Insoles of uniform softer material reduced plantar pressure compared to dual-material insoles during regular and loaded gait

Georgia Melia[a], Petros Siegkas[a], Jodie Levick[a] and Charlotte Apps[a]*

[a]*School of Science and Technology, Nottingham Trent University, Nottingham, UK*

*Corresponding author:

Charlotte Apps

School of Science and Technology, Nottingham Trent University, Clifton Campus, Clifton Lane, Nottingham, UK, NG11 8NS

Phone: +44 (0) 115 848 3831

Email: charlotte.apps@ntu.ac.uk

Abstract

There is limited evidence on the efficacy of insole materials to reduce plantar pressure during regular walking and loaded walking. In-shoe plantar pressures and subjective footwear comfort were recorded in twenty healthy participants at a self-selected treadmill walking speed in six conditions: two commercial insoles or no insole, and with or without carrying a load in a backpack. A single-material insole, comprised of polyurethane, had reduced density and compressive stiffness compared to a dual-material insole with added viscoelastic material in rearfoot and forefoot regions. Load carriage increased peak pressure across the foot. Both insoles reduced plantar pressure in the rearfoot. Yet, the softer single-material insole also attenuated forefoot pressure and loaded walking did not appear to cause bottoming-out of the polyurethane. Plantar pressure changes did not affect perceived footwear comfort. The softer single-material insole was more effective in reducing plantar pressure, further research would confirm if this influences injury prevalence.

Keywords: plantar pressure, density, load-carriage

Highlights

- Backpack load carriage increases peak plantar pressure during walking with and without the use of insoles.
- Softer PU insoles attenuated plantar pressure more effectively than dual-material insoles with viscoelastic elements.
- Plantar pressure changes during load carriage or wearing insoles did not influence perceived footwear comfort.

1. Introduction

Knapik, Harman and Reynolds (1996) defined load carriage as the transportation of an external mass supported on the body during locomotion. The backpack is considered the most ergonomic option for load carriage as it keeps the weight close to the centre of mass, which aids energy efficiency and stability, and keeps hands free for other tasks (Malhotra & Gupta, 1965; Knapik et al., 1996; Chansirinukor et al., 2001; Birrell & Haslam 2010; Pau et al., 2015). This type of load carriage is often used in professions, such as the military and firefighters, or during recreational activities such as hiking, and in daily activities such as carrying a bag to school or work. Biomechanical changes occur as a response to load carriage, which increase injury risk factors (Chansirinukor et al., 2001; Attwells et al., 2006; Birrell & Haslam 2010; Majumdar et al., 2010). Castro et al. (2013) found backpack load carriage increases the vertical and antero-posterior ground reaction forces, as well as, plantar pressure across most foot regions in healthy students. These kinetic alterations are associated with blister development due to the antero-posterior force increasing in-shoe foot slippage and higher pressure on the skin (Knapik et al., 1996, Birell & Haslam, 2010; Castro et al., 2013). Forward lean is also commonly reported as an adaptation to load carriage, to counteract the weight, which increases stress placed on the back muscles and increases back injury incidence (Knapik et al., 1996; Grimmer & Williams, 2000; Attwells et al., 2006). This kinematic response to backpack load carriage is related to the relatively higher plantar pressure reported under the forefoot and toes, which may cause metatarsalgia and stress fractures in these foot regions (Knapik et al., 1996; Pau et al., 2015).

Commercially available shoe insoles are a cheap solution which are proposed to prevent plantar foot injuries. It is the cushioning properties of insoles which are reported to reduce the vertical ground reaction force and redistribute plantar pressure, thus absorbing impact shock transmitted to the lower-limbs (Knapik et al., 1996; O'Leary et al., 2008; Mattila et al., 2011; Caravaggi et al., 2016). Insoles have varying features and characteristics such as the material, degree of wedge, thickness and fibre density, which elicit different effects on comfort, kinematics and kinetics (Mundermann et al., 2001). Realignment and shock absorption are two different outcomes that insoles may be used to achieve, which are favoured by opposite types of insole hardness; stiff and soft, respectively (Butler et al., 2003). High-density material does not deform as much under stress, which eliminates cushioning ability (Rome et al., 1991), but are better for motion control. On the contrary, low-density materials may reduce peak plantar pressure by an effect known as enveloping. The soft, compliant nature of the material allows it to better fit the geometry of the loaded area, in this case the foot, resulting in a larger contact area thus creating a more uniformed pressure distribution (Sprigle et al., 1990). Tsung, et al. (2004) carried out a study on insoles that complements this theory as they found the use of insoles maximised contact area whilst peak pressures reduced. Enveloping also explains the benefits of customised insoles which are produced based on the contour of individuals feet and are more effective at reducing peak pressure than basic insoles (Tsung et al., 2004; Caravaggi et al., 2016). However, bottoming-out occurs if material density is too low and there is early or excessive deformation, in which case the shock absorbing effects are lost. Thus, it's likely an optimal combination of shock absorbing and resilience characteristics exists for reducing plantar pressure.

