Physiological Versus Perceived Foot Temperature, and Perceived Comfort, during Treadmill Running in Shoes and Socks of Various Constructions

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ABSTRACT

The purpose of this investigation was to determine whether people could accurately perceive physiological foot temperature during brief bouts of treadmill running in different combinations of shoe and sock models, and also how perception of comfort was influenced. Sixteen young adult males (21.3 ± 0.8 years, 181.8 ± 1 cm, 74.6 ± 1.5 kg) participated in two separate studies where they alternated running and resting for 10 min each with temperature probes attached at two sites on the lateral dorsal aspect of the right foot. Subjects reported perceptions of foot comfort and temperature after each run using 10 cm visual analogue scales. In the first experiment, different sock models were tested with the same shoe model; in the second experiment, different shoe models were tested with the same sock model. Foot temperature did not differ statistically as a function of shoe or sock model in either experiment. Subjects did not perceive any difference in foot temperature in the shoe experiment, but perceived their foot as being cooler when wearing either a polyester sock or a calf compression sleeve and more comfortable when wearing shoes with less mass. Taken together, the results suggest that subjects' perceptions of foot temperature may not coincide with physiological foot temperature and are more strongly influenced by sock characteristics than shoe characteristics. Further, shoe mass (but not sock fiber weave or composition) may impact comfort perception by subjects.

I. INTRODUCTION

When shopping for footwear, runners face hundreds of options that differ structurally, functionally, and cosmetically. Runners should select shoes that are designed for their foot architecture, gait mechanics, and intended training patterns because such selections will minimize injury risk and maximize performance potential [1]. One factor especially important for distance runners is how well a sock or shoe dissipates heat, primarily through sweat convection. Heat dissipation is important not only for maintaining appropriate heat dynamics during running but also from a comfort standpoint.

The sock is critical for maintaining foot climate because it wicks sweat from the foot to the shoe upper for evaporation.

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Synthetic fibers with better wicking properties such as acrylic and polyester have replaced cotton fibers in most athletic sock models [2]. Cotton fibers are less conducive to moisture transport than synthetic fibers, have longer drying times [3] and, on average, swell 9× more than synthetic fibers [4]. If the foot is wet, evaporation of perspiration is reduced and the cooling effect from sweating is hampered [5]. Data on the effects of sock construction on foot temperature are available but conflicting. A study of five different commercially-available socks showed that both sock material and weave impacted sweat accumulation and foot temperature during running [6]. In a separate study, experimenters asked subjects to run on a treadmill for thirty minutes in either a standard sock or an ergonomic fitted sock. There were no differences in physiological foot temperature as a result of sock model, though subjects perceived the ergonomic sock as being more comfortable and their feet as being more cool compared to the standard sock [7]. This suggests that runners' perceptions of foot temperature may differ from physiological foot temperature. One author team opined that temperature perception is often confused with perception of sweat accumulation [5]. Factors such as sock softness and dryness have also been correlated with perceptions of comfort [8].

In shoes, the upper is the most important component when it comes to heat transfer because it is the component that wraps around the foot surface. Uppers can be made of cotton, leather, polyurethane (PU), polyvinyl chloride (PVC), or other synthetic fibers [5], and may be thin, thick, or perforated to allow for air flow. Across a range of relative humidity, materials such as PU- or PVC-coated woven fabric have much better thermal conductivity than materials such as microporous PU or PU-coated non-woven fabrics, with various types of leather exhibiting intermediate properties [5]. Water vapor permeability is higher for materials like leather and lower for PVC-coated polyester or fabric (Boulanger et al. 1976 in [5]). In terms of comfort perception, the tensile properties of the upper material [5] and foot contact perception mediated by the midsole/insole [9] are also important factors. Despite this knowledge, we are unaware of any published studies that have scientifically characterized the effects of shoe material on actual and perceived foot temperature during running.

