Foot temperature assessment during different activities in healthy individuals – implications for Diabetic foot ulceration risk

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Thesis abstract

Objective: Diabetes-related disorders such as neuropathy, and diabetic foot ulcers have been studied in relation to foot temperatures. Recent studies discussed the potential clinical importance of shear force, as well as temperature differentials in the development of diabetic ulcers. However, little has been reported regarding how physiological and dynamic factors affect foot-sole temperature. This thesis investigated the association between foot temperature and walking-related extrinsic mechanical factors and foot temperature and sitting/standing-related intrinsic physiological factors in healthy participants for translation to diabetes.

Methods: A pilot study confirmed changing walking speed would manipulate shear force during walking. Insoles were designed with thermal sensors positioned at hallux, first, third metatarsal heads and heel. Foot temperature was investigated in healthy participants (*n=21*) during sitting, standing, walking, and recovery. Participants walked at three speeds (means: slow – 1.14m/s, self-selected – 1.39m/s, and fast – 1.72m/s) on the treadmill for 30 minutes. Kinetic and kinematic parameters were assessed during walking, and the fat pad thickness and blood flow were assessed and related to foot temperature during sitting and standing.

Results: The in-shoe temperature increased during every activity: 10 minutes sitting (0.63 ± 0.4°C), 15 minutes standing (0.54 ± 0.4°C) and at 30 minutes walking at different speeds (fast: 3.8 ± 1.9°C, self-selected: 2.8 ± 1.3°C, and slow: 2.8 ± 1.3°C). During 10 minutes seated recovery foot temperature dropped by ~0.32℃. Walking speed, step length, cadence, force-time integral and peak vertical forces were significantly correlated to in-shoe walking temperature. Shear force-time integral was inversely correlated to the walking temperature. Fat pad thickness at first and third metatarsal heads were inversely correlated to the static temperature.

Discussion: These findings provide an additional reference point for evaluating foot temperature changes in pathological situations, which could help in understanding pathophysiology and the development of healthcare guidelines for treating diabetic foot ulceration.

Thesis aims

The overall aim of this thesis was to examine the factors influencing foot temperature changes in healthy individuals during daily activities.

This was achieved by addressing the following objectives within the experimental chapters presented:

1. To determine the most appropriate way to manipulate shear force during walking (to be applied in Chapters four and five)
2. To measure plantar foot morphology and sizes to determine appropriate sensor locations for the temperature insoles (to be applied in Chapters four and five)
3. To examine the extrinsic mechanical factors causing foot temperature change during walking
4. To examine the intrinsic physiological and anthropometric factors causing foot temperature change during sitting and standing

Chapter One: *Literature Studies*

The literature review presented here presents the background information available on foot temperatures, and factors associated with the topic area of the thesis. Although the literature was comprehensively reviewed on these topics, it was not conducted as a systematic review. The information presented within this chapter includes a thorough literature search from databases listed below, using broad-based keywords viz. foot temperature, diabetic foot ulcer, shear force, walking speeds, foot temperature sensors, as well as using relevant references from the reference lists of other articles identified from those searches. The databases searched included PubMed, SAGE, Science Direct, and google scholar.

Studies were screened for their relevance from the title, abstract and full text. Articles that had only qualitative references and no quantitative reference to biomechanical components had less relevance for the present study.

1.1 Diabetic foot ulceration

In patients with diabetic peripheral neuropathy, recurrent stress over an area of the foot that is subject to high stress is a major cause of diabetic foot ulcers (DFU). When present, peripheral artery disease also contributes to the development of DFU. Multiple factors that ultimately result in skin disintegration are the root causes of DFU and subsequent recurrences. These factors include the aftereffects of motor, autonomic, and sensory neuropathies. The neuropathic diseases that cause hyperkeratosis due to severe mechanical stress (motor neuropathy), loss of feeling (sensory neuropathy), and dry skin (autonomic neuropathy), all of which result in skin breakdown and tissue damage, are what lead to calluses, which are the precursors of DFU (Armstrong et al., 2017). Charcot neuroarthropathy, hallux valgus, claw toes, flat foot, Pes Cavus and hammer foot are structural foot abnormalities that play a significant role in the development of DFU as they contribute to increased plantar pressures, which in turn lead to foot ulceration. Previous foot ulceration, amputation, visual impairment, or amputation are additional risk factors for DFU.

1.2 Prevalence of DFU

The development of DFU is a major complication of diabetes associated with morbidity and increased risk of mortality. Diabetic peripheral neuropathy affects 50% of people with diabetes and is a major risk factor for DFU development. Diabetic neuropathy consists of multiple clinical manifestations of which loss of peripheral/foot sensation is most prominent. Apart from other diabetic complications, DFU has a major independent impact on mortality risk and on lower extremity amputation (Chammas et al., 2016). It has been found that 60-80% of cases of DFU heal, whereas 10-15% remain as active ulcers and carry a risk of infection (Alexiadou and Doupis, 2012). Within a 6 to 18-month period of their development, up to 24% of DFU led to a limb amputation (Katsilambros et al., 2010). Moreover, numerous studies have detailed that approximately 85% of all lower extremity amputations were performed only in DFU patients (Moxey et al., 2011, Schaper et al., 2012) indicating that diabetes is the major underlying factor in lower limb amputation. A long-term study has analysed 382 diabetic patients with open foot ulcers and shown that they have a lower 5-year survival rate than diabetic patients without foot ulcerations. This study also reported a 42% rate of ulcer recurrence at the previously healed area within a year (Nelzen et al., 1997). Here in England, approximately 60,000 persons with diabetes in have a DFU each (Jeffcoate et al., 2020).

1.3 Pathophysiology of DFU:

The aetiology of DFU is multifactorial, and the factors that cause ulcerations include vasculopathy, immunopathy, neuropathy, neuroarthropathy, and mechanical stress. Neuropathy is caused by hyperglycemia which causes oxidative stress on nerve cells. These cellular changes manifest to autonomic, sensory, and motor neurons affecting the diabetic foot as well as other parts of the body. Damage to peripheral motor neurons leads to foot deformities causing bony prominences and predisposing DFU; damage to autonomic neurons inhibits sweat gland function, and the foot's capacity to moisten the skin may decrease and lead to skin breakdown and epidermal fissures. Lastly, patients with decreased peripheral sensation will not be aware of the high foot pressures that lead to the development of DFU. Hyperglycemia-induced changes in the peripheral arteries of the foot cause vascular abnormalities, which increase the risk of foot ulcers. The immune changes impair the healing process which in turn develops to a foot ulcer (Aumiller and Dollahite, 2015). Diabetic peripheral neuropathy, peripheral vascular disease, osteomyelitis, Charcot neuropathy are all risk factors for diabetic foot ulcerations. Among the above limited joint mobility and diabetic peripheral neuropathy are the two important aetiological factors causing foot ulcers (Veves et al., 1992). In diabetic peripheral neuropathy patients, sensation loss in the foot leads to the development of pre-ulcerative lesions arising from external (shoes) and internal causes (nails, calluses, corns, and foot deformities). These undetected lesions over a period can subsequently lead to ulceration of the foot. This ulceration if left untreated may become infected potentially leading to amputation of the foot (Schaper et al., 2016). Several other factors also lead to DFU such as changes in foot structure (deformity), leading to higher pressure on small bony areas. The risk factors for DFU include history of foot ulcers, previous lower limb or part of lower limb amputation, foot deformity and poor glycaemic control.

1.4 The gait cycle

Human movement, or the way we walk, is referred to as gait. Surprisingly, every person has a distinct walking pattern. Gait is defined as a mechanism dependent on the person's, bones, muscles, and neurological system working together in conjunction with the central nervous system and peripheral system. The diverse gait patterns are determined by the degree of integration. Gait is a type of bipedal locomotion, according to a mechanical definition, because it involves an alternating action between the lower extremities. For restraining, supporting, and propelling, one leg is in contact with the ground. The other leg is in the process of swinging forward to take a fresh step. As a result, gait is the outcome of a series of rhythmic alternating movements of the legs, arms, and trunk that propels the body forward.

The study of the variations of a person's gait cycle, often known as stride, is the focus of gait measurements. The actions involved between the foot striking the ground and the same foot striking the ground again during walking is defined as a gait cycle and divided into two phases: stance and swing. The initial contact of the foot with the ground when the heel meets the ground through the point in time when the toes leave the ground is referred to as stance. The stance phase accounts for roughly 60% of the gait cycle. The swing phase refers to the time between the toes leaving the ground and the foot striking again. The swing phase accounts for nearly 40% of a gait cycle; that is, the foot is in the air for roughly 40% of the time.

Weight acceptance and single-limb support are two tasks in the stance phase, with five intervals: initial contact (Ic), loading response (LR), mid stance (M-St), terminal stance (T-St), and pre-swing (Pre-Sw). The loading response phase, which lasts around 10% of the gait cycle, is when the double limbs first support each other. The foot makes full contact with the floor during the loading response, and the body weight is fully transmitted to the stance leg. The early period of double-support stance is often referred to as initial stance. The swing phase includes limb advancement with three intervals: Initial swing (I-Sw), mid-swing (M-Sw) and terminal swing (T-Sw) (Laribi and Zeghloul, 2020).

The period when only one foot is on the ground is referred as a single support period, this period lasts between 60-72% of the stance phase. The period when both feet are on the ground is referred to as double support period. During the gait cycle, there are two phases of double support, one at the start of the stance phase and the other at the end. Initial and terminal double-limb stance are the two stages of double support period. The initial double support period occurs between the phase's heel contact and the contralateral foot-off. The sub-phase from the contralateral foot-on to the toe-off is known as the terminal double support period. Both these periods account for roughly 28-40% of the stance phase (Jacquelin Perry, 2010) (Figure 1).

Gait impairments typically occur during the stance phase of gait, when the foot is loaded, and then affect the swing phase. To acquire a better knowledge of how the foot performs, the stance phase can be further broken down into more detailed sub-phases.

Heel strike (14-20% of stance phase) – Begins with the lead leg's first heel contact with the ground and ends with the contralateral leg's "toe-off."

Flat-foot or loading response (16-22% of stance phase) – Its defined as lead leg's heel contact until the first contact with the lead leg's first metatarsal head. Body weight is transmitted to the lead leg which is important for shock absorption, weight bearing and forward progression.

Mid-stance phase (29-37% of stance phase) – Defined as the period between the contralateral leg's toe-off point and the lead leg's heel coming off the ground.

Propulsive phase (45-55% of stance phase) – Helps the body propel forward.

