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The specification of personalised footwear for rapid manufacturing: a pilot study

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Abstract. Although rapid manufacturing has potential in producing personalised footwear, it is not known how best to measure feet in this context nor even whether a personalised shoe can positively affect comfort, performance and prevent risk from injury. A pilot study was conducted to define anthropometric measurement techniques for specifying personalised footwear and evaluate the most effective methods of measuring discomfort, performance and injury risk. Recreational runners were recruited and had anthropometric measurements taken as well as the plantar surface of both feet scanned. Participants then were fitted with footwear under two experimental conditions: control and personalised insole. The footwear were compared in terms of discomfort ratings, performance and injury risks. Metatarsophalangeal joint height and hallux height showed positive correlations ($p \leq 0.05$) with discomfort scores in the forefoot, whereas relative arch deformation showed significant positive correlations ($p \leq 0.05$) with discomfort scores in the midfoot and arch areas. No significant differences were found between the two conditions for discomfort scores and performance. With regard to injury risks, significant differences ($p \leq 0.05$) were found between the two conditions for midfoot peak plantar pressure. The results suggest that producing personalised insoles from scan data and the rapid manufacturing process is feasible.

Keywords. Footwear, Anthropometry, Rapid Manufacturing.

1. Introduction

Rapid manufacturing (RM) works without any tooling and therefore can significantly reduce unit costs because they can be produced near the location they will be used, minimizing transportation and stock space (Hopkinson and Dickens, 2001). In addition, the fact that RM can produce unique elements with geometric freedom allows the industry to provide low production volumes or personalised products economically feasible such as footwear to the final customer.

Footwear is the most important accessory for a runner. Despite aesthetic options becoming available on the market, personalisation of the footwear is potentially beneficial for individuals because of the following: (1) 'perfect fit' could be achieved; (2) the preferences in terms of comfort can be met; (3) the personal requirements for reducing the injury risks can be provided (e.g. amount of cushioning needed by each individual); and (4) personalised footwear could also be important for improving performance.

In order to specify personalised footwear that is optimal to the individual, it is important to bear in mind that foot shape plays an important role in the development of many types of injury (James et al., 1978; McKenzie et al., 1985). Low arched (LA) individuals usually have more spread of plantar pressure and are speculated to have more discomfort because of the lack of arch (Cheng and Perng, 1999). The high arched (HA) foot is characterized by the longitudinal arch being more rigid and not so flexible, which makes it less efficient at absorbing impact shocks (Cavanagh, 1980; McKenzie et al., 1985).

Although it appears that arch height is a crucial measurement that can categorize individuals, other measurements can also be important in determining individual preferences/needs, including instep girth, bottom width, heel height, toe box space and so on (Goonetilleke et al., 1997; Cheng and Perng, 1999; Witana et al., 2004). Hence, it is not known how best to measure feet in this context nor even whether a personalised running shoe can positively (or not) affect performance, comfort and injury risk in comparison to the generic ones currently available on the market.

A pilot study was conducted in order to investigate the important measurement techniques for specifying such personalised footwear. The aims of the study were: (1) to define anthropometric measurement techniques for specifying personalised footwear; (2) to evaluate the most effective methods of measuring discomfort, performance and injury risk. The data and the findings of the study will be presented in this paper.

2. Method

Six recreational runners (3 males and 3 females) were recruited (age 30.5 yrs, \pm 3.9; mass 65.25 kg, \pm 16.5; height 165.8 cm, \pm 12.8). A repeated measures experimental design was utilized and participants were recruited using convenience sampling and snowballing techniques.

2.1. Foot measurements

Detailed anthropometric measurements were taken following Hawes and Sovak (1994), to capture dimensional aspects of the foot. The 16 measurements included girths, lengths, widths and heights. Additional anthropometric data was also collected as described by Williams and McClay (2000). Arch ratio, arch index and relative arch deformation (RAD) were calculated from these measures following Williams and McClay (2000).

Moreover, individuals had the plantar surface of their both feet scanned in a non weight bearing position, using a 3 dimensional laser scanner (Model: 200; 3D Digital Corporation, Newtown, USA).