Material options available for manufacturing orthotics are increasing (Healy et al., 2011), however it is important insoles are designed for specific participant groups or movements (Rome et al., 1991). Despite research in sporting (O'Leary et al., 2008), clinical (Kulcu et al., 2007; Hinman et al., 2008; Chen et al., 2010) and military populations (Windle et al., 1999; Witnell et al., 2006; Mattila et al., 2011), the true efficacy of insoles remains unknown and the mechanisms involved with their use poorly understood. A systematic review attributed this to the inability to compare data across studies due to methodological discrepancies in reporting, measurements and insole materials tested (Rome, 2005).

Recently, Chatzistergos et al. (2017) used in-vitro and in-vivo testing to identify desirable materials for reducing plantar pressure tailored to the individual. Interestingly, participants with increased body mass required stiffer materials, presumably to maximise the enveloping/bottoming out relationship. Moreover, Castro et al. (2014) used finite element analysis (FEA) to develop dual-material insoles for both an obese and load carriage population based on previous plantar pressure data. The insole with harder, thicker cork under the rearfoot and midfoot was effective in reducing the vertical ground reaction force, whilst the insole with softer corkgel under the heel and forefoot successfully redistributing plantar pressure in those regions. Yet, the desired result for each population was not straightforward perhaps due to the FEA method. Knowledge on how materials effect plantar pressure distribution is warranted to enhance future design of commercially available insoles for activities such as load carriage.

The aim of the current study is to compare mechanical characteristics of two different insoles and subsequently identify the material effects on plantar pressure and perceived comfort during regular and loaded treadmill walking. Specifically, two commercially available Sorbothane insoles were tested, one with single uniform material (single-material insole), and one with the same material but added viscoelastic material under the rearfoot and forefoot (dual-material insole). This enabled the effect of material properties to be evaluated under the regions of increased plantar pressure during gait. Based upon past research, we predicted that across foot regions backpack load carriage would increase peak plantar pressure (Castro et al., 2013; Pau et al., 2015), and the commercial insoles would reduce and redistribute plantar pressure (Windle et al., 1999; Tsung et al., 2004; Caravaggi et al., 2016). It was hypothesised the mechanical material properties of the insoles would change plantar pressure during loaded and unloaded walking.

2. Materials and methods

2.1 Participants

Twenty healthy individuals (age: 26.5 ± 8.0 years, height: 170.8 ± 7.9 cm, weight: 70.4 ± 11.8 kg) volunteered to participate in the study. All participants provided written informed consent prior to testing and the study was approved by the Nottingham Trent University Human Invasive Ethics Committee. Participants were asked to abstain from high levels of physical activity for 48 hours prior to their test session.

2.2. Insoles

Walking shoes (Curlews, Mountain Warehouse, London, UK; Figure 1B) were provided to all participants, to prevent different footwear types influencing results. The walking shoes purchased were fitted with thin prefabricated insoles that were the control insole condition (Control). The Control were compared to two commercially available insoles (Figure 1A). The single-material insoles (Cush 'N' Step, Sorbothane, Sutton in Ashfield, Nottinghamshire, UK) are composed of 100% polyurethane foam with a fabric top sheet and are advertised to provide cushioning and comfort to lighter impact activities such as walking and hiking. The dual-material insoles (Double Strike, Sorbothane, Sutton in Ashfield, Nottinghamshire, UK) are also composed of polyurethane foam and a fabric top sheet, but with added viscoelastic areas under the heel and forefoot. These are advertised to aid activities where the heel and forefoot are subjected to increased shock, such as hiking (Performance Health International Ltd, 2020).

