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## Walking cadence affects rate of plantar foot temperature change but not final temperature in younger and older adults

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## ABSTRACT

This study examined the relationship between (1) foot temperature in healthy individuals and walking cadence, (2) temperature change at different locations of the foot, and (3) temperature change and its relationship with vertical pressures exerted on the foot. Eighteen healthy adult volunteers (10 between 30 and 40 years – Age: 33.4 2.4 years; 8 above 40 years – Age: 54.1 7.7 years) were recruited. A custom-made insole with temperature sensors was placed directly onto the plantar surface of the foot and held in position using a sock. The foot was placed on a pressure sensor and the whole system placed in a canvas shoe. Participants visited the lab on three separate occasions when foot temperature and pressure data were recorded during walking on a treadmill at one of three cadences (80, 100, 120 steps/min). The plantar foot temperature increased during walking in both age groups 30–40 years: 4.62 2.00 degC, >40 years: 5.49 2.30 degC, with the rise inversely proportional to initial foot temperature (30–40 years:  $R^2 = 0.669$ , >40 years:  $R^2 = 0.816$ ). Foot temperature changes were not different between the two age groups or the different foot locations and did not depend on vertical pressures. Walking cadence affected the rate of change of plantar foot temperature but not the final measured value and no association between temperature change and vertical pressure was found. These results provide baseline values for comparing foot temperature changes in pathological conditions which could inform understanding of pathophysiology and support development of evidence based healthcare guidelines for managing conditions such as diabetic foot ulceration (DFU).

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## 1. Introduction

Foot temperatures have been studied in relation to various disease conditions including those related to diabetes such as polyneuropathy [1], sudomotor dysfunction [2], acute charcot neuroarthropathy [3] and DFU [4]; and non-diabetic conditions such as neurological impairment [5] and cold extremities [6]. Studies have focussed on how foot temperature changes with these disease conditions and whether they can serve as indicators of disease progression [7]. More generally skin temperature changes of a residual limb articulating against a prosthesis have been investigated [8].

The relationship between foot temperatures and DFUs has received a lot of attention [4,7,9–13]. A recent systematic review and meta-analysis concluded that temperature monitoring is an effective way to predict and reduce DFU incidence [4]. However, sensitivity and specificity of plantar foot temperature as a diagnostic marker of DFU is low and could be improved by better temperature measures and analyses [7].

It is believed that the primary etiologic factors for DFU are repetitive stresses in the presence of peripheral neuropathy [14]. However, though pressure is an important risk factor, its predictive value is very low [15], possibly because most studies have considered vertical pressures while ignoring shear pressures, which are difficult to measure [14]. Temperature may act as a summary measure, indicating the effect of repeated vertical and shear loading of the foot and hence be a more sensitive marker of DFU risk. Monitoring foot temperature fluctuations in response to different physical and environmental perturbations may improve

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understanding of the factors that influence foot temperatures and help establish a baseline against which clinical populations can be assessed. There is however little information about how foot temperatures change with different activities in either healthy or clinical populations, apart from that it increases with walking [3,16,17] and running [6,18]. In most studies, foot temperatures are recorded at discrete times with [1,3,6] or without reference to activity [2,4,5]

The objective of this study was to determine in healthy volunteers: i) how foot temperature changes with walking cadence; ii) if there is a difference in temperature changes at different locations of the foot; iii) if foot temperature is related to the vertical pressures at different locations in the foot.

## 2. Materials and methods

### 2.1. Participants

Eighteen healthy volunteers were recruited. Eight participants aged between 30 and 40 years (3 male, Age: 33.4 ± 2.4 years, Height: 167.7 ± 5.3 cms, Weight: 71.6 ± 11.8 kg) and ten participants over 40 years (5 female, Age: 54.1 ± 7.7 years, Height: 164.8 ± 6.74 cms, Weight: 68.1 ± 10.4 kg). Participants were divided into these groups to investigate the effect of age on foot temperatures – the global prevalence of diabetes starts to increase markedly at age 40 [19]. All participants reported to be free of any foot pathologies and were confirmed to have no loss of foot sensation (10 g filament method [20]). All participants provided informed written consent and the Faculty of Science and Engineering Ethics Committee approved the study.