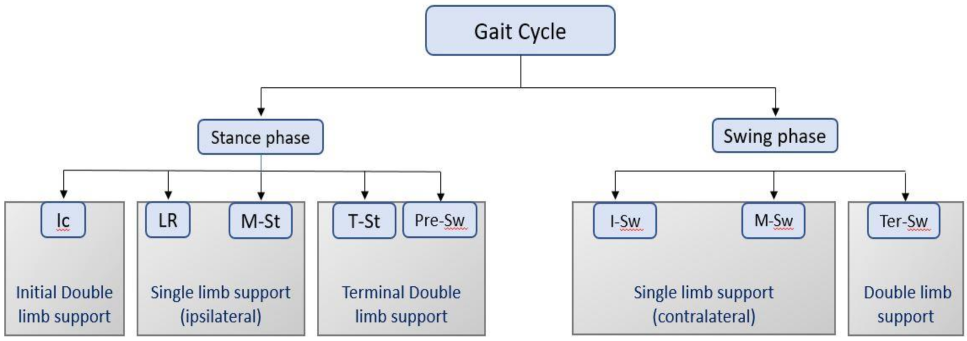


Figure 1 Schematic diagram representing the phases of the gait cycle

With the intervals of stance and swing phase and their relation to the bilateral ground contact. The grey boxes describe the important support phases during the gait cycle.

1.4.1 Gait influence on foot loading

Cadence and step length together determine walking speed (Perry et al., 2002). It is generally known that the size of the GRFs is dependent upon walking speed, (Nilsson and Thorstensson, 1989). People frequently experience a decrease in walking speed with increasing age, regardless of any other movement impairment diagnosis. Given those different combinations of step length and cadence can produce various walking speeds, the peak plantar pressure and GRFs may vary at comparable walking speeds. The distribution of plantar pressure varies depending on a number of gait parameters including walking speed. Peak pressures and total force often rise linearly as walking speed rises. Furthermore, as walking speed increases, peak plantar pressures rise in most parts of the foot (Hennig and Rosenbaum, 1991, Taylor et al., 2004).

Clinicians may be better able to manage the symptoms associated with diabetic neuropathy if they have a better understanding of how these alterations affect gait, and loading. Studies have analysed spatiotemporal measures at self-selected speeds. These studies were helpful in describing the slower, more cautious gait adopted by diabetic neuropathic patients (Allet et al., 2008). Few studies used different methodologies and controlled for speed in any way. Bacarin et al. (2009) controlled cadence, Bacarin et al. (2009) used normal speed, whereas, Yavuzer, Yetkin et al. (2006) used fast speed which can be difficult for diabetic groups to achieve.

1.4.2 Ground reaction force

Walking generates ground reaction force (GRF) that exceed body weight every step, with the vertical GRF being the main contributor. The GRF is the force exerted on the ground when the foot touches the ground during gait. The force exerted by the foot on the ground is equal and opposite to the GRF. The passive (weight acceptance) peak and the active (push off) peak are the two peaks that make up the vertical GRF curve. The foot's impact with the ground causes the passive peak, whereas the active peak is caused by the force that the foot exerts when it pushes off the ground. The GRF is an important factor in gait analysis because it is an external force acting on the body during locomotion and the limb muscles need to respond to and overcome this GRF to undertake gait. magnitude, direction, and a point of application on the foot. These all remain constant in static conditions (standing still), with a magnitude equal to body weight. However, they vary in a repeatable manner in dynamic conditions (Meadows et al., 2008).

During walking, the tissues of the foot will be subjected to greater loading and deformation due to the larger mechanical stresses, which could lead to a greater temperature rise compared to a resting or static condition. One strategy for preventing the development of diabetic foot ulcers in patients with diabetic peripheral neuropathy is temperature measurement. This is because, in people with diabetes, the skin is known to heat up before breaking down to form an ulcer (Bus et al., 2021). All the current diabetic foot research, however, is based on understanding foot temperature changes measured in the resting conditions. Therefore, it is important to examine the GRFs and gait characteristics throughout various activities in order to comprehend the usual temperature changes in healthy individuals so that we can then begin to apply this understanding to people with diabetes.

Gait analysis requires accurate GRF measurement and often uses at least one force platform to measure the GRF that occurs when a person walks. The three components of GRF as well as the moment components are precisely measured by force plates mounted on the floor. In a gait lab, a force platform is often placed with the floor. To prevent the participant from trying to change their gait when walking on the plate, the plate is often hidden from the subject's view and not mentioned in the instructions given to participants.

1.4.3 GRF components – vertical and shear forces

GRFs are developed during gait because of the force exerted to the ground by the body through foot. The GRF is an equal and opposite force applied by the foot to the ground. When a foot contacts the ground, vertical and shear (horizontal) forces are produced. Body weight and its acceleration primarily causes vertical forces, whereas shear force is caused by the friction between the ground and the foot. A shear force acting in the anterior direction on the ground creates an equal and opposite force in the posterior direction and body weight acting downwards causes equal and opposite upward ground reaction force. Vertical force, anterior-posterior force, and medial-lateral force are the three components of the GRF signal during gait.

The vertical component of the load encountered during normal walking spread across the area of the foot is reflected in the measurement of plantar pressure (vertical force divided by foot contact area). The acceleration of the body's centre mass in the vertical direction during locomotion is reflected in the vertical GRF, which is the largest component of GRF. The vertical GRF typically has two peaks during heel landing and pushing off, it reflects the shape of the letter M, a typical representation of the vertical ground reaction force over one gait cycle. During the double stance phase, vertical GRF typically reaches a maximum of 120% body weight and then lowers to 80% body weight during single stance (Kirtley, 2006).

The frictional force of plantar load spread across the contact area of the foot is reflected in the measurement of shear stress (shear force divided by foot contact area), which acts parallel to the foot. It consists of mediolateral (ML) and anteroposterior (AP) components that act perpendicular to the longitudinal axis of the foot and are usually induced by friction between the foot–surface contact (Hosein and Lord, 2000).

From the beginning of the stance phase through mid-stance, the anterior-posterior GRF acts as a braking force before switching to a propulsive force. It usually indicates a sine wave curve with a 25% body weight amplitude. It is divided into two phases: braking and propulsion, with each phase lasting approximately half of the contact time (Wannop et al., 2012). In most cases, the medial-lateral force is of lower magnitude and is related to medio-lateral balance during gait. It acts in the medial direction with a magnitude of 10% body weight or less. This force is responsible for changes in medial/lateral velocity. The pattern and form of the medial-lateral GRF, reveals minimal consistency and significant variation, which may be related to the various foot positions, footwear conditions, and environmental surface (Samaan et al., 2014).

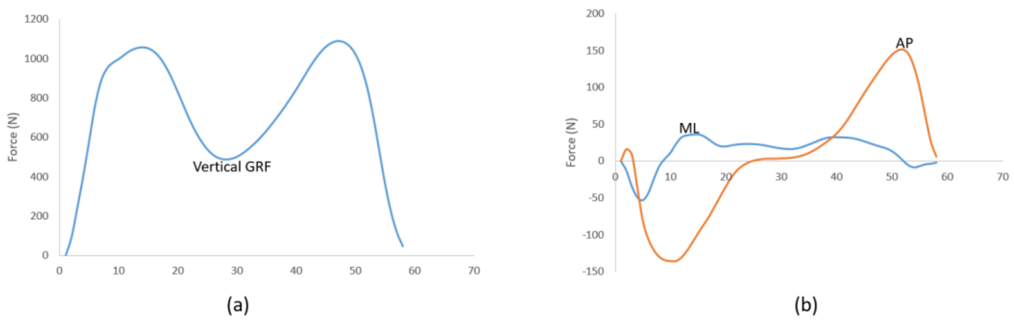


Figure 2 The three components of GRF during normal gait.

a - The vertical force component of GRF; b – the horizontal components of GRF: the anterior-posterior and the medial-lateral force component

1.5 Plantar pressure and DFU locations

Diabetic neuropathic patients with ulceration history have higher peak barefoot plantar pressures when compared with diabetic patients without ulcers. Tissue damage in these patients are due to the magnitude of loading on the foot (Owings et al., 2009). The major risk factors of neuropathic DFU development are (i) peripheral neuropathy (loss of foot sensation) (ii) foot deformities (iii) reduced fat pad thickness (iv) limited ankle dorsiflexion and other factors. All these factors culminate in the development of high pressures on the plantar surfaces of the foot. Investigation of plantar pressure enables practitioners to identify patients at risk of ulceration. Appropriate clinical monitoring and reduction of the plantar pressure in theory should help in the prevention of foot ulcer formation (Fernando et al., 2014). The location of plantar DFU is distinct and site-specific, the great toe and metatarsal heads are predominantly affected. The plantar surface near the metatarsal heads (MTHs) (9–13), is where plantar pressure is often highest, and where 40 percent (14–78%) of diabetic foot ulcers are found (Cowley et al., 2008, Altindas et al., 2011, Pham et al., 2000). Mid-foot areas are frequently significantly affected in Charcot patients (Örneholm et al., 2017, Petersen et al., 2020, Ledoux et al., 2013).

Studies have revealed region-specific high peak plantar pressures. Caselli et al. (2002) showed that 98% of DFUs within a 30-month follow-up were localised at the forefoot, which reveals significant ulceration rates at the forefoot. They also reported the ratio of forefoot to rearfoot pressure and forefoot plantar pressure was able to predict ulceration with a high sensitivity. Certain other studies have also focussed on barefoot forefoot pressures to predict ulcers (Armstrong et al., 2017, Stess et al., 1997). The forefoot and midfoot were found to be more important during push-off when the plantar pressure was evaluated by Sacco et al. (2009) in diabetic and non-diabetic groups at the three regions of the foot (forefoot, midfoot, and rear foot). Another study examined plantar pressure in five different foot regions in people with and without DFU history, diabetic neuropathy, and non-diabetic (Bacarin et al., 2009). While all the diabetes cohorts had higher peak pressures, the group with a history of DFU had significantly higher pressure only in the midfoot region when compared to the non-diabetic participant groups and cohorts without a history of DFU.

In a recent cross-sectional investigation, Abbott et al. (2022) sought to identify the plantar location with past DFU in three separate groups: controls, diabetics, and diabetic polyneuropathy with history of ulcer by determining the site-specific barefoot peak plantar pressure. They measured the peak plantar pressures at 12 different sites of the foot using a basic carbon paper mat methodology. For the first time, a significant, site-specific correlation between 'elevated' barefoot peak plantar pressure and DFU history was found in this investigation. This study also showed that the first metatarsal heads and fifth metatarsal heads DFU sites were most closely linked to higher peak plantar pressure.