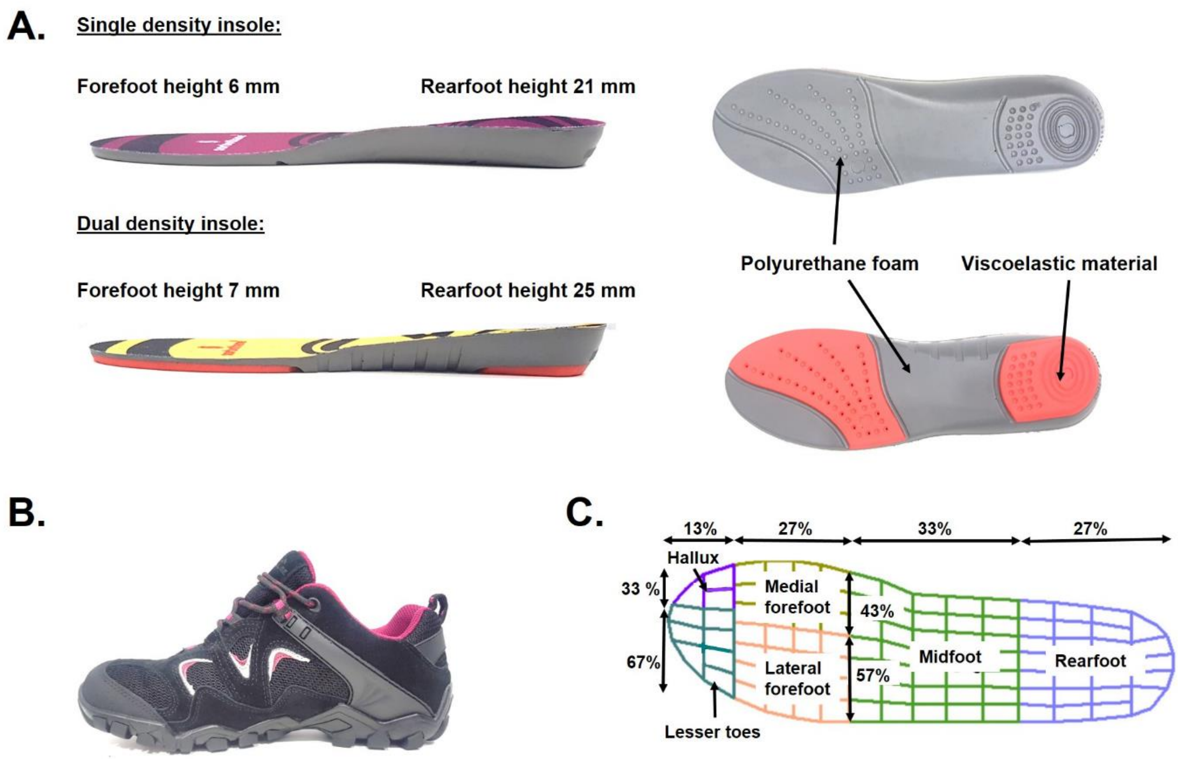

Figure 1. A) Single-material insole (top), dual-material insole (bottom). B) Control walking shoe. C) Segregation of regional masks for plantar pressure analysis.

2.3. Plantar pressure and subjective comfort testing

In-shoe plantar pressure was recorded at 100 Hz by an insole system of 2 mm thickness which contains 99-sensors (Pedar X, Novel, Munich, Germany). Data were recorded from the right insole only, but both right and left Pedar insoles were fitted in the test footwear. Participants completed six walking trials: in the three insole conditions (control, single-material, dual-material) during both regular and loaded conditions. All trials were performed on a treadmill (AMTI, force-sensing tandem treadmill, Watertown, MA, USA) at the same self-selected comfortable pace (average: 1.2 ± 0.2 m/s). The treadmill was selected to collect the plantar pressure data because consecutive steps could be collected at the set self-selected speed within the lab (Chiu et al., 2015). Loaded trials consisted of participants carrying 10% of their bodyweight within a backpack (Albus Flint Backpack, Trespass, Glasgow, UK) by 1 Kg weights being placed inside the main compartment. The backpack straps were tightened or loosened accordingly to fit the participant. The initial trial always consisted of regular walking in the Control insole for 10 minutes in order to familiarise to the treadmill and footwear, before plantar pressure data were recorded for an additional 2 minutes. The remaining five conditions were randomised by computer programme to avoid trial order effects. For these trials, participants walked for 5 minutes for familiarisation to the insole and load condition before plantar pressure data were recorded for two minutes. After each trial participants completed a 100 mm visual analog scale (VAS), a valid measure of footwear comfort (Mills et al., 2010). The VAS was marked with anchors at 0 mm and 100 mm, stating very uncomfortable and very comfortable, respectively. Each trial was separated by a five-minute break to avoid any effect of fatigue. Pilot test results determined the familiarisation periods according to a similar method to Melvin et al. (2014). In this, one participant followed a similar protocol to the present study in the same six test conditions (3 insoles, 2 weights) except they walked for 15 minutes whilst peak plantar pressure was recorded throughout the duration. Peak plantar pressure in each region was analysed by creating a rolling average of 50 steps with the last step being given as the 'representative step'. A range of 2.5% above and below this peak pressure value was created and the first 5 consecutive steps to fall within this pressure range were identified. The first of the five steps within the range was the point described as 'familiarised step'. Multiplying the average step time for the trial by the region with the highest 'familiarised step' number and dividing the answer by sixty gave the longest familiarisation time for each trial. Across both feet, plantar foot regions and conditions, 99% of familiarisation periods fell under 5 minutes (see supplementary data table). It was therefore determined 5 minutes was a suitable familiarisation time for the present study.

Plantar pressure data was processed and analysed in the Pedar-x software step-analysis program (Pedar-X, Novel, Munich, Germany). To assess the effect of the insole material properties on plantar pressure, 6-regional areas were defined based upon the viscoelastic dual-material location, and to improve peak pressure calculations sensors were not split across mask-regions. Firstly, the larger rearfoot, midfoot, and forefoot regions were defined, similar to previous research (Testutti et al., 2010; Cavanagh & Ulbrect, 1994). The forefoot was further subdivided into the medial forefoot, lateral forefoot, hallux and lesser toes (Figure 1C). Peak plantar pressure, maximum contact area and the force-time integral across sensors in each mask region were computed. To ensure an accurate representation of a typical step, the mean of 30 steps were averaged for each parameter in each condition (Melvin et al., 2014).

2.4. Material testing

Cylindrical specimens of approximately 10 mm diameter and 7 mm height were extracted from both types of insoles (i.e. single-material insole and the dual-material insole) using a hole punch tool (Todd et al., 1998). One type of specimen was made from the single-material insole as it contained the same polyurethane material across the insole. Two types of specimens made from the dual-material insole were taken from the polyurethane material area and the composite material area (i.e. polyurethane + viscoelastic material) (Figure 1A). The specimen width, height and weight were measured and recorded.