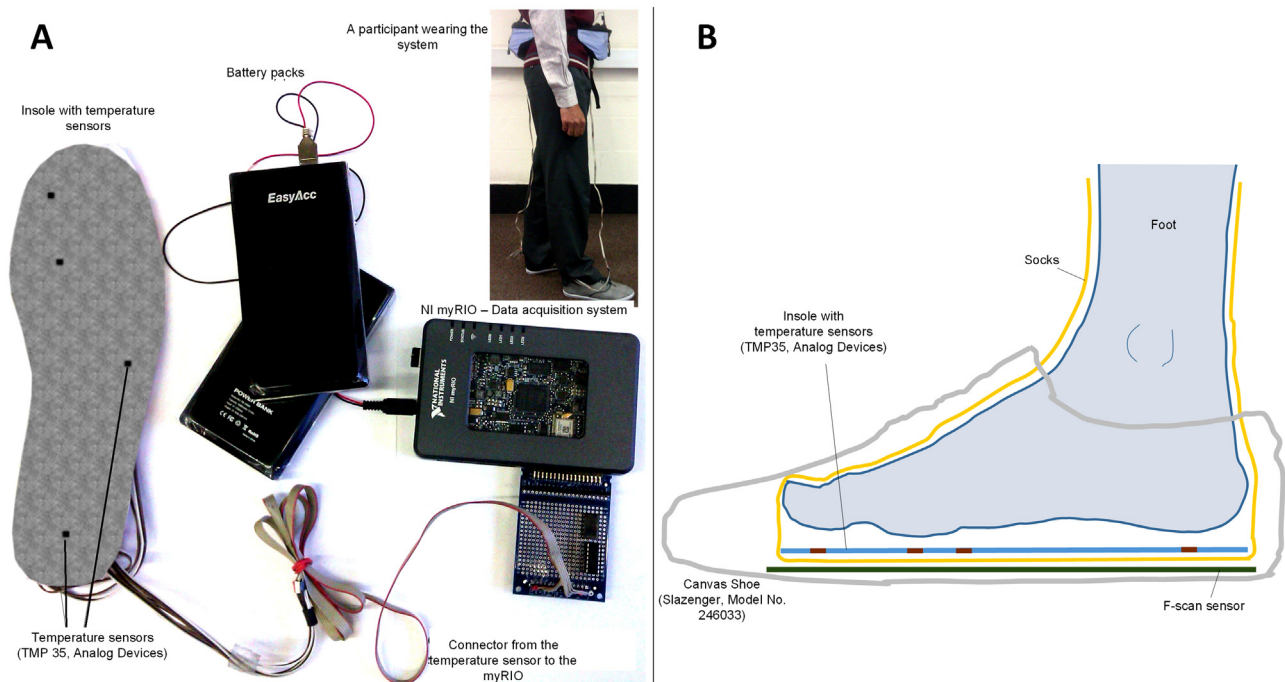
### 2.2. Experimental set up

Four temperature sensors (TMP35, Analog Devices; Range: 40 to 125 degC) were embedded into insoles ((Poron Onyx OB2085,