More insight has typically been provided to site-specific high pressures by studies measuring in-shoe pressures. The total pressure at ulceration locations was higher than the pressure at the same place in patients without ulcers. Ledoux et al. (2013) after examining location-specific data, the hallux and heel, along with the metatarsals, were shown to have the greatest DFU rates. A possible indication of a location-specific association is the fact that higher baseline peak plantar pressure was only substantially linked with an elevated DFU risk at the metatarsals.

A few investigations have indicated caution in the use of plantar pressure as the predominant indicator of foot ulceration, whereas numerous others recommend its use as they found it highly correlated with ulcer risk, plantar pressure's efficacy as a risk factor for DFU, however, is still debated. (Chatwin et al., 2020). Determining shear force could provide further understanding of plantar foot mechanics and their role in the development of DFU.

1.6 Shear force in DFU

When the foot is applied down onto the ground in a forward direction and the other foot presses down in a backward direction, a perpendicular force is being imparted to the opposing sections, which represents the shear force and has been implicated as a potentially important factor in the development of DFU (Brand, 2003). Most of the research focuses on plantar pressure rather than shear, and this could reflect the fact that plantar pressure it is more feasible to quantify using commercial devices. However, studying shear forces might help us comprehend how the plantar foot functions and how DFU develops (Shaw et al., 1998, Perry et al., 2002). The few studies that have assessed both parameters revealed no overall trend in where the highest shear and vertical pressure occurred, with peak shear and peak plantar pressure typically occurring at different sites for participants (Yavuz et al., 2015b, Yavuz et al., 2007a). Furthermore, Yavuz et al. (2015b) conducted a study involving eight diabetic patients with a history of foot ulcers to explore the clinical significance of shear force, where patients walked across a custom-built force plate at a self-selected walking speed, both peak shear and vertical plantar pressure were measured. This study reported that more ulcers had developed at peak shear locations as opposed to vertical pressure locations (50% vs. 38%). However, this study had a relatively small sample size (*n*=8) but introduces the notion that shear force could play a role in DFU formation.

In a further investigation, Yavuz et al. (2017) measured peak plantar shear in 9 DFU patients and 16 patients with diabetic neuropathy. They also gathered peak pressure data while walking at self-selected speeds. Peak pressure in the two groups did not significantly differ, while peak plantar shear was higher in the DFU groups than in the diabetic neuropathy groups. In this study, it was revealed for the first time that diabetic neuropathy individuals with a history of DFU have peak shear that is substantially higher, representing a risk factor for the development of DFU. Peak pressure in DFU patients, however, has a well-established clinical evidence base. This study also highlighted that the small sample size was adequate to detect statistical significance because the difference in peak shear was sufficient to provide an effect size >0.9.

The studies mentioned above measured barefoot shear forces, therefore the findings are unlikely to reflect shear pressure experienced while wearing shoes, which may also vary based on footwear. However, there are currently very few commercially viable instruments that can measure in-shoe shear pressure.

A small number of investigators have developed bespoke instrumentation to measure the plantar shear force. In addition to the need for creating bespoke instrumentation that not all researchers have available, instrumentation created to quantify shear forces has often been restricted in respect of (i) measuring anterior-posterior shear only (Davis et al., 1998) (ii) enduring low spatial resolution and (iii) not being practical due to inconsistency of their results (Akhlaghi and Pepper, 1996, Lord and Hosein, 2000, Tappin et al., 1980). Because of the lack of devices to measure the shear force distribution, various scientific models have been created to anticipate plantar shear forces(Yavuz et al., 2007a). To further understand the contributing factors to DFU, more research into plantar shear is needed.

To completely comprehend the significance of shear force in DFU development, more research into in-shoe shear pressure with larger cohorts and a longitudinal design is necessary. When compared to conventional insole designs, the insoles created by (Lavery et al., 2005) can reduce shear by 2.5 times. They evaluated the effectiveness of these shear-reducing insoles in preventing foot ulcer recurrence and discovered a positive trend and a 70% effect size, but not a statistically significant decrease, in incidence of ulcer when compared to conventional insoles.

Numerous shear experiments make use of platforms specifically designed with a range of force sensors or separate tri-axial force transducers in the shoe. These investigations demonstrate that in diabetic patients, with previous ulceration DFU location can coincide with the regions of peak shear (Pollard and Le Quesne, 1983). The correlation may not be as significant as with plantar pressure, though. According to studies, there is only a moderate correlation between the peak shear and the peak plantar pressure (Yavuz et al., 2007b). Therefore, using shear in the ulceration prediction model is anticipated to increase predictive value.

1.7 Foot temperature and DFU development

The development of a DFU causes abnormal inflammation, numbness, and discoloration of the skin. Erythema, oedema, heat, pain, and loss of function are the five cardinal signs of inflammation. Other than heat, it is difficult to objectively assess the other symptoms. Foot temperature can be easily quantified at rest, and it can serve as a predictive marker for inflammation in diabetic peripheral neuropathy patients. In diabetic individuals, presentations of abnormal foot temperature are frequent. The presence of high temperature in the plantar region of the foot can indicate a sign of inflammation and tissue injury, and an increased tendency of cutaneous ulceration. Hence, measuring and monitoring foot temperature addresses a significant, still growing area of new perspectives for the medical assessment and prevention strategy of the diabetic foot. Increased foot temperature has been depicted as a clinical indication linked to diabetic neuropathy and foot ulcer risk by a number of studies (Ruan and Gu, 2013, Armstrong et al., 1997) (Papanas et al., 2010).

Inflammation in the developing ulcer location will result in higher foot temperature. From the inflammation around the emerging ulcer site the temperature difference can be observed between that area and a comparison site on the contralateral foot. The current optimal skin cut-off temperature for resting measurements between contralateral spots for identification of foot complications related to diabetes was identified to be 2.22°C with a specificity of 40% and sensitivity of 76% between same sites on the contralateral feet (van Netten et al., 2014). Using a 2.22°C temperature difference as a standard threshold for resting measurements has led to successful detection of 97% of non-traumatic diabetic foot ulcers. High temperatures under the foot coupled with reduced or complete loss of sensation can predispose the patient to foot ulceration. Studies have suggested that monitoring plantar temperature would be an effective way in predicting and preventing the onset of diabetic foot ulcers. These studies, however, mostly focus on static temperature measurements, which might only be conducted once or twice a day, rather than on dynamic continuous temperature measures due to their complexity. A few studies have detailed the areas with potential for developing high temperature regions on the foot. These regions occur mainly on the great toe, metatarsal heads, heel, and correspond with areas of high pressure (Brånemark et al., 1967, Armstrong et al., 1997, Peregrina-Barreto et al., 2014). These pressure points on the foot are susceptible to ulcerations that are directly related with sensitive changes in temperature and opens up the possibility for early detection(Murillo et al., 2014). Therefore, measuring resting temperature of the plantar foot surface is a developing tool being used to manage and assess early signs of diabetic foot ulceration.

Monitoring resting foot temperature once a day is an effective, suggested, and growing technique for decreasing diabetic foot problems. It has been incorporated into a number of clinical practise recommendations which is supported by the data from three controlled trials that showed reduced foot ulcer incidence from 61% to 85% (Lavery et al., 2004, Telfer et al., 2014). The risk of developing foot ulcers in diabetes patients is decreased by early diagnosis of DFU areas and monitoring foot temperature (Peregrina-Barreto et al., 2014). These studies, however, have only used temperature measurements taken at discrete times during rest only, whilst the temperature of the foot is likely to fluctuate throughout the day as different activities are performed and the foot is loaded in different ways. 'Home monitoring of foot skin temperature is efficient for decreasing foot ulcer incidence and recurrence,' according to a recent comparative effectiveness study done by the US Health and Human Services Agency for Healthcare Research and Quality (Dy et al., 2017). The quantitative measurement of temperature changes in the plantar surface of the diabetic foot is important to detect risks of ulcerations.

Armstrong et al. (2017) found that the use of thermometry to measure the foot temperature among diabetic patients with a high-risk of developing foot ulceration decreased ulcer recurrence by between four to ten times. Similarly, Bagavathiappan et al. (2010)used infrared thermography to measure the plantar surface temperature and blood flow in diabetic patients. They revealed increased skin temperature on the surface of the feet in diabetic patients with neuropathy compared to patients without neuropathy. Furthermore, they had proposed various parameters, notably, temperature difference, mean foot temperature and normalised temperature as metrics for differentiating neuropathy affected individuals from healthy ones.

In three groups - patients with a history of DFU, those with diabetic neuropathy, and control participants Yavuz et al. (2019) evaluated temperature as a biomarker and as a causative factor in the formation of ulcers. To reveal mean differences for each foot region, mean temperatures were calculated in four regions of the foot: the hallux and the medial, central, and lateral forefoot. In diabetic neuropathy and DFU history groups, the mean temperature in each foot region was greater than 30.0°C also, the mean differences were the greatest, ranging from 3.2°C in the medial forefoot to 4.9°C in the hallux compared to the control group.

It is obvious from the previous studies, that foot temperatures, especially in patients with a DFU history, may rapidly exceed what is considered as dangerous levels. Recurrence of ulcers was 3–10 times less likely when foot temperature monitoring was combined with regular medical care (Lavery et al., 2005, Lavery et al., 2004). Frykberg et al. (2017b) measured foot temperature was measured using a remote temperature monitoring system. If the 2.2 C threshold between identical spots on opposite foot was exceeded, the Podimetrics Smart Mat can warn both patient and clinician the suspectable onset of ulceration.

These studies also necessitate further research into the relationship between foot temperature and ulceration in diabetic feet. Therefore, evaluating plantar foot temperature can be a quantifiable indicator in assessing early signs of diabetic foot ulcerations, however, all the above studies measured the static foot temperature in diabetic patients to indicate the risk of foot ulcers. Golledge et al. (2020), who stressed the need for more user-friendly sensors to automate home foot temperature monitoring, have brought attention to the urgent need for integrating this same functionality into wearable devices. By integrating temperature sensing into insole- or shoe-based wearable devices, which can deliver long-term and continuous measurements of foot temperature, this demand can be satisfied. These devices will make it possible to study the dynamic temperature of the foot, on how rapidly the feet warms up when shoes are put on.