Specimen stress/strain were calculated from cyclical compressive loading tests (TA electroforce mechanical test machine, New Castle USA fitted with a 450N load cell). The specimens underwent 5 loading cycles at two frequencies: 0.83Hz corresponding to 1.2 seconds per two steps, and 1.6 Hz corresponding to 0.6 seconds per two steps. Each test was repeated three times for consistency (18 specimen tests in total). Displacements were taken from the machine stroke. A photron high speed camera and a Matlab (MathWorks, Massachusetts, USA) based object tracking code was used for validation. Compression test data were processed and analysed using Matlab.

2.5. Statistics

For each participant and condition, plantar pressure parameters were averaged for statistical analysis (SPSS inc., Chicago, IL, USA). The Shapiro-Wilk test confirmed peak pressure, force-time integral and comfort data parameters were normally distributed, which were compared using a two-way (insole x weight) repeated measures ANOVA. To account for deviations from sphericity the Greenhouse-Geisser corrected p-values ($p<.05$) are reported. Significant main effects were followed up by least-significant difference (LSD) post-hoc tests and significant interactions by simple contrast post-hoc tests. Contact area parameters failed assumptions of normality and were subsequently compared via the Friedman test and significant results followed up by Wilcoxon post-hocs. For all tests the alpha value was set at $p<.05$ and no adjustment for multiple comparisons were made to limit type 2 errors (Rothman, 1990). Results are displayed as mean standard deviation (SD), unless otherwise stated.

3. Results

3.1. Plantar Pressure

Plantar pressure results for each regional mask area in the insole conditions during regular and loaded walking are reported in Table 1.

3.1.1. Peak Pressure

The 2-way repeated measures ANOVA revealed a significant main effect of weight in all foot regions for peak plantar pressure. Peak plantar pressure increased during the loaded walking compared to the regular walking in the rearfoot ($F = 42.17$, $p < .001$, $\eta^2 = .69$), midfoot ($F = 6.15$, $p = .023$, $\eta^2 = .24$), medial forefoot ($F = 53.85$, $p < .001$, $\eta^2 = .74$.), lateral forefoot ($F = 50.30$, $p < .001$, $\eta^2 = .73$), hallux ($F = 14.05$, $p = .001$, $\eta^2 = .43$) and lesser toes ($F = 19.34$, $p < .001$, $\eta^2 = .50$) (Table 1).

There were also significant main effects for the insole conditions in the rearfoot ($F = 51.67$, $p < .001$, $\eta^2 = .73$), medial forefoot ($F = 4.79$, $p = .015$, $\eta^2 = .20$) and lateral forefoot ($F = 13.65$, $p < .001$, $\eta^2 = .42$). There was no main effect in the hallux region, although the p-value approached significance ($F = 3.42$, $p = .053$, $\eta^2 = .15$), nor the midfoot ($F = .17$, $p = .777$, $\eta^2 = .009$) or lesser toes ($F = 0.61$, p =. 5.38, $\eta^2 = .03$). In the rearfoot, post hoc analysis indicated both the single-material insole ($p < .001$) and the dual-material insole ($p = .001$) reduced peak pressure compared to the Control. The single-material insole reduced peak pressure in the rearfoot compared to dual-material insole ($p < .001$). In the medial forefoot, the single-material insole reduced peak pressure compared to the Control ($p = .010$). In the lateral forefoot, the single-material insole reduced peak pressure compared to the Control ($p = .001$) and dual-material insole ($p < .001$).

There was one significant interaction in the lesser toes ($F = 5.64$, $p = .009$, $\eta^2 = .23$). Simple effects analysis revealed in the loaded trials the dual-material insole increased peak pressure compared to the Control ($p = .040$) and the single-density insole ($p = .045$).

3.1.2. Force-time integral (FTI)

Similarly, in the FTI there was a significant main effect of weight in the rearfoot (F = 35.39 , p <.001, η^2 = .65), midfoot (F =9.65, p = .006, η^2 = .34), medial forefoot (F = 69.21, p < .001, η^2 = .79), lateral forefoot (F = 32.44, p < .001, η^2 = .63) hallux (F = 9.09, p = .007, η^2 = .32) and the lesser toes (F = 6.83, p <.017, η^2 = .26). FTI increased in all plantar regions and the total plantar foot (F = 69.55, p <.001, η^2 = .79) during loaded walking compared to regular walking (Table 1).

Regarding insole conditions, there was a significant main effect across the whole plantar foot (F= 6.46, p = .008, η^2 =.25), post hoc analysis revealed the Control increased FTI compared to the single-material insole (p=.007) and dual-material insole (p = .005). Across the plantar foot regions, significant main effects were observed for the midfoot (F= 8.72, p = .001., η^2 = .32), lateral forefoot (F= 11.00, p < .001., η^2 = .37) and hallux (F= 7.93 , p = .002 , η^2 = .29), but not the rearfoot (F= 0.64 , p = .519, η^2 = .03), medial forefoot (F= 2.29 , p = .122, η^2 = .11) or lesser toes (F= 1.94, p = .158, η^2 = .09). In the midfoot, post-hoc results indicated the Control (p <.001) and single-material insole (p = .023) increased FTI compared to the dual-material insole. Yet in the lateral forefoot it was the Control (p < .001) and dual-material insole (p=.008) that increased FTI relative to the single-material insole. In the hallux, the dual-material insole increased FTI compared to the control (p = .002) and the single material insole (p = .015). There were no significant interactions.