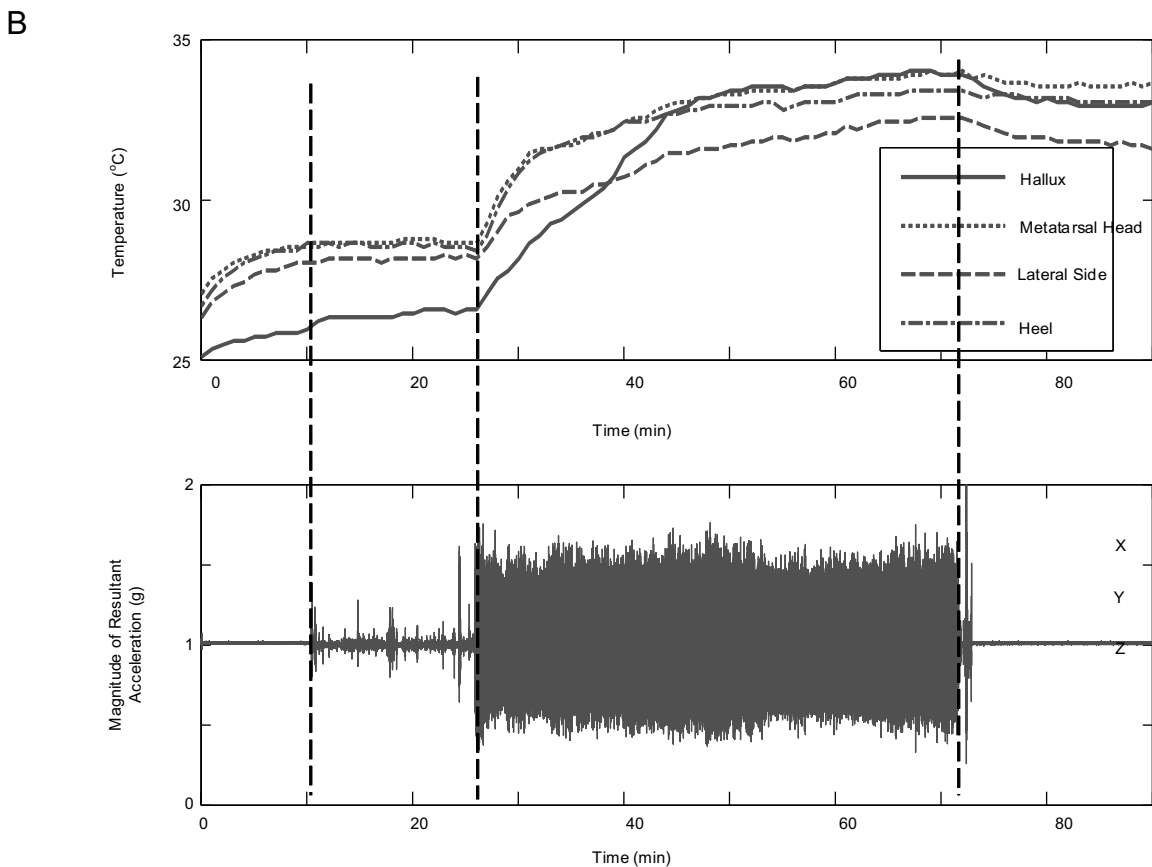
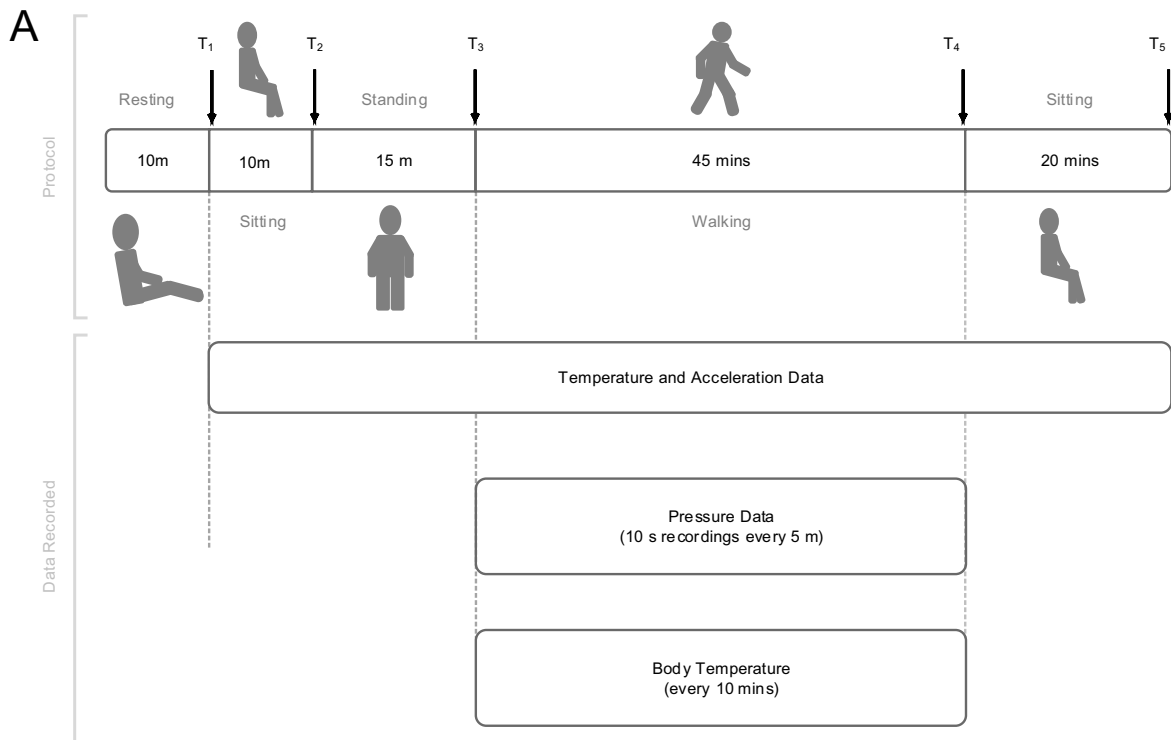
Algeos Ltd (UK), material properties defined in [21])) customised to the foot size of each participant. Temperature sensors were positioned under the hallux, between the first and second metatarsal head, the lateral side of the foot and the heel (Fig. 1A) (plantar foot temperatures recorded are referred to as foot temperatures in the paper). The sensor locations were identified, for each participant, on the insole by aligning their footprints with the insole. Vertical foot pressures were recorded using an in-shoe pressure measurement system (F-Scan, Model 3000E, TekScan Inc.) trimmed to the participant's foot size. The temperature insole was placed directly onto the plantar surface of the foot and held in position using a sock (Gelert Thermal). The sock clad foot, including the temperature insole, was placed on the pressure sensor and the whole system placed in a canvas shoe (Model 246033, Slazenger) (Fig. 1B).