1.8 Foot temperature in healthy individuals

Temperature asymmetry assessments can alert the development of DFU. Most earlier studies have concentrated on monitoring the static temperature, while measurements of dynamic information, such as the rate of temperature change, are still being studied. Reyzelman et al. (2018) used a commercially available Siren socks to continuously monitor foot temperature. However, instead of examining the more complex dynamics of how temperature varies over time, the monitoring of temperature in these commercial devices has concentrated on single, discrete observations (Martín-Vaquero et al., 2019). Beach et al. (2021) was the first to quantify dynamic foot temperature in DFU Observing and understanding the biomechanical risk factors related with diabetic foot ulceration, or the indicators for the breakdown of tissue could further enable early intervention and prevention of further damage. To fully understand pathological temperature changes in diabetic patients it is essential to understand the 'normal' physiological boundaries of foot temperature changes and gradients in healthy individuals. In this way a substantial collection of work should be undertaken in healthy individuals to establish the foundation for studying pathology.

The study of Reddy et al. (2017) measured foot temperatures continuously in healthy individual's with an age range between 30 to 40 years to understand the foot temperature change whilst walking at a range of cadences. Participants were segregated into two groups to examine the effect of age on temperature. This study revealed a foot temperature rise in both age groups with the duration of walking, but no difference in the final temperature was noted with different walking cadences. This study revealed that foot temperatures and vertical plantar pressures did not correlate in healthy individuals, and that changes in foot temperature were inversely related to foot temperature at rest (before walking). In contrast, Yavuz et al. (2015b) analysed the relation between plantar foot temperature and plantar shear pressure in thirteen healthy individuals and observed a significant correlation between peak shear pressure and the increase in plantar temperature. These results indicate that an increase in plantar shear pressure could be a potential factor influencing the rise in foot temperature.

1.9 Factors influencing foot temperature

The internal physiological factors such as foot blood flow, plantar fat pad thickness and foot structure may have an impact on plantar temperature. Among which blood flow has a direct effect on the temperature of the extremities. Studies have shown in diabetic neuropathy patients the phenomenon of increased plantar temperature is caused by increased blood flow in the foot linked to impaired vasodilation (Papanas et al., 2010). Allwood and Burry (1954) determined the variations of foot temperature with variations of blood flow and concluded the skin temperature of the foot increased with increases in blood flow. Heel fat pad determines the plantar loading transmission to the lower extremities across a wide range of loading activities. Bennett and Ker (1990) found between body temperature and the temperature during testing, the tissue's dissipation ability drops less than 3%.And later Grigoriadis et al. (2017) determined the material properties of the heel fat pad at physiological body temperature and room temperature and suggested, this effect of fact on the material property was minimal. Yet, none of the studies have presented the impacts of fat pad thickness over plantar foot temperature.

1.10 Foot Temperature and Shear Force

There are indications to suggest a relationship between shear pressures and foot temperatures may exist. A study on healthy individuals, described the strong correlation between plantar foot temperature and frictional shear stress during walking (Hall et al., 2004). Dr. Paul Brand had suggested that the primary issue causing foot ulceration is shear induced softening of the plantar tissue with the result of elevated temperature that results in skin cell injury. He has also demonstrated that repeated cell injury ultimately causes focal plantar temperature to rise and has a strong association with repeated shear forces causing breakdown (Brand, 2003). His hypothesis was confirmed in other studies showing that shear stress contributes to an increase in both chronic and acute plantar temperature which makes tissue susceptible to ulceration (Heiderscheit et al., 2011, Yavuz et al., 2015b). This suggests that shear pressures may play an integral part in the aetiology of the development of diabetic foot ulcerations associated with temperature rises. Another examination analysed shear force in relation to several factors such as cadence, stride length, velocity and revealed shear force seems to appear mostly under the forefoot for approximately 73-80% during stance time (Tappin and Robertson, 1991). Unfortunately, studies do not explain the shear stress during different step length.

Likewise, Yavuz et al. (2015b) investigated twenty-eight diabetes patients to comprehend the association between shear stress and plantar pressure with foot temperature. The results of his investigation indicate that the peak temperature is correlated with peak shear stress, but that there is no significant relation between peak vertical plantar pressure and peak foot temperature. The statement of no relation between vertical plantar pressure and temperature has also been supported by the findings of Reddy et al. (2017) confirming vertical pressure on different locations of the foot was not correlated with the rise in foot temperature at the prime anatomical locations. The other study performed on diabetic patients to assess the effectiveness of monitoring temperature to reduce the risk of foot ulceration concluded high foot temperature gradients may predict the onset of foot ulceration. The above-mentioned studies are the best examples to consider peak temperature and foot temperature gradients as potential indicators/predictors.

According to the literature, the temperature has a significant impact on how diabetic neuropathy patients develop difficulties. There is, however, limited information on how different activities affect foot temperatures in healthy or clinical populations. Therefore, the work for this thesis aims towards identifying a more optimal indicator for diabetic foot ulcerations using real-time temperature measurements through a series of systematic experimental measurements on healthy individuals and understanding their implications and application in people at risk of DFU. Specifically, in healthy individuals, this thesis aims to determine the impact of different activities on foot temperature changes measured in real-time and establish the influence of external gait factors and internal physiological and anthropometric factors on foot temperature changes.

Chapter Two: *Manipulating shear force by altering step length through changes in walking speed and cadence*

Pilot Study

2.1 Abstract

Objectives: Foot temperature changes during various activities including walking. Shear forces developed during walking may be a key contributing factor to increases in foot temperature. This pilot aimed to identify the optimal method (for application in subsequent studies of the thesis) for manipulating shear force by altering step length through changes in walking speed or cadence.

Methods: Participants walked under two conditions: walking speed (without limiting cadence) and cadence manipulations. Based on this, six different walking conditions (slow, self-selected, and fast speed; low, self-selected and high cadence) were examined during level ground and treadmill walking (30 mins) sessions. Temporal-spatial gait parameters and force-time integrals (FTI) of GRF components were analysed using motion analysis and force platforms.

Results: Step length, cadence and anterior-posterior FTI increased consistently with increasing walking speed manipulation across both level ground and treadmill modalities. In contrast, manipulating cadence did not lead to changes in these parameters in the intended direction and showed inconsistencies across modalities.

Discussion: Manipulating walking speed consistently increased step length and shear forces across both level ground and treadmill modalities, whereas the same did not occur for cadence manipulation. Manipulating walking speed was therefore considered the optimal method for manipulating key parameters believed to influence foot temperature and will be implemented in a subsequent experimental study of this thesis.

2.2 Introduction

As many diabetic foot ulcers develop at sites of hyperkeratosis tissue (hard skin), which is itself driven by friction (shear) on the foot, although evidence is relatively light, shear force is thought to be a key component in the development of diabetic foot ulcers. The ability to predict and prevent diabetic ulcers is dependent on a comprehensive understanding of plantar tissue mechanics and the full scope of foot-ground contacts (Yavuz et al., 2007a, Chatwin et al., 2020). Shear force has been identified as a major contributing element in the development of diabetic foot ulcers by a small number of studies, where it is suggested that plantar shear force rather than vertical pressure is responsible for the destruction of tissue that occurs deep beneath the skin. Shear stress has always been undervalued in this field of study, and there is lack of technology to evaluate it. Over the decade, new research has emerged indicating the clinical importance of shear to foot ulceration in diabetic patients (Yavuz et al., 2015b, Yavuz et al., 2015a, Yavuz, 2014).

Jones et al. (2022) conducted a meta-analysis and a comprehensive evaluation to see if increased shear stress had a major role in causing foot ulcers. They primarily looked at biomechanical shear assessment methods to examine if greater shear stresses are associated to ulceration and if shear measurement has been employed as part of an offloading strategy to reduce DFU formation risk and they concluded that high-risk individuals with diabetes and a history of ulceration experience more shear stress.

Upon foot-ground contact, shear forces act tangentially in the anterior-posterior and medio-lateral directions, transferring a complicated pattern of stress and strain to the different layers of the plantar tissue. The plantar surface is subjected to these alternating forces, which are particularly abrasive during walking. Shear stress can cause calluses to form under the diabetic foot frequently and can abrade the skin and plantar tissue in addition to damaging the tissue's sublayers, both of which are known risk factors for diabetic foot ulcers. The skin and underlying tissues may become fatigued because of this phenomenon which is referred as “repetitive moderate stress” by many researchers.

Shear stress on the foot is technically difficult to measure whilst walking. Shear force at the foot-ground interface can be measured with force plates and captured as part of motion analysis. (Davis et al., 1998, Schmiedmayer and Kastner, 1999). Yavuz et al. (2008) measured the temporal shear parameters in diabetic and control groups, which are believed to be useful in the prediction of ulcer formation, using a custom-built shear and pressure platform. They measured the peak pressure and shear stress magnitudes in the horizontal direction on one foot whilst walking at self-selected speeds. They observed resultant shear magnitudes and peak in anterior-posterior direction were larger by 31% and 33% in diabetic group, and the AP and ML shear time integrals were significantly higher in diabetic groups though the average speed was less than the control groups. In this way, plantar shear carries the potential of bridging knowledge gaps in the complicated aetiology of plantar ulceration.

As shear force is a function of both the direction of the GRF vector and the deceleration/acceleration of the foot/body, a faster walking speed will result in greater deceleration and acceleration upon each step. It is also important to note that a change in speed is associated with a change in step length, thus changing speed is likely to impact both factors (step length and acceleration/deceleration). Normally when people walk at different speeds, both their cadence (number of steps per minute) and step length are adjusted accordingly where the step length increases monotonically with increasing walking speed. A few studies have analysed the relation between step length, cadence and walking speed and reported a linear relationship between these parameters with walking speeds (Sekiya et al., 1997, Tanawongsuwan and Bobick, 2003).

Several researchers have developed 2D models to predict plantar shear and attempted to evaluate shear stress distribution using plantar pressure data and ground reaction forces (Abuzzahab et al., 1997). The variability of temporal (cadence and velocity) – spatial (step length /stride length) step kinematics can serve as a biomechanical marker for shear forces. Both shear components (i) ML friction forces and (ii) AP forces have a direct relation with spatial and temporal components of the gait cycle.

During the normal gait cycle, the anterior-posterior shear depends on the body centre of mass position and the location of the foot. The heel strike in the posterior direction slows down the forward progression whereas the toe off in the anterior direction propels the body forward (Hamilton, 2002, G.G, 2002). Thus, due to the greater angle between the ground and the foot, greater anterior-posterior shear force is developed with a larger step length. Martin (1992) conducted research in which 10 young people walked on level ground over force platforms at five different step lengths to assess the effects of step length and frequency on GRF, and the results demonstrate that the AP propulsive and braking force, as well as contact time, increased systematically with step length. Despite the consistent influence of step length on various GRF characteristics, it is not suggested to restrict step length in gait evaluations since this would prevent the measurement of appropriate gait kinematics and kinetics.