3.1.3. Contact Area

The Friedman test revealed a significant contact area differences across the total plantar foot (χ^2= 36.33, p < .001) the midfoot (χ^2= 32.59, p < .001) and the lateral forefoot (χ^2= 22.77, p < .001), but not the rearfoot (χ^2= 11.02, p = .051), medial forefoot (χ^2= 6.36, p = .273), hallux (χ^2= 5.06, p =.408) and lesser toes (χ^2= 5.90, p = .316). Post-hoc analysis revealed the single-material insole increased total foot contact area compared to the dual-material insole during regular (p <.001) and loaded walking (p= .003). During loaded walking, the single-material insole increased total foot contact area compared to the Control (p=.037). In the midfoot, the single-material insole increased contact area compared to the Control (regular walking p = .04; loaded walking p = .021) and the dual-material insole (regular walking p = .001; loaded walking p = .002). During regular walking, the Control increased midfoot contact area compared to the dual-material insole (p= .015). In the lateral forefoot, absolute differences in contact area between conditions were less than 0.6 cm^2 (Table 1). Significant post-hocs revealed an increased contact area in the Control compared to the dual-material insole during regular walking (p = .012) and compared to the single material insole during loaded walking (0.028).

Table 1: Mean (SD) peak pressure, force-time integrals (FTI) and maximum contact area in the plantar regions during regular and loaded walking in the insole conditions (control, single-material and dual-material) across participants.

Region	Parameter	Regular walking			Loaded walking			Post-hocs ($p < .05$)	
		Control	Single-material	Dual-material	Control	Single-material	Dual-material	Walking	Insole
Total foot	FTI (N.S)	386.1 (76.0)	377.8 (75.6)	375.1 (74.3)	442.3 (82.1)	403.3 (85.7)	424.6 (83.3)	Loaded > Regular	Control > Single, Dual
	Contact area (cm^2)	126.1(12.8)	128.3 (10.9)	122.5 (11.4)	127.9 (11.3)	131.2 (13.5)	126.8 (13.8)	Single, Dual: Loaded > Regular	Single > Dual; Loaded Single > Control
Rearfoot	Peak pressure (kPa)	196.5 (39.8)	165.5 (42.7)	186.8 (45.3)	220.2 (49.6)	176.8 (45.8)	200.8 (42.4)	Loaded > Regular	Control > Dual > Single
	FTI (N.S)	117.2 (23.7)	121.5 (26.5)	122.5 (27.1)	142.1 (32.8)	130.7 (25.1)	137.1 (31.4)	Loaded > Regular	
	Contact area (cm^2)	40.1 (4.2)	39.9 (4.0)	39.4 (3.9)	40.1 (4.0)	39.8 (4.2)	39.7 (4.0)		
Midfoot	Peak pressure (kPa)	109.6 (29.0)	117.4 (42.4)	114.4 (37.3)	124.7 (38.4)	114.7 (33.5)	114.8 (36.8)	Loaded > Regular	
	FTI (N.S)	81.4 (28.0)	82.5 (33.3)	73.0 (30.0)	92.7 (32.2)	85.0 (33.9)	79.7 (36.9)	Loaded > Regular	Control, Single > Dual
	Contact area (cm^2)	43.1 (8.0)	45.6 (7.0)	40.4 (7.3)	43.5 (7.7)	45.7 (9.5)	42.0 (8.5)	Dual: Loaded > Regular	Single > Control, Dual Regular: Control >Dual
Medial forefoot	Peak pressure (kPa)	246.0 (64.0)	230.6 (67.3)	243.6 (75.7)	282.2 (84.9)	251.1 (73.7)	257.4 (62.5)	Loaded > Regular	Control > Single
	FTI (N.S)	69.7 (19.7)	67.1 (20.6)	67.1 (22.6)	78.0 (20.9)	72.7 (23.3)	74.4 (23.3)	Loaded > Regular	
	Contact area (cm^2)	18.8 (1.8)	18.7 (1.7)	18.6 (1.7)	18.7 (1.8)	18.6 (1.8)	18.6 (1.6)		
Lateral forefoot	Peak pressure (kPa)	231.8 (67.6)	214.5 (68.5)	232.6 (58.4)	271.5 (82.5)	225.3 (55.1)	265.1 (87.7)	Loaded > Regular	Control, Dual > Single
	FTI (N.S)	88.7 (24.3)	76.8 (23.3)	79.8 (21.2)	97.9 (25.7)	81.1 (21.8)	94.6 (26.6)	Loaded > Regular	Control, Dual > Single
	Contact area (cm^2)	25.0 (2.3)	24.7 (2.3)	24.4 (2.1)	25.0 (2.3)	24.7 (2.3)	24.7 (2.2)	Dual: Loaded >Regular	Regular: Control > Dual Loaded Control > Single
Hallux	Peak pressure (kPa)	203.0 (105.1)	204.1 (81.9)	235.5 (88.6)	218.9 (97.2)	225.8 (82.1)	261.6 (98.8)	Loaded > Regular	
	FTI (N.S)	14.0 (8.0)	14.8 (7.5)	18.1 (8.4)	14.6 (7.8)	17.5 (8.4)	20.4 (9.2)	Loaded > Regular	Dual > Control, Single
	Contact area (cm^2)	4.5 (0.4)	4.5 (0.5)	4.5 (0.5)	4.6 (0.4)	4.6 (0.4)	4.5 (0.5)		
Lesser toes	Peak pressure (kPa)	99.4 (38.2)	99.4 (25.0)	96.1 (34.9)	101.7 (36.5)	102.8 (28.9)	116.9 (43.4)	Loaded > Regular	Loaded: Dual > Single, Control
	FTI (N.S)	15.1 (5.5)	14.1 (4.9)	12.9 (4.3)	15.1 (5.5)	15.5 (5.8)	15.2 (5.2)	Loaded > Regular	
	Contact area (cm^2)	9.9 (1.2)	9.2 (1.3)	9.1 (1.3)	9.6 (1.5)	9.6 (1.1)	9.3 (1.8)		