Temperature data from each sensor were recorded (100 Hz, 0.08 degC resolution) throughout the protocol (Fig. 2A) using a programmable data acquisition device (myRIO, National Instruments) and stored on a USB memory drive. The myRIO along with battery packs (2 EasyAcc, Model No. PB 10000) were placed in a waist pouch; wires from the foot to the pouch connected the temperature sensors to the myRIO (Fig. 1A). Acceleration data from an inbuilt 3-axis accelerometer in the myRIO were also recorded (100 Hz sampling rate), throughout the experiment to assess the activity of the person, synchronously with the temperature data. Data acquisition was controlled using custom-written LabVIEW code (LabVIEW 2013, National Instruments).

The pressure data from the F-Scan sensor was stored (100 Hz) during pre-set periods of the experimental protocol (Fig. 2A) on a separate desktop PC using a custom software (F-Scan Research 6.50, TekScan Inc.). The locations of each temperature sensor in the pressure map were identified by manually applying pressure to each sensor with the temperature insole overlying the pressure insole. The pressure exerted by the foot at these different regions was calculated using these locations.



**Fig. 1.** A. Illustrating the temperature measurement equipment utilised. The temperature data from the sensors in the insole was digitized and stored on a USB memory drive by a NI myRIO embedded hardware device. The system was powered by a battery pack. The myRIO along with the battery packs were held in a waist pouch. B. Schematic representation of the arrangement of the F-Scan in-shoe pressure measurement insole (Sensor model 3000E, TekScan Inc., USA) and the temperature insole under the foot.



**Fig. 2.** A. An illustration of the experimental protocol, which consisted of: acclimatisation phase, where participants sat with legs stretched out (10 mins); sitting phase (10 min); standing phase (15 min); walking on the treadmill (45 min) and a cooling off phase where the participant sat on a chair (20 min). The type and timing of plantar temperature, acceleration, pressure and body temperature data collected is indicated by the lower boxes. B. Exemplar plantar temperature and acceleration data recorded for participant 1 while walking at a cadence of 80 steps/min. Visual inspection of the acceleration data enabled its division into the different phases i.e. sitting, standing, walking and sitting. Note that the sharp rise in temperature in the first sitting phase is attributed to the warming of the temperature sensors in response to contact with the foot and does not reflect an increase in the foot temperature itself.

### 2.3. Experimental protocol

Each trial started with a 10-min acclimatisation phase where participants reclined barefoot, allowing the foot temperature to stabilise. Participants were then asked to wear the shoes with the embedded sensor insoles. Recording of foot temperatures and acceleration data began, with the participants sitting on a chair with their feet on the floor for 10-min. Participants then stood for 15-min, before walking for 45-min on a motorized treadmill (Ergo ELG 70, Woodway GmbH) and finally sitting for a 20-min period (Fig. 2A).

Each participant visited the laboratory on three separate occasions, to walk at one of three different cadences – 80, 100, 120 steps/min – completed in a randomized order. Cadence rather than velocity was controlled (by changing the treadmill velocity) to standardise the number of strides across people of different heights and leg lengths.

Pressure data were recorded during treadmill walking with 10-s recordings taken every 5-min. Core body temperature (using Braun Thermoscan in-ear thermometer IRT6520) was measured every 10 min during the walking phase to determine body temperature changes during activity.

### 2.4. Data analysis

#### 2.4.1. Preprocessing foot temperature and pressure data

Example foot temperature and acceleration data throughout the protocol are shown in Fig. 2B. Acceleration data were used to denote the different phases of the trial. Mean temperatures at the start of each phase were calculated (Table 1). Temperature rise curves (calculated relative to the foot temperature before walking,  $T_3$ ) were obtained for the walking segment (Fig. 3: Middle panel), which enabled the effect of walking on the foot temperature to be characterised. Pressure-time integrals were calculated for the regions corresponding to the position of the temperature sensors. Pre-processing of the data was done in MATLAB (2014a; Mathworks Inc.).

#### 2.4.2. Statistical analysis

One-dimensional Statistical Parametric Mapping was applied to the temperature data, enabling identification of statistically different regions within the temperature time series recorded at different walking cadences and avoiding the bias which may be introduced through pre-selection of data points (e.g maximum; minimum values) which is required for 0-d analysis (SPM1D [22]).

A three-way repeated measures ANOVA (between subjects factor: age, within subjects factors: speed and location) revealed the factors

that affected foot temperature rise with walking. Paired *t*-tests with Bonferroni's correction were done for post-hoc analysis, to reveal the effects of different levels of each statistically significant factor ( $p < 0.05$ ).