It is important to concentrate on the temporal spatial components of gait while assessing shear. The area under the foot may encounter forces in opposing directions during a single stance, for example, because of braking forces during the foot contact and propulsive forces during the push-off phase. This demonstrates clearly that the frequency of both AP and ML shear is double that of pressure for a single step. The biomechanical component necessary for forward motion during normal gait and running, is the propulsive shear force, is vital for human locomotion (Hamilton, 2011).

According to a study, step length and gait speed are strongly linked with the propulsive component of plantar shear, where they measured the horizontal GRFs in 47 healthy children who walked at three different treadmill speeds. The determined correlation coefficients (r) between gait speed and the propulsive and braking AP shear forces were 0.981 and 0.916, respectively (Diop et al., 2005). Martin and Marsh (1992) measured GRFs in 10 persons walking on a treadmill and level ground while using various step lengths. Their findings showed correlation coefficients of 0.999 for relationships between step length and propelling shear force and 0.988 for associations between step length and braking shear force. In a related study, van der Linden et al. (2002) had 36 healthy children walk at five different speeds. Their findings also showed a strong linear correlation between step length and the propulsive (r = 0.987) and braking (r = 0.971) shear forces. These studies revealed a nearly perfect linear relationship between peak propulsive plantar shear force and gait speed and/or step length. Studies have implemented various methods to alter step length, change in speed (Orendurff et al., 2008, Lim et al., 2017, Scherer et al., 1998) and change in cadence (Ardestani et al., 2016, Goto et al., 2021) to measure shear forces during gait.

Walking speed has a substantial impact on the characteristics of ground reaction forces and changes in step length also affects the GRF patterns. By changing the vector direction of the force delivered from the body to the ground, step length alters shear force. The horizontal direction of the vector is increased as the distance between the foot and the body is increased, resulting in an increase in the amount of force transferred in that direction. Whereas shorter steps produce a higher vertical force and a lower shear component (Yu et al., 2021). Similarly Young and Dingwell (2012) examined how people's margins of stability were affected by deliberately changing step width and step length, wherein 14 participants underwent two distinct manipulations to complete three 3-minute treadmill walking trials. Similarly, Young and Dingwell (2012) examined how people's margins of stability were affected by deliberately changing step width and step length, wherein 14 participants underwent two distinct manipulations to complete three 3-minute treadmill walking trials. The findings show that AP and ML stability during human walking were significantly affected by voluntary modifications to gait parameters. Mean AP stability was significantly altered during walking with any change in step length.

It is evident from the literature studies, that walking speed is purely a result of step length and cadence, where these gait characteristics are interrelated, which can impact shear forces. Based on this information, this study attempted to determine the most effective strategy to change step length by (i) varying speed and (ii) varying cadence.

In both overground and treadmill walking, Lake and Robinson (2005) evaluated the walking kinematics in two shoe conditions, which involved ten healthy young women walking on a treadmill and level ground in two different pairs of shoes (a flat sandal and a training shoe). Five walking attempts across a force platform during level ground testing in addition to walking for 10 minutes on a treadmill while wearing each pair of shoes, both at 1.25 m/s speed. The GRF were recorded using force platforms and the kinematic parameters were recorded using 8 camera system using reflective markers in the lower body. Results from several test procedures were compared. The researchers found that the walking kinematics measured using the treadmill and level ground procedures were largely similar. The heel velocity during heel strike varied significantly more on the treadmill than it did on the overground.

In order to determine the GRFs using an instrumented treadmill and to foresee the variations between treadmill and overground walking, Riley et al. (2007) conducted a study. The magnitude of the differences was equal to the variation in a normal gait parameter, even though all GRF maxima were discovered to be statistically substantially smaller in treadmill than in overground walking (p 0.05). The study concluded that "treadmill and overground gait mechanics are identical." Goldberg et al. (2008) compared the anterior-posterior GRF and impulses in healthy persons during treadmill and overground walking to develop the hypothesis that there wouldn't be any change in the creation of anterior/posterior propulsion. However, no significant differences between propulsion impulses were discovered. The study found a small but statistically significant difference between treadmill and level ground walking in anterior-posterior GRF. However, the researchers concluded that treadmill walking can be employed to study propulsion creation.

Like this, a few other studies have examined the joint kinetics, GRFs, and temporal spatial parameters and compared the walking at different speeds/running between treadmill, and level ground (Zeni Jr and Higginson, 2010, White et al., 1998, Lee and Hidler, 2008, Sohn et al., 2009, Fellin et al., 2010, Watt et al., 2010, Pavei et al., 2019). From these study outcomes it is apparent that most of the gait parameters are similar in both treadmill and level ground.

This study aims to pilot two different methods of altering walking to determine the most appropriate way to manipulate shear force during walking. This would determine the most appropriate and practical method for manipulating shear forces to be used in a subsequent experimental study presented in Chapter 4 of this thesis.

2.3 Methods

2.3.1 Participants

Three participants were recruited from the Manchester Metropolitan University. Data was collected at John Dalton tower; Biomechanics Lab (T0.18). Three healthy male participants (Table 1) were recruited, who were free of any medical conditions based on self-report and visual observations. Following procedures approved by the University Ethics Committee, each subject gave their informed consent to participate in this study. The test protocols were explained to participants prior to the study session.

Table 1 Participant demographics

Participant	Age (Years)	Height (m)	Weight (kg)
1	41	1.78	71.6
2	30	1.87	89.5
3	45	1.72	90.3

2.3.2 Walking conditions

In this pilot study walking speed was used in two different manipulation methods to alter step length; 1. Speed (without constraining walking cadence), 2. Cadence (constraining walking cadence). Based on these conditions, six different walking scenarios were examined, it was examined if step length would correlate with shear force. Like other studies, these trials involved carefully adjusting the cadence and speed. These tests were conducted on both level ground and on the treadmill, to measure forces on the ground, and to establish consistency of maintaining a walking pattern for the kinematics on the treadmill. For this pilot study speed and cadence manipulation methods were applied initially while walking over level ground and then applied to the treadmill tests. Cadence manipulation was assessed with the use of metronome. Participants were given adequate time in each condition to become acclimated to the different walking speeds and metronome rhythms. Participants then undertook self-selected, fast, and slow speeds, followed by the three walking conditions controlling for cadence determined by the metronome as described above.

Speed manipulation:

Walking on level ground at three different speeds slow, self-selected, and fast represented the speed manipulation. On level ground, speeds were measured for slow, self-selected, and fast, and then replicated on the treadmill.

Self-selected speed

After the experimental set up, as the initial process participants were asked to walk over the force platforms at their preferred walking speed. The walking speed and cadence were then measured from the self-selected walking.

Fast and Slow speed

The participants were then instructed to walk over level ground in a random order at a speed that they chose to be faster, then slower than their self-selected speed. The speed was assessed for the fast and slow walk and once established by the participant, maintained constant with feedback from the experimenter based on the motion analysis.

Cadence manipulation:

For the cadence manipulation, a metronome was used to control the cadence while walking on the level ground. Participants were given time to acquaint themselves with the metronome after the cadence was determined and placed on the metronome. The following three walking conditions were performed on level ground with metronome cueing after the familiarization period.

Self-Selected metronome

From the assessed self-selected walking cadence, the metronome speed was fixed according to the normal walking speed. They walked in time with a metronome count to match their self-selected walking cadence.

High metronome

The metronome count was increased above the normal walking cadence, where the participants were able to walk. The metronome count was increased by a minimum of 10bpm, up to as close to a maximum of 20bpm or whenever a participant was unable to walk at the speed dictated by the metronome (Young and Dingwell, 2012).

Low metronome

The metronome count was decreased below the normal walking cadence, where the participants were able to walk. The metronome count was decreased from 10bpm - 20bpm.

2.3.3 Measurements

Using the output from the Vicon motion capture system, the self-selected speed and cadence was assessed on level ground. Based on the self-selected cadence, the metronome count was adjusted for the cadence manipulation.

Speed - Distance covered by one of the pelvic markers during the walking period.

Cadence – Timings of the toe on and toe off during the walking.

Table 2 Speed and cadence manipulation walking conditions

With descriptions of the walking conditions performed during level ground and treadmill walking, ✓ denoting conditions performed and ✗ denoting not performed

Walking Condition	***Description***	***Level ground***	***Treadmill***
	Speed Manipulation		
Self-selected	Normal speed	✓	✗
Fast	Fast speed	✓	✓
Slow	Slow speed	✓	✓
	Cadence Manipulation (using metronome)		
Self-selected cade	Normal speed and metronome count	✓	✓
High	Normal speed with ▲ metronome count	✓	✓
Low	Normal speed with ▼ metronome count	✓	✓

2.3.4 Experimental procedure

Data for the pilot study were collected over the course of several visits. Kinematic data were collected to determine temporal spatial measurements using the lower body Plug in Gait model (Vicon®, 2002), markers were placed on everyone. To collect lower body 3D joint kinematics, 16 retro-reflective markers were placed on specific locations on each subject's pelvis, legs, and feet. The eight camera Vicon system recorded marker trajectories sampling at 100 Hz and synchronized with force platform data sampling at 1000 Hz. Participants walked barefoot and wore tight-fitting shorts to obtain accurate marker placement and Vicon was used to measure the motion data on both level ground and treadmill data.

2.3.5 Walking on level ground

Kinetic data was collected using Kistler force plates (Kistler, Winterthur, Switzerland) (Figure 3). Participants walked across a 10m walkway on level ground over the force plates mounted on the floor. In this work, GRFs from the force plates were collected directly using Vicon Nexus (Vicon Motion Systems Ltd, UK).

Participants walked at their self-selected speed, without paying attention to the existence of force platforms. Participants were not informed of the necessity to achieve complete foot strikes (to avoid attempting to alter their gait when they walk over the force plates) on the force platforms without manipulating their gait; instead, the start point of each walk was controlled to achieve clean foot strikes without overlapping the edge of the force plates during each walk. Before leading each test, the participants were given the opportunity to do a few practices preliminary trials, which helped to inform participants start position and foot-strike positioning on the force platform.

Several numbers of trials were collected from each participant, with the force plates reset before each trial to obtain six trials with clean strikes (the foot fully within the boundaries of the force platform), which included three left foot good contact and three right foot good contact. Trials were deemed "good" if the participant did not aim for the force plates and made only one foot strike per force plate were used in the data analysis. The average walking speed for each walking condition were determined using the six recorded trials. Following self-selected walking, participants walked on level ground for the further five different walking conditions (Table 2) with the same methodology for kinetic data capture.