2.2. Experimental conditions

Once the scan data were taken, they were manipulated and personalised insoles for trainers were manufactured from the scans using polyamide and utilizing selective laser sintering, a RM technique. The insoles were designed to match the form of the participants' feet like a glove, but not to provide correction of the lower limb abnormalities. Two conditions, control (standard shoe) and personalised (shoe + personalised insole), were compared through single blind trials.

2.3. Performance, discomfort and injury risks assessments

Running economy was used to measure performance. Participants were asked to wear one of the two running shoe conditions (randomly assigned) and run on a treadmill for 6 minutes in each condition. Expired air was collected using an Ultima Cardio2 (Medical Graphics Corporation, St Paul, USA) equipment.

At the end of each run on the treadmill for the running economy trial, participants were given a 150 mm Visual Analog Scale (VAS) to measure self-perceived discomfort (Mundermann et al., 2002). Six aspects of the foot were evaluated: heel, midfoot, forefoot, fit, arch height and overall. A 7-point ('hot' to 'cold') thermal sensation scale was also used as described by the International Organization for Standardization (ISO 7730, 1994) to assess thermal comfort.

An F-Scan Mobile (Tekscan Inc, USA) in-shoe plantar pressure distribution sensor (N/cm^2) was placed in the shoe. The participants were asked to run for 5

times under each condition (control and personalised) for 10 meters whilst their plantar pressure distribution was recorded.

Furthermore, participants were asked to run for 5 times under each experimental condition, while the Vicon MX system (250Hz; Oxford Metrics, Oxford, UK) was used to collect data. Ground reaction force was also recorded (50Hz; Type: 9281; Kistler Instrumente AG, Winterhur, Switzerland).

The variables chosen to evaluate the injury risks were: peak plantar pressure, rearfoot eversion, tibial rotation and peak vertical impact forces. These variables allowed to assess the angles of the ankle joint, pressure and force applied on the ground.

3. Results

Anthropometric measures were within the range of the normal distribution of the population (Hawes and Sovak, 1994).

Metatarsophalangeal joint height (MPJH) showed significant ($p \leq 0.05$) positive correlations with discomfort scores in the midfoot ($r = 0.918$) for the control condition and with discomfort scores in the forefoot ($r = 0.824$) and overall discomfort ($r = 0.872$) for the personalised condition. Hallux height showed positive correlation with discomfort scores in the forefoot ($r = 0.896$) and overall discomfort ($r = 0.836$) for the personalised condition. No other significant correlations were found between anthropometric measurements and the discomfort, performance and injury risk variables. There were also no significant correlations between arch ratio and arch index and these variables. However, RAD showed significant positive correlations ($p \leq 0.05$) with discomfort scores in the midfoot ($r = 0.910$ for the control condition and $r = 0.926$ for the personalised condition), in the arch ($r = 0.930$ for the control condition and $r = 0.906$ for the personalised condition), and fit ($r = 0.757$ for the control condition and $r = 0.861$ for the personalised condition) aspects.

Student's t-test showed no significant differences between the two conditions for discomfort scores. The mean ratings for foot discomfort are illustrated in Figure 1.

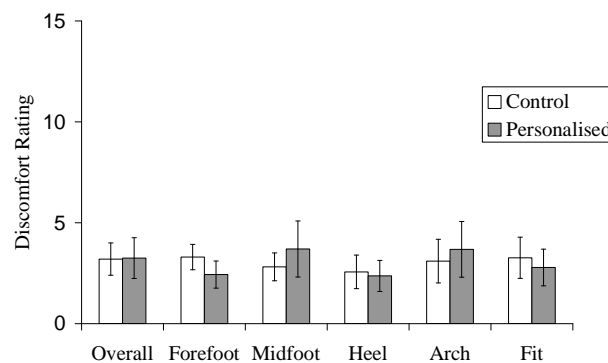


Figure 1. Mean discomfort ratings and standard error for the control and personalised conditions.

No significant differences were found for peak plantar pressure under the heel and forefoot areas. The t-tests revealed significant differences for peak plantar pressure under the midfoot ($p \leq 0.05$) between the two conditions.

No statistical differences were found between the two conditions for tibial internal rotation, rearfoot pronation and impact peak force (Table 1).

Table 1. Biomechanical data.