The purpose of this study was to test if people could perceive differences in foot temperature as a consequence of running in shoes and socks of varying construction. In the first experiment, three different sock models and a calf compression sleeve were tested while runners wore the same shoe. In the second experiment, four different shoe models were tested while runners wore the same sock. Three hypotheses were tested. Regarding *physiological* foot temperature, we hypothesized that there would be differences in physiological foot temperature based on shoe/sock materials such that the sock with the lowest percentage cotton and the shoes with the highest amounts of mesh would be associated with lower physiological foot temperature (Hypothesis A). Regarding *perceived* foot temperature, we hypothesized that there would be differences in perceived foot temperature based on shoe/sock materials such that the sock with the lowest percentage cotton, the compression sleeve, and the shoes with the highest amounts of mesh would all be associated with lower percevied foot temperature (Hypothesis B). Finally, we hypothesized that subjects' perceptions of comfort would be inversely proportional to those of foot temperature as a hotter foot is perceived as less comfortable (Hypothesis C).

II. METHODS

The Drake University Institutional Review Board gave approval for the study (ID 2009-10088). Inclusion criteria were that potential subjects had to be male, capable of exercising safely in a men's size 11.5 shoe, and able to run for at least 30 min continuously. Exclusion criteria were any injuries or disabilities that precluded running for that length of time, or that predisposed one to run with an abnormal gait. Sixteen young adult males (21.3 ± 0.8 y, 181.8 ± 1 cm, 74.6 ± 1.5 kg) who self-reported as regular exercisers participated in each of two separate studies (total n=32). Eight subjects participated in both the shoe and sock experiment; thus, anthropometric

Figure 1. Experimental technique. Flexible thermometers were attached midway on the lateral dorsal surface of the right foot. One thermometer was placed directly against the skin (left), and one thermometer was placed just medial to the same site against the sock surface (middle). Thermometers were held in place with electrical tape at the measurement site, above the ankle, and just below the knee. A shoe was then placed over the foot (right).

characteristics did not vary by group (sock experiment = 21.3 $\pm$ 1.4 y, 181.9 $\pm$ 1.6 cm, 73.8 $\pm$ 2.4 and shoe experiment = 21.3 $\pm$ 1.4 y, 181.6 $\pm$ 1.9 cm, 75.5 $\pm$ 2.6).

Subjects reported to the lab wearing a T-shirt and shorts. After completing a medical history questionnaire to ensure it was safe for them to participate, subjects were fitted with a heart rate monitor (Polar Electro Oy) and two flexible termperature probes or thermistors (YSI Instruments). One thermometer was placed directly against the skin surface midway on the dorsal lateral aspect of the right foot (Fig 1, left) and held put with electrical tape. We chose this site from all possible choices because 70% of sweat secretion from the foot occurs on the upper surface [10]. A second thermometer was placed just medial to the first over the sock (Fig 1, middle) in similar fashion, and then both probes were taped at the ankle and just below the knee before being threaded up through the waistline. The test shoe was then placed over the sock (Fig 1, right). Thus, in the shoe experiment the probes were placed once initially and never adjusted, whereas in the sock experiment the second probe had to be reattached each trial because the sock changed. We only measured temperature at one site because a previous study that examined foot temperature during treadmill running at multiple sites reported that all sites showed similar patterns [7] and the lateral dorsal aspect was deemed least noticeable by subjects during pilot trials.

The sock experiment tested three different sock models (all ankle length) and a calf compression sleeve. The three sock models varied by fiber composition: one sock was 100% cotton (“cotton”); one sock was 53% polyester, 37% cotton, 8% olefin, and 1% each natural latex and spandex (“blend”); and one sock was 98% polyester and 2% spandex (“polyester”). The graduated calf compression sleeve was made of 70% polypropylene and 30% spandex and had a compression level of 26 mmHg. Each subject’s calf circumference was measured prior to being fitted with either a medium-sized (12-13.5 in circumference) or large-sized (14.5-16 in circumference) sleeve which was worn at the same time as the blend sock. Subjects wore the same shoes (Asics GT-2110 size 11.5; Fig. 1, right) for all four sock trials. The Asics GT-2110 was used only in the sock trials and never in the shoe trials.