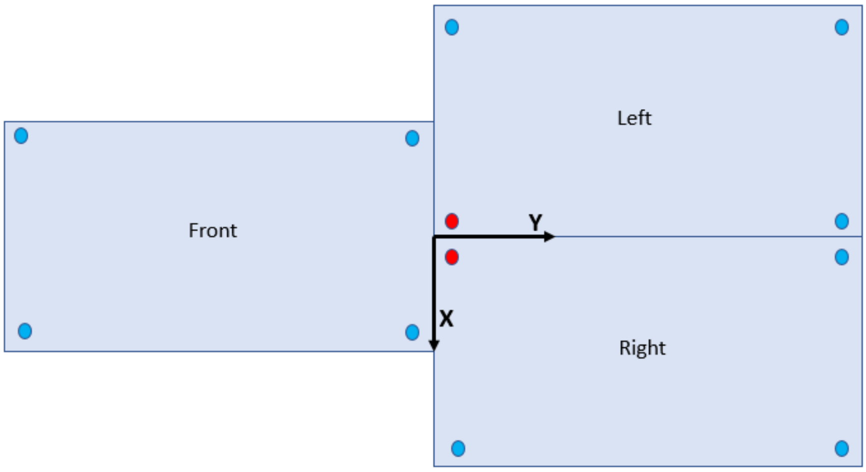


Figure 3 Kistler force plates arrangement used in this pilot study

Showing the direction of walking along the y-axis. This configuration maximised natural footfall of subsequent footfalls on separate plates, but only ever employed 2 plates per walk.

2.3.6 Determining walking condition speeds

The six level ground walking trials were averaged for each specific walking condition to get the walking speed for that condition. Similarly, the average speed for each walking condition was determined and set on the treadmill. Speed was assessed separately for both fast and slow speed tests during level ground walking condition and the treadmill velocity was altered according to the level ground walking condition.

2.3.7 Walking on the treadmill

The treadmill was used to determine the consistency of walking in a controlled manner for 30 minutes as well as to evaluate how the method for altering step length is implemented across the 30-minute measurement period.

The treadmill test involved 30 minutes of treadmill walking at each of the manipulated conditions. Since, each test requires 30 minutes of walking, treadmill walking session data was collected based on the participant's availability. Participants walked on the treadmill (Ergo ELG 70, Woodway Gmbh) in 5 different walking conditions (Table 2). Self-selected waking speed was not conducted for the treadmill walking as self-selected walking speed without a metronome was assumed to be the most consistent walking parameter due to it being the participant's natural strategy, therefore any variability within that condition should be below that of the manipulated walking conditions. Treadmill walking included kinematic data capture, but no kinetic data.

2.4 Data processing

The 3D motion data for each walking trail was labelled (Plug-in-gait model) and gap fill - small gaps Woltring (less than 10 frames) and larger gaps were pattern filled in using Vicon Nexus. The recorded kinematic (movement) and kinetic (force) data were processed using Visual 3D (C-motion, Maryland, USA). The following variables were evaluated from the collected data (i) maximum anterior ground reaction forces (ii) maximum posterior ground reaction forces [measured with force plates] and other gait-related parameters including (iii) step length (m), (iv) walking speed (m/s), (v) walking cadence (steps/min) and (v) FTI (NS).

In each gait trial for the six walking conditions, participant means and standard deviations (SD) of the above-mentioned variables were determined throughout the repeated trials. For data analysis, the treadmill sessions were broken up into intervals, with one minute of 3D motion data being collected every 6th minute for the whole 30-minute walking duration. The treadmill data was averaged across 60 seconds of data collection for each timepoint, and the mean and SD for each walking session was calculated, and the data was averaged across all three subjects (i.e., six datasets).

2.5 Results

Data were displayed in a table and graphical representation. Table 3 & Table 4 presents the key temporal-spatial variables for the different walking conditions on both level ground and treadmill walking. In Table 4 the treadmill walking for each of the walking conditions, speed was assessed from the level ground walking and maintained on the treadmill as it is self-determined velocity, the standard deviations for the walking speed were not provided.

During level ground walking, the pattern and amplitude of force-time integrals for all three GRF components were measured. In Figure 4 shows a consistent increase in anterior-posterior FTI with speed but no consistent alteration in anterior-posterior FTIs when altering cadence. Manipulating speed and cadence did not show consistent alterations in medial-lateral FTI (Figure 5). Vertical FTIs decreased consistently with both speed and cadence (Figure 6), where slow speed and low cadence are shown to have higher peaks in all three participants due to more ground contact time, which is represented in the vertical FTI, and fast speed and high cadence are shown to have relatively low vertical FTI due to less ground contact time (Adams et al., 2018).

Table 3 Temporal-spatial parameters (mean ± SD)

During six different walking conditions on the level ground

Walking Conditions	Participant 1			Participant 2			Participant 3		
	Walking Speed (m/s)	Step Length (m)	Cadence (steps/min)	Walking Speed (m/s)	Step Length (m)	Cadence (steps/min)	Walking Speed (m/s)	Step Length (m)	Cadence (steps/min)
Speed Manipulation									
Slow speed	1.39 (0.03)	0.64 (0.67)	101 (3)	1.16 (0.01)	0.69 (0.03)	102 (2)	1.52 (0.04)	0.76 (0.01)	120 (3)
Self-selected	1.49 (0.02)	0.76 (0.02)	118 (5)	1.45 (0.03)	0.82 (0.04)	107 (5)	1.44 (0.03)	0.73 (0.03)	117 (4)
Fast speed	1.72 (0.01)	0.88 (0.07)	113 (10)	1.62 (0.07)	0.90 (0.05)	109 (14)	1.69 (0.05)	0.82 (0.03)	122 (6)
Cadence Manipulation									
Low Cadence	1.52 (0.01)	0.85 (0.03)	107 (4)	1.34 (0.04)	0.82 (0.02)	101 (8)	1.51 (0.03)	0.78 (0.03)	115 (5)
Self-selected Cadence	1.53 (0.02)	0.78 (0.02)	118 (2)	1.31 (0.08)	0.73 (0.08)	112 (3)	1.56 (0.05)	0.75 (0.02)	122 (4)
High Cadence	1.44 (0.02)	0.67 (0.08)	129 (4)	1.38 (0.02)	0.77 (0.02)	108 (4)	1.74 (0.03)	0.75 (0.02)	131 (4)

Table 4 Temporal-spatial parameters (mean ± SD) during six different walking conditions on the treadmill

Walking Conditions	Participant 1		Participant 2		Participant 3	
	Step Length (m)	Cadence (steps/min)	Step Length (m)	Cadence (steps/min)	Step Length (m)	Cadence (steps/min)
Speed Manipulation						
Slow Speed	0.60 (0.02)	117 (2)	0.64 (0.09)	105 (4)	0.57 (0.02)	109 (2)
Self-selected Speed	0.76 (0.02)	118 (5)	0.82 (0.04)	107 (5)	0.73 (0.03)	117 (4)
Fast Speed	0.90 (0.02)	117 (2)	0.93 (0.05)	113 (2)	0.79 (0.07)	126 (2)
Cadence Manipulation						
Low Cadence	0.85 (0.04)	103 (3)	0.86 (0.02)	103 (2)	0.69 (0.02)	114 (2)
Self-selected Cadence	0.74 (0.02)	117 (2)	0.81 (0.08)	111 (2)	0.68 (0.02)	117 (2)
High Cadence	0.69 (0.03)	127 (5)	0.77 (0.03)	114 (3)	0.66 (0.02)	121 (3)

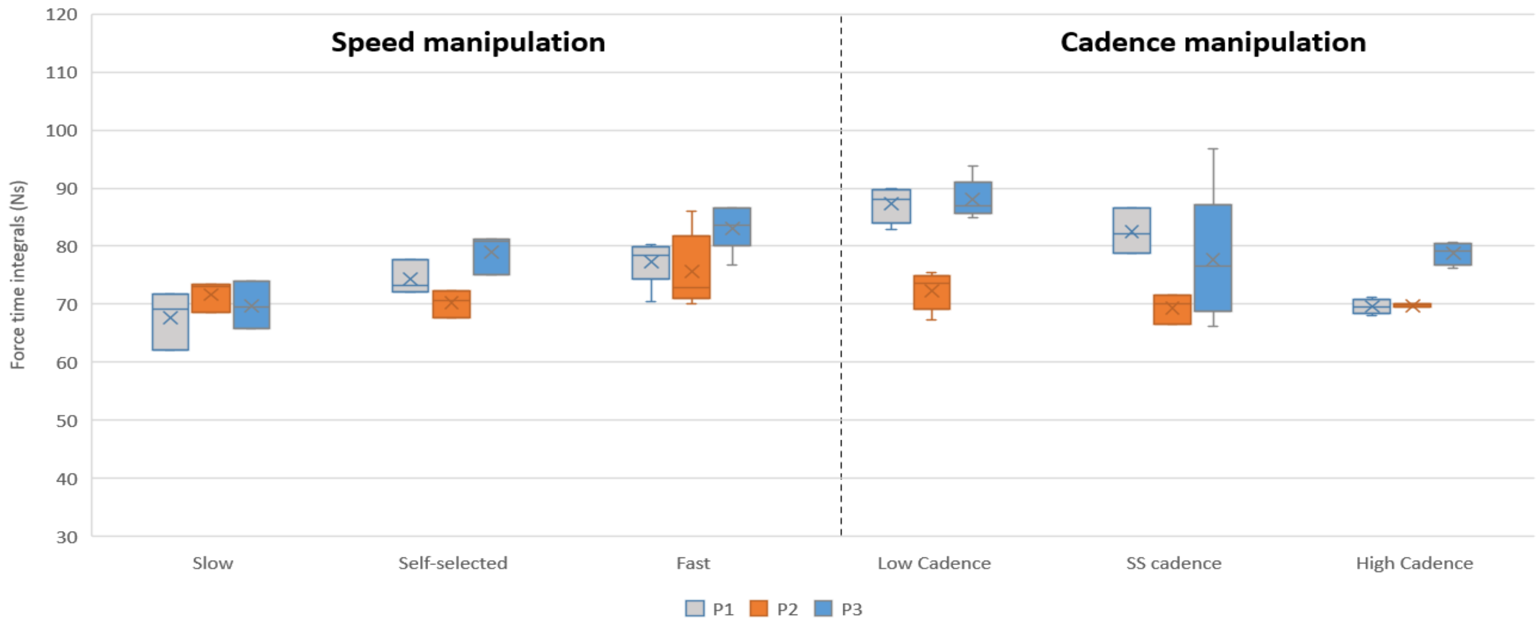


Figure 4 Anterior-Posterior force-time integrals

Box plots during different walking conditions (speed and cadence manipulations) of three participants (P1, P2 & P3 denotes participants).