3.2. Footwear Comfort

Subjective footwear comfort ratings from the VAS results revealed there was no significant main effects of weight ($F = 0.84$, $p= .370$, $\eta^2 = .04$) or insole: ($F= 1.54$, $p= .231$, $\eta^2 = .08$) or interactions ($F= 0.41$, p= ,664 , $\eta^2 = .02$) (Figure 2).

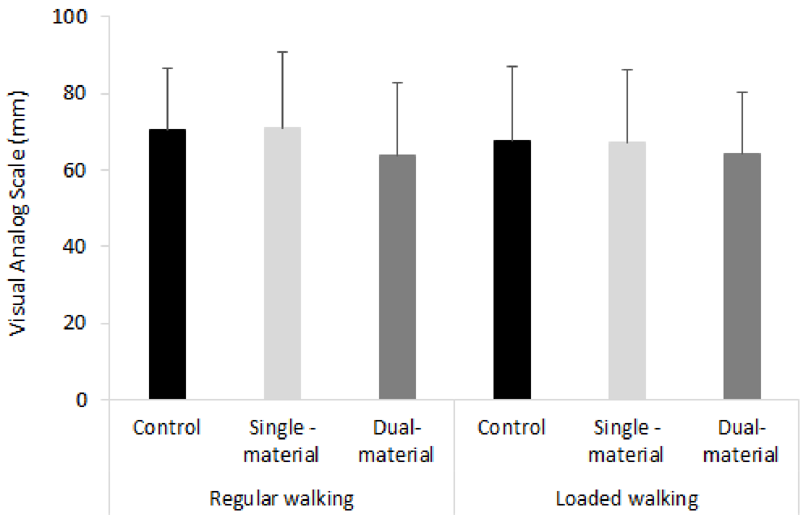

Figure 2. Mean (SD) subjective perception of shoe comfort VAS ratings across participants

3.4. Material testing

Tests were analysed and the stress-strain response was plotted for all specimens (18 in total). All samples exhibited a similar hysteresis loop-type of behaviour as an effect of energy loss (Figure 3A). Polyurethane foam samples (Poly) from both types of insole (Figure 3B) seemed to behave very similarly. Samples from the composite part of the insole (Vis) exhibited higher stiffness i.e. higher stresses for the same strain. Figure 3C and 3D show the mechanical test results for all specimens as a function of density. Stresses were taken from the 3rd loading cycle at 0.3 strain for both 0.8 and 1.6 Hz tests (Figure 3C, 3D). Stiffness seemed to increase with density. Increasing the frequency of cyclic loading by a factor of 2 didn't seem to have a significant effect on the material response. The loading and unloading values were averaged and compared. The difference between loading and unloading values for each material was approximately 33% and 28% for the single material specimens (Poly from single and dual-material insole respectively), and 28% for the composite specimens (Vis). The effect was consistent for values at both 0.8 and 1.6 Hz.