The shoe experiment tested four different shoe models all men’s size 11.5. Two different brands were used. For each brand, we selected one shoe model whose upper was made of mostly mesh (“mesh”) and a second shoe model whose upper was made of leather and/or vinyl with ventilatory grommets. These shoes will be referred to as “Brand X Mesh”, “Brand X Solid”, “Brand Y Mesh,” “Brand Y Solid” in this article. Subjects wore the same socks (blend) for all four shoe trials.

In the shoe experiment, all 16 subjects completed a 5 min warm-up at approximately 70% of the treadmill speed they wanted to use for the actual trials followed by a 5 min rest. In the sock experiment, half of the subjects (n = 8)

		Cotton	Blend	Blend+Sleeve	Polyester
Warm-Up	**Skin Site**	+2.06 ± 0.33	+2.23 ± 0.33	+2.68 ± 0.32	+2.14 ± 0.32
	Sock Site	+1.95 ± 0.39	+2.35 ± 0.38	+3.15 ± 0.38	+2.84 ± 0.38
Cold-Start	**Skin Site**	+2.19 ± 0.3	+2.53 ± 0.29	+2.44 ± 0.3	+1.91 ± 0.27
	Sock Site	+2.25 ± 0.38	+2.88 ± 0.37	+3.09 ± 0.39	+2.35 ± 0.35

Table 1. Change in physiological foot temperature in the sock experiment after treadmill running for 10 min. Values are average in °C ± standard error. There were no statistically significant differences by site or shoe.

		Cotton	Blend	Blend+Sleeve	Polyester
Warm-Up	**Comfort**	4.0 ± 1.4	4.2 ± 1.3	5.0 ± 1.3	5.7 ± 1.3
	Temp.	5.9 ± 0.7*,†	5.8 ± 0.6**,‡	3.7 ± 0.6*,**	4.0 ± 0.6†,‡
Cold-Start	**Comfort**	6.2 ± 0.9	4.7 ± 0.8	5.4 ± 0.9	5.7 ± 0.8
	Temp.	5.9 ± 0.6	5.9 ± 0.6	4.3 ± 0.6	3.8 ± 0.6

Table 2. Perceived foot comfort and temperature in the sock experiment after treadmill running for 10 min as assessed on a 10 cm visual analogue scale. A "0" indicates most uncomfortable/hot imaginable whereas a "10" indicates most comfortable/least hot imaginable. Values are average measurements ± standard error. The single asterisk and double asterisks represent statistically significant differences between the blend+sleeve compared to either the cotton or blend alone, respectively. The single dagger and double daggers represent statistical trends towards a difference between the polyester compared to either the cotton or blend alone, respectively.

completed a similar warm-up and half started cold (n=8). We did this so that we could investigate whether a warm-up period influenced our results, and the data from the two shoe experiment subpopulations were analyzed separately. No data was collected during warm-up.

Trial order in both the shoe and sock experiments was counterbalanced. After being fitted with the sock and shoe for their first trial, subjects ran for 10 min at a constant speed on the treadmill with foot temperatures from both the skin and sock sites recorded pre- and post-run. Subjects ran at the same constant speed for each trial. Heart rate was also recorded pre- and post-run. Subjects were allowed water *ad libitum*. At the end of 10 min, subjects stopped and straddled the treadmill belt so they could immediately complete two 10 cm visual analogue scales assessing foot comfort and foot temperature. The foot comfort scale was anchored with the phrase "least comfortable imaginable" on the left and "most comfortable imaginable" on the right. The foot temperature scale was anchored with the phrase "most warm imaginable" on the left and "least warm imaginable" on the right. Subjects marked their perception by drawing a vertical line on the continuum. Subjects then sat on a physical therapy table for 10 min to rest. After the 10 min rest period, subjects received their next shoe/sock combination and repeated the cycle until all four trials were completed.

