner, Ruffini and Pacinian corpuscles associated with pressure, vibration, and some touch sensations. Pain nociceptors belong to the first group. The spatial distribution of receptors in the skin is not even (Kilinc-Balci, 2011b). Typically, it ranges from 2.5mm on finger tips to 50mm at the back and the calf. This has complications with regard spatial stimuli discrimination for different body parts. Another characteristic of receptors is adaptation occurring when the duration of the stimulus is long, causing sensory magnitude decrease. The perception of a sensation may alter and even disappear even though the magnitude of the stimulus remains constant. Differences in adaptation exist. Free nerve endings adapt quickly but Merkel discs, Ruffini corpuscles and nociceptors slowly.

Touch is localized and mostly related to free nerve endings. Pressure sensation originates from deformation of larger tissue areas. Vibration sensation is realized through repetitive signals from Meissner and Pacinian corpuscles, detecting low and high-frequency vibrations respectively. Pain is caused by excessive stimulation of sensory receptors and large deformations.

Sensation is about receiving and partly integrating low level stimuli information. Context augmented stimuli receive attention depending on sensory or cognitive thresholds. Attention involves selective processing of some sensorial and environmental aspects to the expense of others. Attended input is recognized and organized into meaningful information involving higher brain processes. Organized information is interpreted and inferences are made thus leading to perceiving a phenomenon. Thus, perception is an active transformational mental process involving the selection, organization, structuring and interpretation of information to make inferences, create experiences and give meaning to sensorial information. It is driven by both sensory data and cognitive processes influenced by beliefs and attitudes about the product and its use in a specific context. These are not restricted to function. They are often shaped by financial, self flattering, cultural, religious, social and peer influences (Fan, 2009b).

Comfort, as subjective perception of physiological effects of physical quantities, is addressed by a combination of psychophysics, objective physical measurements and psychological scaling (Fan, 2009a). The focus, in this paper, is on the identification and presentation of physical-mechanical effects in foot comfort studies.

DEFINING AND DETERMINING MECHANICAL PLANTAR COMFORT

Foot comfort is related to sensations and homeostatic response. Mechanical comfort is about interaction of the foot with footwear and the ground, mainly related to the upright stance and gait mechanics that are well documented (Kirtley, 2006). It concerns foot deformation, vector mechanics and walking kinetics and kinematics (Braune and Fischer, 1987; Keller *et al.*, 1996; Luximon and Zhang, 2006; Whittle, 2007). Instrumentation exists for measurements and verification of analytical and numerical techniques (Cobb and Claremont, 1995).

The plantar foot side contacts the ground, either directly or through the footwear sole. Most loads are applied to the foot and the human body through this side (Goonetilleke, 1999). Sole geometry and material properties affect foot plantar mechanics. Geometry affects insole shape conformance (fitting) to the foot and the resulting areas of contact (Williams and Nester, 2010), as well as contact between the outsole and the floor. It also affects stress-strain distribution internally within the solid bodies of the sole parts. Reverse heeling, wedged soles and rocker bottoms complicate force transfer characteristics (Tyrrel and Carter, 2009). Plantar mechanical comfort is concerned with interactions between footwear sole geometry and materials with the plantar side of the foot and the ground, for different environmental conditions and activities. On the other hand, the dorsal foot side does not bear any significant loads, though it is subject to upper assembly restrictions. Restrictive pressures or touch forces are much smaller compared to plantar loads. Dorsal mechanical comfort is limited to fitting and stability (Fong *et al.*, 2007).

Loads, due to the reaction of the ground to the action of body weight while standing or on impact with the floor, are of utmost importance in plantar mechanics (Whittle, 2007). The normal vector of the plantar forces is transmitted to the leg and body through the long rod-like shin bone. Shear loads are minor compared to normal ones (Whittle, 2007). Shear transverse and longitudinal forces are not important to body loading, however they cause skin deformation and superficial damages (Frederick and Wojcieszak, 2005). Touch concerns localized loads. Contrary to pressures spreading over greater areas, these concentrated loads may cause pain and local tissue damage.

Besides loading, cushioning is also fundamental. In biomechanics, it is the ability of material to reduce forces that may cause injury (shock absorption). In ergonomics, the bias is on material hardness or compression characteristics related to fatigue and discomfort. Goonetilleke (1999) reviewed cushioning and proposed metrics of hardness, compression and deceleration. Instead of deceleration, rebound resilience or percentage energy lost can be used, extracted from stress-strain hysteresis graphs. If recovery time for the sole material exceeds gait cycle time, then residual compression affects sole mechanics (Alcántara *et al.*, 2001).

Footbed conformance to foot shape has also attracted attention. Insole shape affects plantar pressure distribution. Experiments on patients with plantar fasciitis support claims that footbed shapes affect comfort perception (Witana *et al.*, 2009). The midfoot area is critical since it can change shape independently of the forefoot and heel. Comparison between flat and contoured shapes has been carried out to establish effects on the comfort experience, however, such investigations are complex due to effects of hardness and percentage energy lost on the perception of touch and pressure sensations (Mills *et al.*, 2011).