Correlation of the starting foot temperature and pressure-time integrals with the temperature rise during walking was performed for each foot region in every participant. The starting foot temperature was the temperature measured before standing by which time the sensors would have equilibrated with the foot ( $T_2$ , Fig. 2A).

## 3. Results

### 3.1. Changes in foot and body temperatures

Fig. 2B shows a representative recording of temperature from one trial. Table 1 shows the temperatures of the foot at different times within the protocol averaged across the four regions of the foot and all participants (statistical analysis, described below, did not show any difference across foot regions). These data illustrate the general trend of increasing foot temperature in both age groups from sitting to standing and then from standing to walking.

There was a significant increase in temperature during the sitting phase ( $T_1$ - $T_2$ ) and during walking ( $T_3$ - $T_4$ ) when it was accompanied by a decrease in temperature variance (Table 1,  $T_4$ ). The foot temperature did not change significantly during standing ( $T_2$ - $T_3$ ). The temperatures of the foot decreased during the time the participant rested after walking ( $T_4$ - $T_5$ ).

Body temperature did not change significantly during walking in either age groups (30–40 years:  $p = 0.215$ ; >40 years:  $p = 0.084$ ), with values of 37.0 0.4 degC and 36.9 0.4 degC, respectively.

### 3.2. Temperature rise of the foot with walking

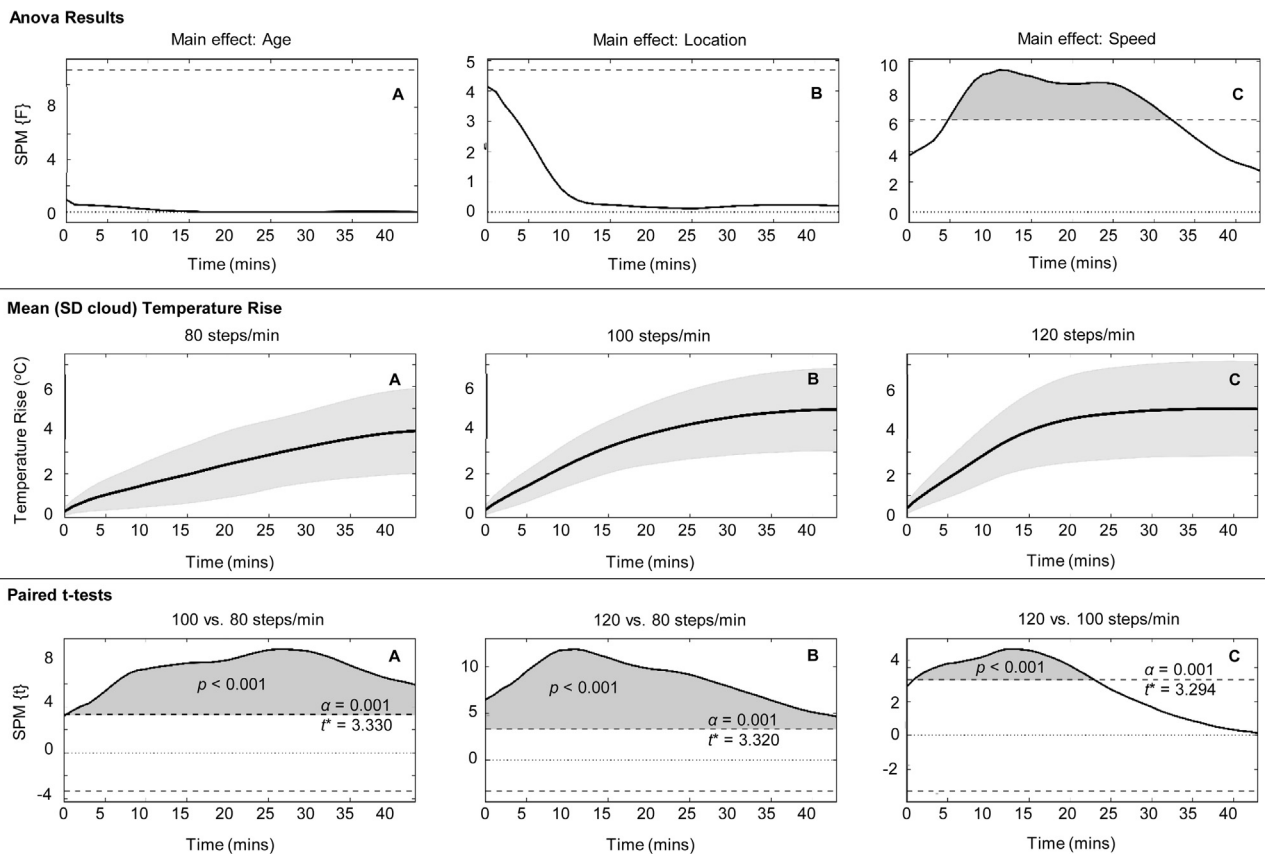
The foot temperature increased with walking in both age groups: 30–40 years (4.62 2.00 degC) and >40 years (5.49 2.30 degC). There were no differences in the temperature rise with walking between the two age groups and no differences between the different locations of the foot (Fig. 3, Top). However, walking cadence did have a significant effect on foot temperature rise, with differences occurring between minutes 10 and 30 of the walking period (Fig. 3, Top Panel). Assessing the effect of each cadence separately revealed a much slower rate of temperature rise for the 80 steps/min compared to 100 and 120 steps/min (Fig. 3, Middle). T-tests confirmed this observation, revealing a significantly lower temperature rise during walking at 80 steps/min compared to both 100 and 120 steps/min for the duration of the walking protocol (Fig. 3,