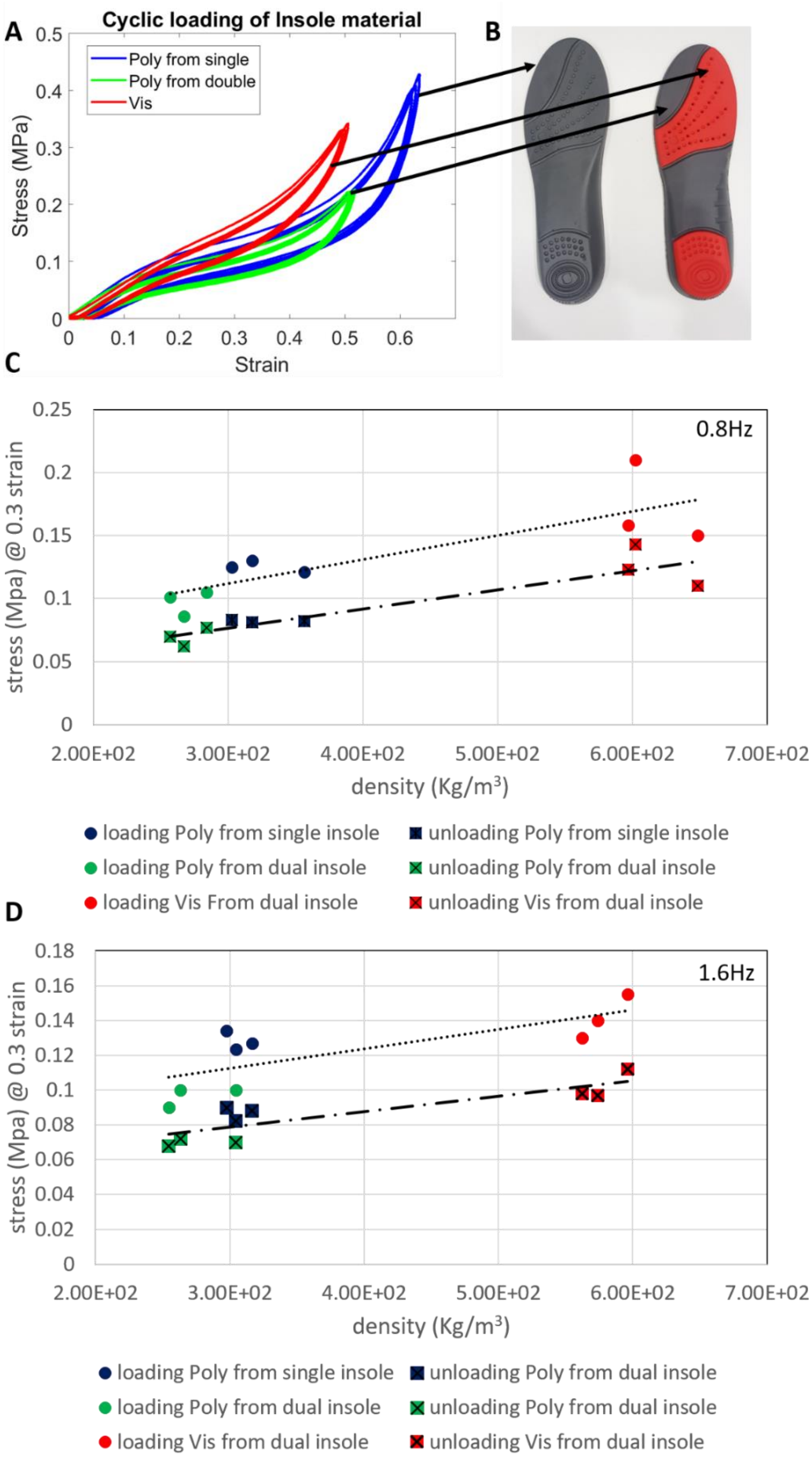

Figure 3. A) stress-strain curves of 5 cycles of compressive loading on specimens of polyurethane foam extracted from the single-material insoles (blue), polyurethane foam extracted from the dual-material insole (green) and composite specimen extracted from the dual-material insole (red). (B)

The two types of insoles used in this study and general areas from which specimens were extracted. (C) The loading and unloading stress of specimens at 0.3 strain loaded at 0.8 Hz, and linear fit (D) loading and unloading stress of specimens at 0.3 strain loaded at 1.6 Hz, and linear fit.

4. Discussion

The material properties of both commercial insoles were effective in reducing rearfoot peak plantar pressure but did not influence perceived footwear comfort during regular and loaded walking. The insole material was thickest in this region (Figure 1A) providing heel cushioning, as reported previously (Goske et al., 2006). Thus, increased insole thickness in the heel region is arguably an important feature in limiting the impact forces from foot-strike that are associated with repetitive overuse injuries. Corroborating research found both static and dynamic insoles reduce tibial shock whilst walking at different speeds (Lavender et al., 2019) and running in Sorbothane insoles (O'Leary et al., 2008). The softer polyurethane of the single-material insole performed better in reducing pressures under the forefoot and rearfoot compared to the stiffer composite of viscoelastic material and polyurethane foam in the dual-material insole (Figure 3A) and the Control during both regular and loaded walking. This is associated with improved pressure redistribution from enveloping (Sprigle et al.,1990; Tsung et al., 2004). The viscoelastic material of the dual-material insole increased the stiffness of the system, reducing deformation across the plantar foot, resulting in a smaller midfoot contact area. Yet, results were limited to the resolution of the pressure sensor size (0.57-0.78 per cm^2), which overestimates of contact area in the pedar system (Price et al., 2016). This resulted in the same contact area in some regions for steps across all conditions.

Insole material specimens were tested under compressive cyclic loading for 5 cycles and at two loading frequencies (i.e. 0.8, 1.6 Hz). The frequencies were chosen within possible human physiological conditions. Increasing the frequency by a factor of 2 seemed to have no significant effect on the material behaviour. Perhaps testing the material in higher frequencies would reveal a more noticeable effect of the viscoelastic parts of the insole, nevertheless these might be outside reasonable physiological range. Moreover, across the range of self-selected walking speeds (average: 1.2 ± 0.2 m.s; range 0.9-1.6 m.s) lateral forefoot pressure generally increased in the dual-material insole compared to the single-material insole but was not perceived to be more comfortable. Bonano et al. (2020) observed the same range of self-selected walking speed (range 0.9-1.6 m.s) to have no influence on perceived comfort in healthy participants in their contoured insoles which also reduced forefoot pressure. More dynamic conditions that increase forefoot plantar loading could reveal differences in perceived comfort, such as running (Yang et al., 2019; Hennig et al., 1996), fatigue (Biseaux and Moretti, 2008), faster walking (Burnfield et al., 2004; Castro et al., 2015) or a greater load (Pau et al., 2015). In addition, insole materials which further increase to the relative midfoot contact area and pressure may also be subjectively perceived as more comfortable (Anderson et al., 2020; Wintana et al., 2009).