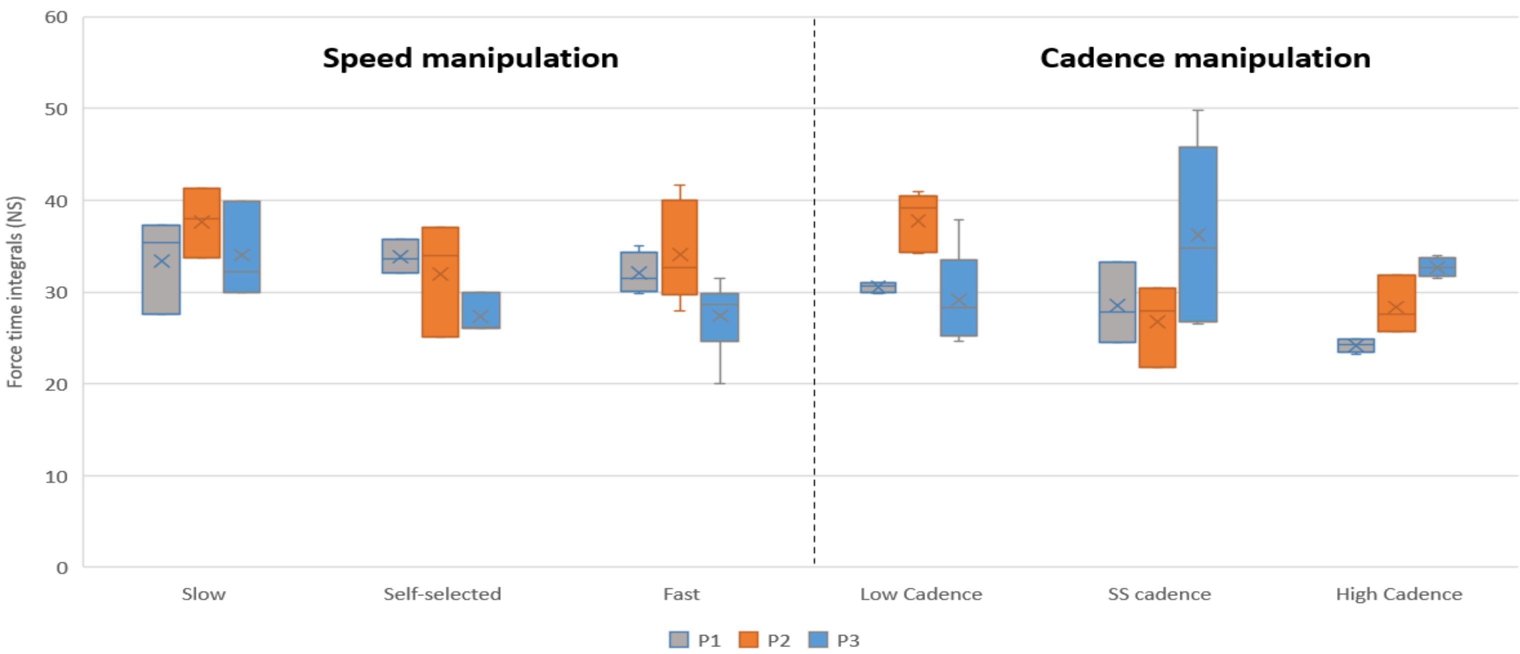


Figure 5 Medial-Lateral force-time integrals

Box plots of different walking conditions (speed and cadence manipulations) of three participants (P1, P2, P3 denotes participants).

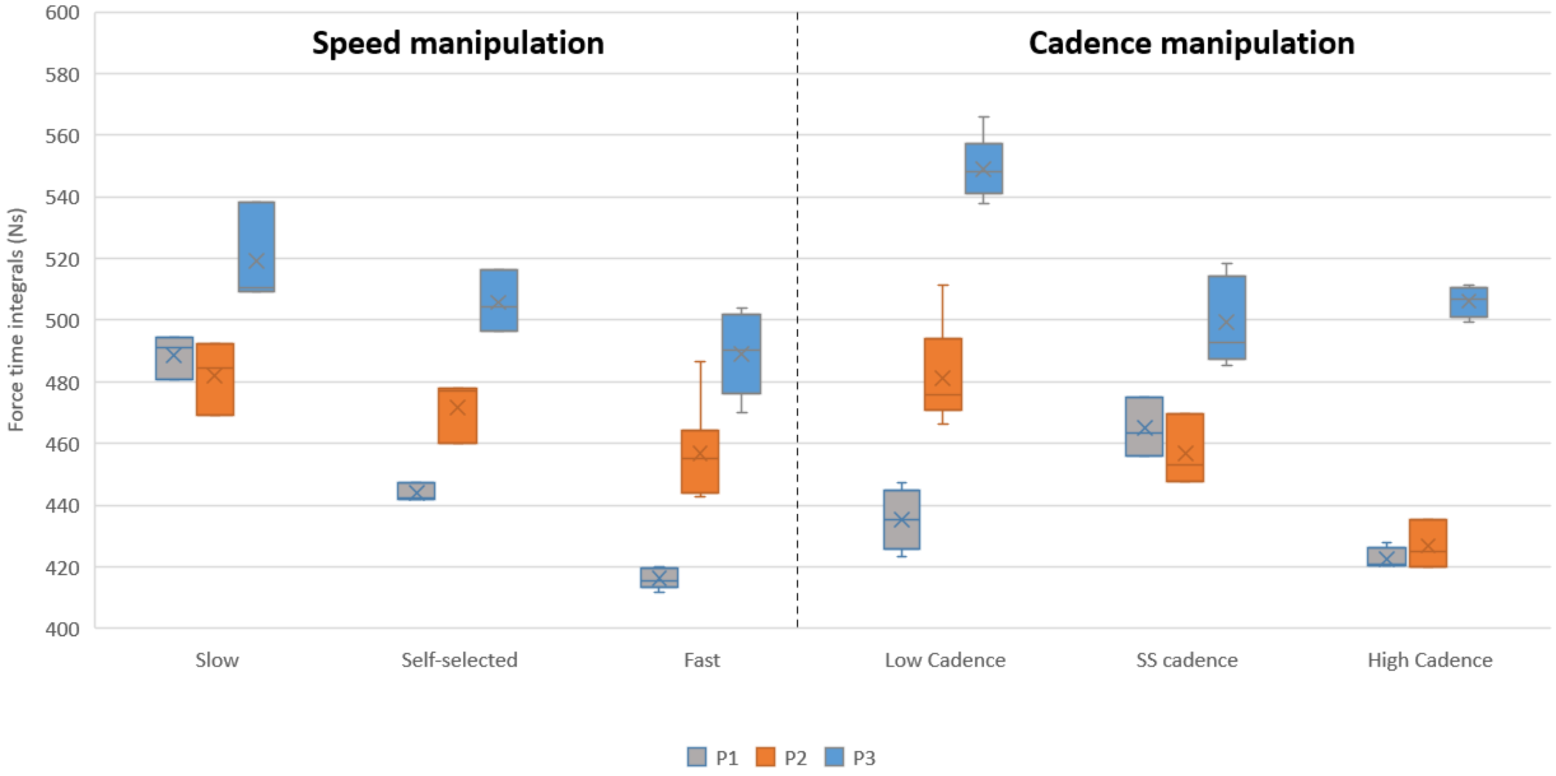


Figure 6 Vertical force time integrals

Box plots of different walking conditions (speed and cadence manipulations) of three participants (P1, P2, P3 denotes participants).

2.6 Discussion

The aim of this pilot study was to determine an appropriate gait manipulation method to control shear stress on the foot, for assessing the impact it has upon foot temperature in a future study. Two methodologies were trialled to adjust the shear stress, both use the principle of manipulating step length using two separate techniques: 1) changing walking speed (independent of cadence) and 2) changing walking cadence. To achieve this, three speed conditions and three cadence conditions were investigated, with step length, peak shear force, and shear FTI serving as the key dependent variables since they are essential for understanding plantar foot loading. As such, no definitive sample size calculation was deemed necessary, and no statistical comparison required to provide the direction for informing methodology in a subsequent thesis chapter. This was a pilot study comparing two techniques for manipulating shear stress. This was primarily about understanding the impact of the two manipulation approaches.

The results in Table 3 & Table 4 demonstrate that with speed manipulation increases in walking speed were followed by a consistent and graded increase in step length and anterior-posterior FTI increase for both level ground and treadmill conditions. In contrast, manipulating cadence did not lead to changes in these parameters in the intended direction and showed inconsistencies across modalities.

On the treadmill, increasing cadence without a change in walking speed results in a decrease in step length. Higher cadences make it necessary for more frequent foot strikes, which limits the length the leg can move forwards. This is important to note because, the speed only varied between 1.46 to 1.52 m/s and cadence varied between 108 to 123 steps/min on level ground, instead of the much larger change that occurred when speed was manipulated over level ground. On level ground and on the treadmill, the cadence was controlled using a metronome; however, it was anecdotally noted that because the participants were aware of the metronome sound, they planted their feet more purposefully on the force platforms as if trying to jab their foot down as soon as they heard the tone, rather than a natural and smooth forward swing. This likely further reduced step length as the metronome speed increased, compared to the expected shorter steps already associated with higher cadences (Table 2). Additionally, there were instances of higher forces at lower speeds believed to be a result of the higher, and lower cadences in some cases. This could be explained by the anecdotal observation of more forceful foot planting, rather than being a result of a lower/higher cadence *per se*, but participant's attempt to time their strikes with the sound of the metronome, was observed for both slow and fast metronome speeds, which may have offset any decrease in force that would have been expected with a lower cadence.

It shows that both speed and cadence manipulations had an influence on step length. However, when employing the metronome, the effect on step length and forces was not in a consistent and graded pattern as found for manipulating walking speed. Despite being adjusted to their cadence during level walking, the metronome seemed to produce an unnatural walking pattern. This deviation from natural gait when using the metronome is highlighted by the differences for the two self-selected tests (metronome vs. no metronome) when the metronome was set to the participant's self-selected cadence so should have been comparable (Table 3).