ANOVA was used to analyze the results, with "trial order" and either "sock model" or "shoe model" as included factors. ANOVA was performed separately for the sock and skin thermometer sites, heart rate, comfort perception, and temperature perception. An alpha level of 0.05 was used for significance, with statistical trends defined as p-values between 0.05 and 0.1.

III. RESULTS

a. Sock Experiment

Temperature recordings for all four trials in the sock experiment are shown in Table 1 for both the warm-up (n=8) and cold-start (n=8) groups. Changes in foot temperature pre- to post-running were not statistically different for any sock model in either group (all p>0.504). There were no trial order effects for foot temperature at either the skin or sock site in the warm-up group, nor for the sock site in the cold-start

	Brand X Mesh	Brand X Solid	Brand Y Mesh	Brand Y Solid
Skin Site	+2.00 ± 0.35	+1.88 ± 0.36	+2.18 ± 0.35	+1.82 ± 0.35
Sock Site	+1.80 ± 0.43	+1.77 ± 0.44	+2.07 ± 0.43	+2.16 ± 0.43

Table 3. Change in physiological foot temperature in the shoe experiment after treadmill running for 10 min. Values are average in °C ± standard error. There were no statistically significant differences by site or shoe.

group; however, there was a significant trial order effect in the cold-start group at the skin site (p=0.033) such that later trials had a smaller increase in foot temperature, as expected given the lack of a warm-up. There were no significant differences in heart rate change seen in either the warm-up or the cold-start group.

Perceptions of foot comfort and temperature during the sock experiment are shown in Table 2 for both the warm-up and cold-start groups. In the warm-up group, there were significant differences in foot temperature perception by sock. Subjects perceived their feet as being cooler when wearing the blend + sleeve as compared to when wearing the blend alone (p=0.034) or the cotton sock (p=0.026). There were also statistical trends such that subjects perceived their feet as being cooler when wearing the polyester sock as compared to blend alone (p=0.076) or the cotton sock (p=0.058). Similar effects, though not significant, were seen in the cold-start group. There were no differences in comfort ratings for either the warm-up group (p=0.789) or the cold-start group (p=0.669).

b. Shoe Experiment

All subjects in the shoe experiment completed a 5-minute warm-up prior to data collection as described in the Methods. Despite the warm-up, there was a significant main effect of trial order at the skin site (p=0.012), and a trend for a main effect of trial order at the sock site (p=0.086), such that in both situations the changes in foot temperature from pre- to post-exercise was much greater for trial #1 than any subsequent trial (p≤0.026). To examine this further, we removed all data points from trial #1 and re-ran the ANOVA using only the data from trials #2-4. There were no trial order effects in the edited data set. However, more importantly, all p-values that were significant in the original analysis *remained* significant in the second analysis, and all p-values that were non-significant in the original analysis *remained* non-significant in the second analysis. This suggests that the main effect of trial order did not meaningfully influence the main effect of shoe condition. Consequently, the data presented for the shoe experiment includes all trials.

Temperature recordings for all four trials in the shoe experiment are shown in Table 3 (n=16). There were no significant differences in foot temperature change pre- to post-running for any shoe model at either the skin thermometer (p=0.934) or sock thermometer (p=0.893) sites.

There were no significant differences in heart rate change and no trial order effects.

Perceptions of foot comfort and temperature during the shoe experiment are shown in Table 4. There were significant differences in subjects' perceptions of shoe comfort (p<0.001) such that subjects perceived "Brand X Mesh" as significantly more comfortable than "Brand X Solid" or "Brand Y Mesh" (both p<0.001), and demonstrated a trend towards perceiving it as more comfortable than "Brand Y Solid" (p=0.087). Subjects perceived "Brand Y Solid" as being significantly more comfortable than either "Brand X Solid" (p=0.031) or "Brand Y Mesh" (p=0.011). There were no significant differences in subjects' perception of foot temperature across shoes (p=0.123).