Bending and torsional deformation of the sole are of no less significance to other aspects. The influence of longitudinal bending characteristics on push-off forces during walking has been demonstrated (Cikajlo *et al.*, 2007). Also the relationships between longitudinal rotation and rotation along the toe break line with comfort have been established along with relevant measurement arrangements (Hillstrom, 2005).

Another aspect of plantar footwear comfort is insole roughness affecting sensation of touch and pressure mechanoreceptors. Relevant research is still limited and the phenomenon not well understood (Nurse *et al.*, 2005). The opposite of roughness is softness; however, certain researchers use this term to describe materials that are not very stiff rather than surface properties (Kilinc-Balci, 2011b)

Static and dynamic balance issues, as affected by footwear sole materials and geometry, also affect the comfort experience (Emery, 2003; Menant *et al.*, 2008). Static balance is approached in terms of centre of mass and base of support statics. Dynamic balance is related to staying upright while moving and impacting the floor. Wikstrom *et* *al.* (2005) have proposed the Dynamic Postural Stability Index, based on plantar force vectors, as a candidate dynamic balance metric.

Identification of stimuli, related mechanical phenomena and their effects on physiology is the first step on defining mechanical plantar comfort. Comfort is related to tactile psychophysics, therefore amplitude, spatial distribution and adaptation effects analysis is necessary. Objective analysis should be followed by subjective analysis (e.g. psychological scaling) and corresponding objective phenomena to subjective perceptions (Kilinc-Balci, 2011b; Fan, 2009a). Most research on comfort stimuli and mechanical aspects focus on specific aspects (e.g. pressures, prickle, shock absorption) and it appears that in the wider apparel field a truly integrated approach is missing even in distinct comfort sectors (e.g. tactile). This is a view supported also by Kilinck-Balci (2011b). The footwear industry, however, has to demonstrate an interesting multi-aspect approach proposed by the European CEC-MADE-SHOE project and called Virtual Shoe Test Bed (Azariadis *et al.*, 2007). This was based on the concepts of normal plantar pressure, cushioning, shock absorption, bending, torsion, friction, stability, footwear weight and thermal aspects of footwear. Simplified differential and analytical models were developed for simulation purposes. The VSTB approach is fairly integrated; however, a complete view of mechanical plantar comfort would require that the following phenomena and quantities be considered: plantar loading (normal and shear), compression, hardness, rebound resilience, compression recovery time, longitudinal bending and torsion, torsion along the toe brake axis, shape conformance (on deformation), static balance, dynamic postural stability index and weight. Given current scientific knowledge, insole roughness cannot be considered as a comfort metric. These aspects can be measured by analytic, numerical and laboratory tools and most can be normalized to body weight (Shorten, 2002).

Arrangements for measuring and analytic tools for predicting individual comfort aspects have been developed (Kilinc-Balci, 2011b; Fan, 2009a). Modern trends are moving towards numerical and simulation techniques. Finite Element Analysis (FEA) is one of these techniques and it is suited to analyzing complex structures, combining different materials, loading and boundary conditions. Accuracy depends on the accuracy of geometric models, initial and boundary conditions and meshing density. FEA has been used for calculating stress-strain relationships on tissues due to the interaction of the foot with the sole and the floor. Early works by Nakamura *et al.* (1981), Lemmon *et al.* (1997), Jacob and Patil (1999), and Chen *et al.* (2001) resulted in simple though adequate models. FEA was used for material sensitivity studies by Lewis (2003) and Cheung *et al.* (2005) and for investigating the effects of insole geometry on plantar pressure distribution (Chen *et al.*, 2003). Modern models (Verdejo and Mills, 2004; Cheung and Zhang, 2005) and simulation cases (Cheung *et al.*, 2005; Yu *et al.*, 2007; Hsu *et al.*, 2008; Antunes *et al.*, 2008; Gu *et al.*, 2010) are realistic, accurate, verified (through testing) and validated.

Modern biomodels for FEA are developed from CT and MRI medical imaging scans acquired from the feet of healthy research subjects in neutral position. Areas of bones, soft tissue and anatomical features are extracted from density based segmentation, with the aid of medical imaging software and 3D models of these elements are developed. So far, researchers have made certain assumptions (e.g. cartilage is treated as extension of osseus tissue and tarsal bones are considered as one large solid) to facilitate calculations (Cheung and Zhang, 2006; Chen *et al.*, 2001). Then, the 3D model of the foot, containing both hard and soft tissues, is assembled. FEA of foot structures is often combined with surfaces other than simple flooring. Sole multi-layered multi-material assemblies, have been designed, meshed and simulated by several researchers.

A similar approach is followed in the OptShoes (2012) project, in which it is attempted to develop an integrated tool for plantar comfort simulation for different multi-layer and multi-material sole arrangements.

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