**Table 1**

The mean (SD) foot temperatures (degC) across the four foot regions and across all participants at different times of the protocol. The timings are shown in Figs. 2 and 3.

Cadence (steps/min)	Average Foot Temperature <sup>a</sup> (degC)				
	Start of sitting after acclimatisation phase ( $T_1$ )	Transition between sitting and standing ( $T_2$ )	Start of Walking ( $T_3$ )	End of Walking ( $T_4$ )	End of resting phase after walking ( $T_5$ )
	30–40 years				
80	28.1 2.5	30.0 2.9	30.0 2.8	33.9 1.3	32.7 1.5
100	28.4 1.6	30.3 2.1	30.9 1.9	35.4 1.1	33.1 1.3
120	28.6 2.0	30.6 2.4	30.5 2.2	35.9 0.9	33.5 0.9
Mean	28.4 2.1	30.3 2.5	30.4 2.4	35.0 1.4	33.0 1.3
	>40 years				
80	27.5 2.1	29.6 2.4	30.0 2.1	34.5 0.7	33.8 0.9
100	26.9 2.1	28.5 2.4	29.1 2.0	35.0 0.8	33.8 0.9
120	27.3 3.4	29.1 3.4	29.7 3.2	35.7 1.1	34.0 1.2
Mean	27.2 2.6	29.0 2.8	29.6 2.5	35.1 1.0	33.6 1.3

<sup>a</sup> Since statistical analysis did not reveal differences between the temperatures of different regions of the foot, we use the average foot temperature here.



**Fig. 3.** Graphical representation of the statistical analysis of temperature rise of the foot during walking. *Top Panel:* Results from a 3D ANOVA (3 way with 2 repeated measures (Location and Speed)) using SPM1D. Note that only the speed has a significant effect. The effect of speed is in the middle of the walking time not at the end, suggesting the effect of different walking cadence is on the rate of temperature change. *Middle Panel:* The mean (solid, black line) and standard deviation (grey shaded region) temperature rise of the foot at different walking cadence. The rate of temperature change differs between walking cadences, but the final recorded temperatures are similar (See also Table 1). *Bottom Panel:* Pairwise comparison of the temperature rises at the three walking cadences. Note that there is a difference in temperature rise between speeds 100 steps/min and 120 steps/min only until about 23 mins after which there is no difference in temperature change.

Bottom). The temperature rise while walking at 120 steps/min was higher compared to 100 steps/min, but significant only for the first 23 min of the walking protocol (Fig. 3, Bottom).

### 3.3. Temperature rise and the initial foot temperature

The temperature rise of the foot during walking was inversely correlated to the foot temperature before the start of the protocol ( $T_2$ ) for both age groups: 30–40 years ( $R^2=0.669$ ,  $p$  0.001; Fig. 4A), and >40 years ( $R^2=0.816$ ;  $p$  0.001; Fig. 4B), indicating that foot temperature change was greater when the foot was cooler to start with. The relationship was much stronger in the older age group compared to the younger age group.

Another way of examining the relationship between the initial and the rise in temperature is to explore the variation in temperatures of the foot during walking (Table 1). The variation of foot temperature decreased in every case after walking, illustrating that the foot temperature plateaus at a defined temperature.

### 3.4. Temperature rise and its relationship with plantar pressure

The temperature rise of the foot was not strongly correlated with the normal pressure time integrals exerted on the foot for either age group (30–40 years:  $R^2=0.049$ ,  $p=0.003$ ; >40 years:  $R^2=0.009$ ,  $p=0.184$ ). We explored this relationship for different foot regions and walking cadences but did not find any statistical significance.