IV. Discussion

The main finding of this study was that even though there were no differences in *physiological* foot temperature across the different shoe and sock trials, subjects *perceived* differences in foot temperature in

	Brand X Mesh	Brand X Solid	Brand Y Mesh	Brand Y Solid
Comfort	6.8 ± 0.5*,**,•	4.0 ± 0.5*,†	3.7 ± 0.5**,‡	5.6 ± 0.5•,†,‡
Temperature	3.5 ± 0.6	5.2 ± 0.6	5.4 ± 0.6	4.6 ± 0.6

Table 4. Perceived foot comfort and temperature in the shoe experiment after treadmill running for 10 min as assessed on a 10 cm visual analogue scale. A "0" indicates most uncomfortable/hot imaginable whereas a "10" indicates most comfortable/least hot imaginable. Values are average measurements ± standard error. The asterisk indicates a statistically significant difference between Brand X Mesh and Brand X Solid whereas the double asterisks indicates a statistically significant difference between Brand X Mesh and Brand Y Mesh. The dot indicates a trend towards a statistically significant difference between Brand X Mesh and Brand Y Solid. The dagger indicates a statistically significant difference between Brand X Solid and Brand Y Solid whereas the double dagger represents a statistically significant difference between Brand Y Mesh and Brand Y Solid.

the sock study and in foot comfort in the shoe study.

In Hypothesis A, we speculated there would be differences in *physiological* foot temperature based on shoe/sock materials such that the sock with the lowest percentage cotton and the shoes with the highest amounts of mesh would be associated with lower physiological foot temperature. Neither the sock data (Table 1) nor the shoe data (Table 3) support this hypothesis as there were no differences across trials within either experiment. We initially thought that a shoe upper made from mostly mesh would allow for better air flow compared to one that had a solid upper with ventilation grommets, so these findings were somewhat surprising (Table 3). Regarding the sock data (Table 1), other teams have also shown that sock sweat accumulation and foot temperature are unrelated to sock cotton content [6; 7]. For instance, in the study mentioned earlier involving treadmill running, the standard sock was 76% cotton and the ergonomic sock was 44% cotton and 42% polypropylene, yet no difference in physiological foot temperature was found post-run between the two socks. Consistent with those findings, another team investigating two sock models of equal weave but different fiber content (100% acrylic vs. 100% cotton) wrote that there were no differences in runners' perceptions of foot temperature or comfort between the two sock models [11].

For Hypothesis B, we predicted that there would be differences in *perceived* foot temperature based on shoe/sock materials such that the sock with the lowest percentage cotton, the compression sleeve, and the shoes with the highest amounts of mesh would all be associated with lower perceived foot temperature. Our sock trial findings partially support this hypothesis (Table 2) but our shoe trial findings do not (Table 4). Considering the sock data first (Table 2), we predicted that the calf compression sleeve would elicit lower perceptions of foot temperature. Ratings of perceived foot temperature were statistically significantly lower for the blend+sleeve trial compared to both the cotton sock and blend sock, but not the polyester sock. Further, statistical trends were seen for lower ratings of perceived foot temperature in the polyester sock compared to both the cotton sock and blend sock. No differences in temperature perception were found in the shoe trials (Table 4).

Our last hypothesis (Hypothesis C) related to both experiments and was that subjects' perceptions of foot comfort would be inversely proportional to their perceptions of foot temperature. Stated another way, we hypothesized that the two measures would coincide with one another. The data in Tables 2 and 4 do not support our hypothesis and suggest that subjects separated perceptions of foot comfort and foot temperature in this study. We were somewhat surprised that there were no differences in comfort ratings for the sock experiment (Table 2) given that the socks were made of different fibers and had slightly different weaves. It is possible that the proprioceptive abilities of the foot were not sensitive enough to detect the fiber/weave differences, or that these particular fibers/weaves have similar enough textural properties as to be indistinguishable.