Previous studies have assessed Sorbothane material, yet comparisons to the literature are challenging due to the varied measurements and protocols (Rome, 2005). Brodsky et al. (1988) mechanically assessed common insole materials and found Sorbothane was least effective in attenuating the applied to transmitted force. It is contemplated this measure may relate to increased stiffness compared to the other polyurethane samples, as found in our study. Contrary to the results of this study, Windle and colleagues (1999) reported the viscoelastic Sorbothane insoles were most effective in reducing plantar pressure in the rearfoot and forefoot compared to Cambion and PPT insoles whilst marching. If the military boot and heavy bergen (32 Kg) tested benefitted from the stiffness or other mechanical property of Sorbothane that aided cushioning due at higher plantar loads is unknown. We assessed the stress-strain response of new insole materials, aligned with the in-vivo protocol, yet polyurethane foam has also been found to be an effective material for durability. However, the effect might reduce over prolonged use, whilst alternative elastomers may retain their properties for longer (Saraswathy et al., 2009). Perceived comfort also changes over a longer wear time due to both material insole and foot properties (Anderson et al., 2020).

All specimens exhibited a hysteresis type of response to the cyclic loading (Figure 3A). The difference in the surface area under the loading and unloading curve would indicate the energy loss between these two phases i.e. the loading and unloading parts of the cycle. The percentile average difference between stresses during loading and unloading seemed to increase in the polyurethane specimen from the single-material insole (33%) compared to the polyurethane (28%) and composite (Vis) specimens (28%) from dual-material insole, suggesting larger relative energy dissipation for the single-material insole specimen. The polyurethane foam specimens taken from the dual-material insole (i.e. Poly form double Fig. 3C) appear to be of lower density and produce a lower stress response. It unclear whether this is by design, e.g. to counter the added stiffness of the viscoelastic material, or perhaps an unintended result of the process e.g. changes in the manufacturing method to produce composite insoles that might introduce more or larger air bubbles within the foam. Of note, both insoles tended to increase peak pressure in the hallux region ($p = .053$). Similar findings have been reported previously in some (Healy et al., 2011; Castro et al., 2014), but not other studies (Tsung et al., 2004). This could be related to the different functions during terminal stance phases to generate force and move the body forward, opposed to absorb shock during the loading phase. The increased energy absorption of the single-material insole during propulsion may increase oxygen consumption and reduce perceived comfort, as found in running (Sinclair et al., 2016). Perhaps the use of materials and design that would be aimed at a balance of pressure reduction and energy return in different areas of the foot could have had a more pronounced effect in perceived comfort. Footwear comfort perception is also affected by foot sensitivity (Mills et al., 2018), so individual analyses may have been more appropriate. Further testing would be required to distinguish how and why subjective footwear comfort is influenced by materials and insole design during regular and loaded walking.

There were some limitations to the present study. The viscoelastic material was tested as part of the composite (i.e. attached to the polyurethane foam). In addition, the insole was part of a general complex system including the walking shoes and treadmill belt. Furthermore, manufacturing artefacts and material flaws (e.g. unintended bubbles within the material) could be a source of scatter in material properties (Todd et al., 1998). It should be acknowledged the participants were healthy with no reported foot problems and they only accommodated and walked in the insole and load conditions for a limited time at a self-selected comfortable walking pace. If the reductions of plantar pressure in the softer single-material insole are effective in preventing injuries, such as foot blisters and metatarsal stress fractures, is unknown and requires further investigation. Lastly, the plantar pressure data collected during treadmill walking may not be equivocal to overground walking, as differences have been reported during running (Hong et al., 2012; Garcia-Perez et al., 2013). However, we do not expect this confounded our findings on plantar pressure during backpack load carriage or insole material properties.

4.1. Conclusion

Backpack load carriage significantly increases peak plantar pressure during walking with and without the use of insoles. The more compliant single-material insole was more effective in reducing rearfoot and forefoot plantar pressure by increasing the midfoot contact area compared to the stiffer composite in the dual-material insoles. Therefore, the soft uniform polyurethane material is recommended for insoles designed to reduce plantar pressure in regular and loaded gait up to 10% bodyweight.

Further research is needed to assess if the stiffer material of the dual-material insole improves pressure distribution after a longer wear time or at increased intensities such as greater backpack load, faster walking or running. Only measurement approaches that test the mechanical properties, in-vivo biomechanical and perception of insole material properties provide designers and clinicians comprehensive knowledge to base decisions (Sterzing et al., 2012). Finite element modelling might also be able to shed more light into quantifying insole material effects to the system behaviour in these different conditions (Cheung & Zhang, 2008). This would support a clearer picture, and to identify an optimum combination of design and insole materials for specific use and individual biomechanical needs (Craptree et al., 2009).

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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