## 4. Discussion

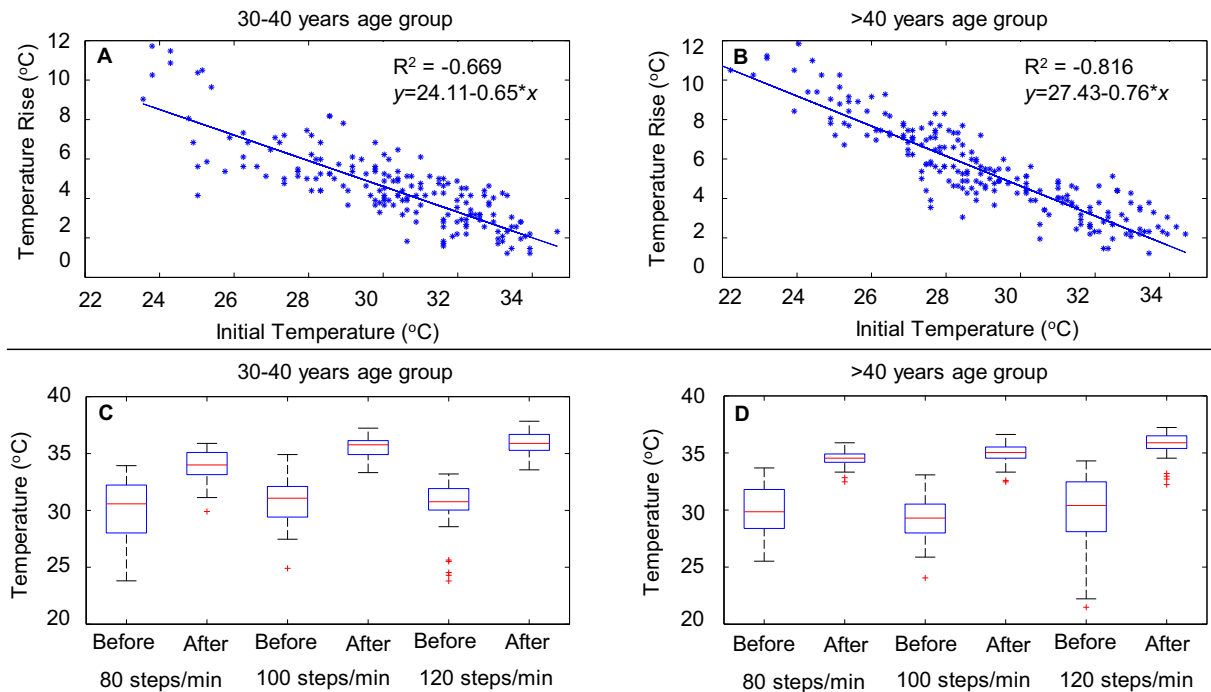
To our knowledge, this work represents the first attempt to continuously monitor plantar foot temperature and investigate the effects of walking cadence on these temperature changes.

The key findings of this study are:

- The measured foot temperature increased with walking, with the rate of temperature change increasing with increasing walking cadence.
- The measured foot temperature during walking had a maximum plateau value above which the foot temperatures did not rise.
- Measured foot temperature rise during walking was inversely correlated to the initial foot temperature, with a stronger relationship in the >40 years age group.
- The vertical pressure on the foot at different locations was uncorrelated to the foot temperature rise at those locations.

### 4.1. Temperature rise and cadence

Foot temperature increased by  $\sim 5$  degC with walking which is similar to previous work [12,17]. In addition, we show that the rate of temperature change depended on walking cadence while the final foot temperatures did not differ. The foot temperature rise during walking did not differ between age groups or between the different locations on the plantar surface of the foot. The footwear provided insulation to the foot during walking as in daily life. This insulation,



**Fig. 4.** The relationship between the temperatures of the foot while walking, showing plots of the temperature rise of the foot during walking ( $T_4 - T_3$ ) as a function of the initial foot temperature ( $T_2$ ) for participants in younger (A) and older (B) age groups. It is evident that the (inverse) relationship is stronger in the >40 years age group ( $R^2 = 0.816$ ,  $p < 0.01$ ) as compared to the 30–40 years age group ( $R^2 = 0.669$ ,  $p < 0.01$ ). Box plots of the temperatures before and after walking for the three cadences in younger (C) and older (D) participants. Note that the variance of the temperatures reduces after walking in each case. In each box, the centre is the median, the 25th and 75th percentiles are denoted by the box and the whiskers extend to the most extreme data points which are not outliers that are shown separately.

probably, reduces the differences in the temperature of different locations of the foot, as heating of one part of the foot causes the temperature of the entire foot to increase by increasing the temperature of the environment inside the shoe.

