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A mechanical protocol to replicate impact in walking footwear

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ABSTRACT

Impact testing is undertaken to quantify the shock absorption characteristics of footwear. The current widely reported mechanical testing method mimics the heel impact in running and therefore applies excessive energy to walking footwear. The purpose of this study was to modify the ASTM protocol F1614 (Procedure A) to better represent walking gait. This was achieved by collecting kinematic and kinetic data while participants walked in four different styles of walking footwear (trainer, oxford shoe, flip-flop and triple-density sandal). The quantified heel-velocity and effective mass at ground-impact were then replicated in a mechanical protocol. The kinematic data identified different impact characteristics in the footwear styles. Significantly faster heel velocity towards the floor was recorded walking in the toe-post sandals (flip-flop and triple-density sandal) compared with other conditions (e.g. flip-flop: 0.36 ± 0.05 m s^{-1} versus trainer: 0.18 ± 0.06 m s^{-1}). The mechanical protocol was adapted by altering the mass and drop height specific to the data captured for each shoe (e.g. flip-flop: drop height 7 mm, mass 16.2 kg). As expected, the adapted mechanical protocol produced significantly lower peak force and accelerometer values than the ASTM protocol ($p < .001$). The mean difference between the human and adapted protocol was $12.7 \pm 17.5\%$ ($p < .001$) for peak acceleration and $25.2 \pm 17.7\%$ ($p = .786$) for peak force. This paper demonstrates that altered mechanical test protocols can more closely replicate loading on the lower limb in walking. This therefore suggests that testing of material properties of footbeds not only needs to be gait style specific (e.g. running versus walking), but also footwear style specific.

1. Introduction

Testing is undertaken by footwear manufacturers to analyse properties of footwear prior to mass-manufacture to make design and component decisions. The testing undertaken depends on the style of footwear and can include sole traction or friction, outsole longitudinal stiffness and impact testing. Impact testing aims to quantify the shock absorbing capability of footwear midsoles by replicating the collision, and resulting transient, between the shod foot and the ground at heel-strike. The nature of this transient has been linked to degenerative changes to tissue such as knee osteoarthritis [1], clinical symptoms like lower back pain [2], as well as subjective comfort in healthy populations [3]. The manipulation of footwear or insole characteristics (thickness, shape and material properties) can attenuate loading from heel-strike, reducing the magnitude of forces and loading rate experienced by soft tissue, bone and joint cartilage in clinical [2] and healthy populations [4].

Some methods for examining heel-strike impacts involve dropping a mass onto the midsole and quantifying force, acceleration, energy dissipation and deformation [5,6]. Mechanical testing has obvious economic and time-saving advantages for footwear companies and allows a larger range of potential midsoles to be tested compared with testing on humans. For example Frederick et al. utilised mechanical testing to quantify a range of heel thickness (10–30 mm), midsole flare (0–30°) and hardness (25–45 Shore A) constructions, measuring peak gravity (g) in 36 footwear conditions [5]. Human testing, however, has the advantage of including the interaction of the human system with the footwear, for example any effect that the footwear may have on heel pad confinement [7], gait kinematics [8] and muscle activation [9] and therefore impact characteristics. Comparisons between mechanical and human impact data generally report low correlation with biomechanical tests [10]. For example, Hennig et al. identified a low, non-significant, correlation between peak tibial accelerations during running in 19 different athletic shoes in 27 subjects and the acceleration scores from a mechanical impact

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tester (r = .26) [11]. Making mechanical testing as representative of the real-life situation as possible therefore has significant benefits for the footwear technician who needs to make decisions based on the outcomes of mechanical testing alone.

The American Society for Testing and Materials (ASTM) stipulate a specific protocol to quantify the shock absorption properties of footwear (F1614 Procedure A, 2006), originally designed to replicate running impacts. This protocol utilises a drop-height (50 mm) and a missile-mass (8.5 kg) to replicate the impact velocity and effective mass of the running leg and foot of a male running [12]. Despite the protocol replicating the energy apparent in ground-impact in running, it is used in footwear research considering marching [10], tennis [13] and walking [14]. It is also utilised by the Shoe and Allied Trade Research Association (SATRA) to test shock attenuation in all footwear styles from trainers to sandals [15]. These are conditions where impact energy will typically be significantly lower in a real-life situation. These loads and the duration over which they are applied are not relevant measures of the shock absorption properties of materials and constructions of walking footwear. The assessment of walking is relevant as it is a more frequent activity for the general population and in particular for clinical and ageing groups to whom the heel-strike magnitude may be more detrimental [1,2]. It is also more relevant for orthopaedic and walking footwear styles, which are unlikely to be used for running. Therefore quantifying the cushioning properties of different walking footwear is highly relevant. It is likely that the differing uppers in footwear styles also influence the kinematics and therefore the impact experienced [16,17]. Thus adapting this protocol to better replicate the energy apparent in walking and specific styles of walking shoes would be an effective step in footwear biomechanics development for footwear manufactures. Testing protocols on material construction and data analysis and interpretation could then be undertaken more rapidly in footwear style-specific protocols.

The purpose of this study was to modify a mechanical test method (ASTM F1614 Procedure A, 2006) to better replicate walking impacts in a variety of walking shoes. The protocol was adapted using kinematic data from participants walking to produce a more valid method for testing walking footwear styles mechanically. Results from the new protocol were compared with the standard ASTM method in addition to the human results in real-life walking.

2. Methods

Ethical approval for the study was obtained through the University ethics committee and volunteers were recruited from the University staff and student populations.

2.1. Footwear tested

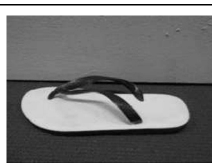
Four footwear conditions were tested (Table 1 and Fig. 1), as well as barefoot using human and mechanical methods. The order of footwear testing was randomised among subjects.

2.2. Human testing and processing

Thirteen healthy subjects (2 males, 11 females, 27.5 ± 8.8 years, 62.0 ± 10.3 kg, 1.65 ± 0.05 m) with shoe size U.K. 6 participated in the study. Subjects, who reported no lower limb injury, were instrumented with a lower limb marker set-up for 3-D motion capture and one uni-axial accelerometer resonant at 3.0 kHz.

A 10 camera Qualisys Pro-Reflex system (Qualisys, Sävebalden, Sweden) was used to track 3D motion at 240 Hz. Spherical retro-reflective markers and clusters were positioned to define the lower limbs in accordance with the CAST technique [18]. The foot was defined with markers on the posterior calcaneus and the dorsal aspects of the 1st, 2nd and 5th metatarsal heads. The shank was defined with anatomical markers on the medial and lateral malleoli and the medial and lateral knee with a rigid plate tracking marker on the anterior tibia. The accelerometer was mounted on the right anterior-medial tibia above the medial malleolus on a small piece of light flexible plastic. It was positioned 5–10 cm above the malleolus, on an area with least adipose tissue,

Table 1
Characteristics and images of the footwear conditions tested alongside barefoot.

Condition	Image	Style	Heel material/construction	Heel depth (mm)	Heel hardness (Shore A)
Flip-flop		Havaiana Brazil	EVA	16	33
Trainer		New Balance 539	EVA with microfibre linings	27 footbed 5 insole	52 footbed 26 insole
Shoe		Ecco Unisex (comfort brand)	Rubber outsole, cloth lining and EVA insole	5 outsole 5 insole	65 outsole 30 insole
Triple-density sandal		FitFlop Walkstar I	EVA	41	55