Subjects reported comfort perception differences in the shoe trials (Table 4). Whether a shoe was “mesh” or “solid” did not influence comfort ratings in this study, as the two shoes with higher comfort ratings were “Brand X Mesh” and “Brand Y Solid.” Notably, “Brand X Mesh” and “Brand Y Solid” had substantially less mass than “Brand X Solid” and “Brand Y Mesh” (330.8 and 318.8 g versus 457.9 and 430.9 g, respectively). It is tantalizing to suggest that mass may have played a role in comfort perception. To explore this possibility, we weighed the shoes that our subjects normally trained in (e.g., their own shoes). Across the 16 subjects in the shoe trial the average training shoe mass was 355.4 $\pm$ 5.4 g (range 323.2 to 381.6 g). Therefore, both the “Brand X Mesh” and “Brand Y Solid” shoes were more similar in mass to the shoes that subjects normally ran in and, by comparison, both “Brand X Solid” and “Brand Y Mesh” had greater mass than shoes that subjects normally ran in. This follow-up supports the idea that mass may have played a role in comfort perception.

Curiously, the two shoes that were perceived as most comfortable had the two lowest prices—both “Brand X Mesh” and “Brand Y Solid” cost \$40-45 whereas “Brand X Solid” cost \$125 and “Brand Y Mesh” cost \$100. Superficially our finding that the lower-priced shoes were rated as more comfortable than the higher-priced shoes is congruent with findings reported by another group. Researchers used low-, mid-, and high-cost running shoe models from two different brands to examine plantar pressure distribution and compared those findings with subjects’ perceptions of comfort using visual analogue scales similar to ours [9]. As in our study, they found that the lower-cost shoes were rated as more comfortable by the subjects. Shoe mass values were not reported, and it is unknown whether these researchers factored shoe mass into their analysis. If the higher-cost shoes contain additional materials or parts that are lacking in the lower-cost shoes (hence “justifying” the higher price), then the reduced comfort ratings seen in these studies may be partially explained by the increased mass of the higher-cost shoes. To explore this possibility, we recorded the make and model of the running shoes that our subjects normally trained in and retrospectively determined purchase price using the Internet based on the most recently-available model. The average purchase price was \$103 $\pm$ \$5.40 (range \$60-\$140). This follow-up does not support the idea that shoe cost and shoe mass are related. Nevertheless, it is clear that shoe mass is an important factor to consider when performing experiments that measure comfort perception across different footwear.

This study has several limitations. First, we used only a 10-min running bout. Most people, especially trained runners, do not run for only 10 minutes and it is possible that differences in physiological foot temperature dynamics are only manifest after longer running times. (However, one previously-referenced study discounts this notion [7]). Second, although a treadmill in a laboratory environment provided for a controlled experiment, it does not mimic the real environment and does not account for any environmental factors. It is possible that physiological foot temperature dynamics would be different under different environmental conditions. Third, subjects were able to see the shoes and socks and may have made inferences based on preconceptions of or prior experiences with particular brands or styles that influenced their perceptions. This problem is difficult to address; for instance, had we used athletic tape to mask certain features on the running shoes, it would have altered ventilation properties of those shoes, and it would be extremely difficult to hide dyed or sewn-in identifying information on the socks. Fourth and finally, because we wanted to minimize inter-subject variability our subject pool was one of convenience and included only males who could exercise in a men’s size 11.5 shoe. Our results may be different for females or males of different stature, and we did not account for training status in our experiment.

There are several options for future experiments that build on these findings. Considering the limitations of the present study, future experiments could run for longer times, run in different environments or terrains, or include a more diverse subject pool. The role of shoe mass in perceptions of comfort needs to be better clarified, for example, it is unclear what threshold of difference is necessary for subjects to perceive differences in shoe mass, or whether subjects can judge shoe mass similarly when wearing shoes versus hefting them. Wool socks represent a different type of sock fiber and could be investigated in a similar model.

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