#### 4.2. Plateauing of foot temperatures while walking

The foot temperature before walking was inversely related to the change in foot temperature during walking (Fig. 4). In addition, there was a marked reduction in the variation of the temperature of the feet after walking compared to before (Table 1). Both these results point to the fact that there is a significant plateauing effect in foot temperatures during walking. Surprisingly, this effect was stronger in the older population even though the age difference between the groups was not so marked. This finding warrants further investigation.

It might be considered that the variation in initial foot temperature simply reflects differences in participant's activity immediately before entering the laboratory. However, this effect is circumvented by having an acclimatisation period when the participants arrive in the laboratory. Moreover, if this were the case, the temperatures of the foot would be expected to decrease during the sitting and the standing phases of the protocol (as happens in the resting phase after walking). However, this was not seen (see Table 1), strongly supporting the notion that the variation in initial foot temperatures may reflect individual differences resulting from physiological factors.

The concept of a foot temperature plateau seems intuitive given the physiological mechanisms underpinning heat generation and factors controlling heat loss. The heat accumulation in the foot could be due to muscle contractions, frictional forces and viscoelastic heating. These will be counteracted by mechanisms of heat loss including radiation, conduction and evaporation. The flow of blood may bring heat to an area or help dissipate heat from an area.

#### 4.3. Temperature rise and pressure on the foot

Neither temperature rise of the foot nor final temperature were related to the vertical pressures recorded at specific foot locations. Studies have suggested that shear pressure might play an important role in controlling the foot temperature and in different foot pathologies including DFU [11,12,14,23] than normal (vertical) pressure. This may be the missing link between foot loading and foot temperature changes.

It should also be considered that we have investigated an insulated setup with the foot inside a shoe. Although this is typical of daily life, it potentially makes it more difficult to detect temperature variations due to pressure differences. Whilst the present observations are from healthy participants, further work is required to investigate whether they occur in clinical populations such as those with diabetic foot deformities where the foot pressures are known to be much higher than in healthy populations [14].

#### 4.4. Methodological consideration and limitations

Temperature measured using sensors integrated into an insole would reflect foot temperatures only to the extent that the foot is in contact with the insoles. We have tried to ensure this by keeping the foot and the insole together using a sock but it is possible that the foot lifts off the sensors at points during the step cycle. This could be quantified in future studies by having contact sensors that measure foot lift-off.

We have not controlled the ambient temperature during the experimental protocol. We, however, used an air conditioned room with the thermostat set at 22 degC. Moreover, the direct influence of ambient temperature on the foot would be minimal as the foot was well insulated during walking.

#### 4.5. Implications in relation to diabetic foot ulceration

One of the main findings of the study is that walking cadence changes the rate at which the foot temperature increases but does not change the final temperature of the foot after walking. If the foot temperature is a factor in damage to the foot leading to ulceration in diabetes patients, as previously suggested [24], reducing foot temperatures, by either reducing the heat generation or increasing the heat dissipation, could be a good strategy to reduce the risk of diabetic foot ulceration. This could be achieved through a change in walking cadence of diabetic patients [25]. Footwear could also be designed so that heat from the foot is taken away easily and prevents the foot from becoming too hot [26].

We observed the participant's feet were sweaty at the end of the experiment. Further, investigation should be carried out to understand how sweating changes foot temperatures especially in patients with diabetes and associated autonomic nerve dysfunction.

The increase in foot temperature during walking was  $\sim 5$  degC. It is reported that the metabolism of a tissue increases by 10% for every 1 degC increase in temperature [27]. This means that there is a large increase in the metabolic demand in the feet during walking. If there is a failure to meet demand for blood flow, the tissue may experience ischaemic damage. Vascular disease is often concomitant with diabetes [28] and this may increase the difficulty in modulating blood flow to the feet and lead to tissue damage in the foot [29]. There may be additional problems in controlling the perfusion to the feet because of autonomic neuropathy [30] and loss of neural control of blood flow. Understanding normal and pathological patterns of foot temperature change could therefore provide valuable clinical insight to support management and treatment of foot health in patient populations. Continuous monitoring of foot temperature changes is however required to underpin such developments.

## 5. Conclusions

We have investigated the change in foot temperature with walking at different cadences and found that the rate of change of foot temperatures increased with cadence but there is no difference in final temperatures after walking at different cadences. The temperatures in every case plateau at some value. A closely related result was that the temperature rise during walking inversely depended on the initial foot temperature, i.e. if the initial foot temperatures were low the temperature rise during walking was higher and vice versa. We found that age, the foot location and vertical pressures at those locations have no effect on foot temperatures. This work provides a baseline against which to study foot temperatures in pathological conditions potentially leading to a better understanding of pathophysiology and ultimately development of evidence based healthcare guidelines for managing conditions such as DFU.

### Conflicts of interest

None.

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### Conflicts of interest

None.

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