Variable	Control condition mean \pm SD	Personalised condition mean \pm SD	p
Rearfoot eversion ($^{\circ}$)	2.92 \pm 0.62	2.64 \pm 0.97	0.374
Tibial internal rotation ($^{\circ}$)	13.4 \pm 3.85	13.55 \pm 3.38	0.771
Vertical impact peak (bw)	1.3 \pm 0.36	1.16 \pm 0.23	0.381

Student's t-test showed no significant differences between the two conditions for the VO₂ consumption (25.762 mL/kg/min, \pm 5.359 for the control condition and 26.379 mL/kg/min, \pm 4.98 for the personalised condition).

4. Discussion

The research presented was a pilot study, therefore only six individuals were recruited. This must be borne in mind when interpreting the results and thus, it was expected that there would be inconsistencies with the literature.

Discomfort ratings were low and no significant differences were found between the two conditions. This lack of significance is not consistent with the literature. For instance, Mundermann *et al.* (2003) reported that a molded orthotic, was more comfortable in comparison to posting orthotics and nonmolded control conditions. In addition, Yung-Hui and Wei-Hsien (2005) showed that total contact inserts are effective in reducing discomfort when wearing high-heeled shoes. This absence of agreement could be anticipated due to the small sample size and the short period of time that the insoles were worn (6 minutes) in the current study.

With regard to the plantar pressure distribution, there were similarities with the literature. Although peak pressure in the heel region was not significantly different in the two experimental conditions, the midfoot area was significantly greater for the personalised condition in comparison to the control. There was also a trend for higher peak pressure ($p = 0.073$) in the forefoot region for the control condition. Studies have documented that total contact inserts significantly reduced peak plantar pressure in the metatarsal and heel regions and redistribute pressure to the midfoot area, in comparison to a flat insert (Chen *et al.*, 2003; Yung-Hui and Wei-Hsien, 2005).

The anthropometric measurements, arch index and arch ratio did not correlate significantly with: discomfort ratings, peak plantar pressure, vertical impact peak,

tibial rotation and rearfoot eversion. Similarly, other studies did not find any correlation between arch height and running injuries (Nigg et al., 1993; Wen et al., 1997; Hreljac et al., 2000). On the other hand, Williams III *et al.* (2001) reported that LA individuals have increased rearfoot eversion excursion in comparison to HA runners. A possible explanation for this is the fact that Williams III *et al.* (2001) compared HA and LA runners, rather than analyse the correlation between arch height and injury risks. The pilot study sample was within the range of the normal distribution of the population and as such, no LA or HA runners were recruited. The of correlation of the anthropometric measurements MPJH, hallux height and RAD with discomfort ratings may indicate what types of individuals (e.g. with stiff arches) can have more discomfort wearing the insoles. However, more evidence is needed to confirm or reject these correlations.

The literature reports a positive correlation between arch stiffness and tibial rotation (Nigg et al., 1998), however as expected due to the small sample size, that was not found in the pilot study. Furthermore, individuals with stiff arches are thought to be poor shock absorbers in comparison to people with flexible feet (Butler et al., 2007), which would influence the vertical impact peak values. In the same manner as the arch height data, the results suggest that more evidence is needed to confirm or reject a relationship between impact peak and arch stiffness.

The pilot study had limitations (i.e. the short running time on the treadmill and the small sample size). It also believed that the performance results may not be reliable. For practical reasons, performance tests were not duplicated to reduce within subject variations (Williams et al., 1991). Furthermore, many variables must be controlled (e.g. time of the day) in order to get reliable running economy data and differences proved difficult to be found. Nevertheless, the peak plantar pressure distribution, discomfort assessments and the anthropometric measurements showed promise for future studies.

With regard to the rapid manufacturing, the process of capturing the plantar surface of the foot, manipulating and manufacturing worked well. The positive attributes of polyamide, were that the insoles did not show signs of breaking and did not cause significant discomfort (compared to the control condition). This pilot work is the pre-cursor for a longitudinal study involving a broader sample of the population and which will commence in 2009.

5. Conclusion

The anthropometric measurements MPJH, hallux height and RAD showed potential in determining which individuals might develop discomfort wearing the glove fit personalised insoles. Similarly, the injury risks assessments indicated potential in identifying possible benefits of such insoles. On the other hand, the performance test proved to be difficult to find differences.

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