It is also clear from Table 3 that there was a clear difference in the effect of the two conditions on step length. The speed manipulation condition progressively increased step length with increasing speed and this was seen consistently over level ground and on the treadmill. In contrast, the cadence condition progressively decreased step length with increasing speed over both level ground and treadmill. Walking on level ground and on a treadmill, both have their relative merits and limitations, but we observed in this pilot study that by manipulating speed the key variables were comparable across level ground and treadmill modes. The ability to measure forces and few treadmill measures during gait walking are the benefits of level ground walking but shear forces are especially difficult to measure. The advantage of using the treadmill is the ability to control walking patterns more tightly and their impact on variables like foot temperature, which take sustained time periods to detect noteworthy effects. Using the level walking speeds to set the treadmill speeds, the results varied by up to 0.2 m/s (Table 3). In Figure 4 the shear FTI increased progressively with increasing walking speed. The AP shear force (Figure 4), were consistently increasing in participants with increasing walking speed, which was consistent with Hamilton (2011), (Young and Dingwell, 2012), reporting that the AP shear force increases with longer step length. Since shear force causes friction between tissues in the sole, the AP forces are anticipated to be important when examining temperature. Because the medial-lateral force component is substantially smaller than the other two, the ML forces in Figure 5 did not alter consistently when speed or cadence increased. Also, it is difficult to alter ML forces, as the direction of motion is in the anterior direction, so the main effects of changes in that direction primarily affect that plane rather than ML. Vertical FTI were found to not change consistently with either speed or cadence conditions and could reflect the fact that as walking speed increases, foot-ground contact time decreases, and this results in the FTI being fairly equivalent across walking speeds and cadence manipulations.

2.7 Conclusion

To conclude, manipulation of walking speed rather than cadence led to a consistent and distinct increase in step length and shear FTI with increases in walking speed. This was also seen to occur consistently across both level and treadmill walking modes. In contrast, manipulating cadence did not lead to consistent changes in the key parameters of interest in the intended direction. Therefore, the approach of manipulating walking speed is the method of choice to be applied to investigate the association between alterations in gait characteristics and foot temperature during a 30-minute treadmill walking session in a subsequent chapter of the thesis.

Chapter three: *Kinetic and Kinematic factors contributing to foot temperature changes while walking at different speeds in healthy individuals*

Experimental study

3.1 Abstract

Objective: Foot temperature changes with foot loading/activity and there is a need to understand 'typical' real-time changes before determining pathological changes in the diabetic foot. This study aimed to compare changes in foot sole temperature during walking across a range of walking speeds and determine the key external factors/gait parameters contributing to the temperature change in healthy individuals.

Methods: 21 healthy individuals were recruited, and foot temperature was measured continuously during walking using bespoke sensors. Walking was performed at three different speeds (slow, self-selected, and fast) over level ground and on the treadmill (30 mins), with gait analysis conducted using motion analysis and force platforms. Temporal-spatial gait parameters, ground reaction forces (GRFs), and foot sole temperature were analysed.

Results: Step length and peak anterior-posterior shear GRFs increased progressively with increasing speed. Foot temperature increased with increasing walking speed and the increase was highest whilst walking at a fast speed (3.8*°C* increase) than slow (2.8*°C* increase) and self-selected (2.8*°C* increase) walking. The range in temperature changes was also greatest at the fast speed compared to self-selected and slow speeds. During 10 minutes of recovery after walking the temperature only reduced by ~0.32℃. Anterior-posterior peak GRFs and force-time integrals were inversely correlated to foot temperature changes during walking.

Discussion: Foot temperature changes markedly when measured in real-time during walking Fast walking increases foot temperature the most compared to slow and self-selected speeds. Longer steps and higher peak vertical and shear GRFs may be factors contributing to foot temperature rises, however, surprisingly we found an inverse correlation between shear force time integrals and temperature. Foot temperature was very slow to recover towards initial values during recovery after walking, indicating temperature dissipation is slower than temperature generation due to foot loading.

3.2 Introduction

The hallux and metatarsal heads are high-risk regions for diabetic foot ulceration, as seen by previous studies (Ince et al., 2007, Beckert et al., 2006, Galea et al., 2009, Boulton, 1988). Biomechanically, with each step, the forefoot bears a load that is significantly more than the body weight. The anatomy of this area is complex and heterogenous, with variety of tissues and thin plantar soft tissue (Bojsen-Møoller, 1979). Metatarsals are also where the effect of a tight Achilles tendon, which is significant and is associated with increased plantar pressure, would be most noticeable (Orendurff et al., 2006).

On the other hand, the anatomy of hallux and heel is less complex and has thicker plantar soft tissue. It’s likely that ulcers at these sites are caused by additional factors such ischemia or shear stress (Gooding et al., 1986). Heel ulcers are predominantly neuro-ischemic and typically thought to heal slowly in clinical practice, and some research suggests that they heal less quickly than ulcers on the metatarsophalangeal joint or toes (Pickwell et al., 2013, Boulton, 1988). Structure was dominating in the midfoot and 1st metatarsal head when predicting plantar pressure, but structure and function were equally important in the heel and hallux (Morag and Cavanagh, 1999).

Repetitive shear stress in the presence of diabetic peripheral neuropathy is thought to be a significant risk factor in the aetiology of diabetic foot ulcers (DFU) (Yavuz, 2014). Although there is considerable evidence to show that plantar pressure is a significant risk factor, few studies have considered shear stresses, which are challenging to measure due to equipment constraints (Lavery et al., 2003). The foot’s temperature may reflect the impact of repetitive vertical and shear foot loading, potentially making it an accurate indicator of DFU risk. Monitoring real-time foot temperature changes of healthy participants in response to various physical activities inducing different foot loading conditions may assist in establishing a baseline against which clinical populations can be evaluated and may improve knowledge of the factors that influence foot temperature changes.

Two main mechanisms influence the heat transmission inside footwear: (1) heat produced inside the body that is released through the foot, and (2) heat exchange to/from the surface and surrounding areas of the footwear including environmental forces acting on the foot. Internal heat production brought on by metabolism in combination with forces applied to the foot may be the major cause of foot temperature increases. Heat often moves from a location of higher temperature to one of lower temperature. As a result, another reason for a rise in temperature is that the person's immediate environment (i.e., the footwear) is hotter than their skin. The conversion of the mechanical energy generated during gait into thermal energy is one mechanism that could potentially result in heating inside footwear. For example, running at 3.3 m/s was reported to cause the maximal contact force upon landing to exceed the body weight by 2 to 2.9 times (Chuckpaiwong et al., 2008). Running for 15 minutes while wearing shoes caused forefoot and midfoot temperatures to rise by 0.5–2.2°C and 0.9–2.4°C, respectively. Running barefoot caused the rearfoot's temperature to increase more, by between 0.1 to 10.4% (Quesada et al., 2015) although the variance in temperature changes was high. The energy generated and imparted on the foot during running, therefore appears to have transferred heat to the sole of the foot. The peak plantar pressure is substantially influenced by walking speed (Pataky et al., 2008), and this elevated pressure may also contribute to the development of an elevated thermal environment in footwear.

The temperature of a human foot has been shown to increase during walking (Reddy et al., 2017). The mechanisms causing temperature variations at the foot's sole are not yet fully understood. Shear forces during locomotion may play a role in increasing foot temperature, according to earlier studies (Gonzalez et al., 2021).

The force loading patterns under the Hallux and rear foot have been demonstrated to be significantly influenced by walking speed; however, increases in walking speed had a less significant effect on the forefoot loading patterns. At slower walking speeds, the medial forefoot loading initially increases; however, as people start to walk faster, the medial forefoot loading either stays constant or decreases, which is attributed to a decrease in the contact time (Segal et al., 2004).

Studies on healthy people have shown temperature variations between pre- and post-activity, suggesting that the foot temperature may be markedly influenced during and after locomotor activities (Carbonell et al., 2018, Reddy et al., 2017). Thus, physically demanding locomotor tasks may predispose the foot tissue to harmful consequences such as ulceration within neuropathic individuals with diabetes. The thermal response of the foot has been shown to significantly change in response to different locomotor tasks or footwear in healthy adult participants, including both increase and decrease in temperature from pre- to post-activity. For instance, after 30 minutes of running, the heel temperature has been shown to rise by ~8.2°C (Shimazaki and Murata, 2015). Additionally, a person's gait speed can affect how quickly their feet warm up, but for different walking cadences a study has shown that a relative plateau in temperature develops after 30 minutes of walking, and the foot temperature increases by 4.6°C across the foot (Reddy et al., 2017). Similarly, both the affected and unaffected limbs of people with diabetic peripheral neuropathy show an overall increase in foot temperature as the speed increases when walking in shoes (Najafi et al., 2012). Also as a potential element influencing heat dissipation within the foot is the type of sock material (Van Roekel et al., 2014).

Research that focused on relatively short duration activities has discovered a drop in foot temperature from pre- to post-activity. For instance, it has been noted that in Charcot neuropathy patients, the plantar temperature drops after walking for 50 steps compared to the initial baseline temperatures although this temperature decrease is less as more steps are taken (Najafi et al., 2012). According to a different study, walking 100 m can decrease foot temperature by ~1.3 °C in adults in good health and by 2.0 °C in people with diabetes (Carbonell et al., 2018). The fundamental mechanism causing this variation in foot temperature during walking is unclear, even though various parameters (such as the mode of locomotion, speed, duration, and insulation) are known to alter the temperature response.

The mechanical efficiency of the human body is between 20-25% (Stellman, 1998), and the remaining energy is lost as heat to the environment. As a result, the foot acts as the body's thermal radiator and dissipates heat (Taylor et al., 2014). Plantar soft tissue injuries are more likely as the foot temperature increases. Therefore, it is crucial to develop a comfortable shoe sole with appropriate thermal parameters. The complexity of the effective parameters and the processes that controlled foot temperature makes the insole design difficult.

The temperature change of the foot during walking may be influenced by the mechanical interaction between the foot and the ground. The foot has been described as a dynamic system having the capacity to conform to changes in the external environment, function as a spring and lever for push-off during gait (Ray and Takahashi, 2020, Farris et al., 2020) and provide sufficient stability for carrying body weight (Kelly et al., 2018, Kirby, 2017). The foot can act as a shock absorber because of a combination of these features, potentially allowing mechanical work to transform into thermal energy. In fact, more recent methods utilizing foot modelling work have shown that during walking (Papachatzis et al., 2020, Takahashi et al., 2017) and running (Kelly et al., 2018), the foot structures can deform and dissipate mechanical energy. Given that the foot releases mechanical energy, the repeated forces that are encountered during walking may be one of the primary causes of the increase in foot temperature.

The change in foot temperature during walking was originally attributed to mechanical stress that tends to compress the foot vertically (Houghton et al., 2013), but more recent research using custom built pressure-shear plates has shown that shear stress has a better predictive value compared to vertical pressure of DFU (Yavuz et al., 2015b, Yavuz et al., 2007b, Yavuz, 2014). Most recently Leister and Wurdeman (2020) examined the dynamic foot temperature in type 2 diabetic patients with and without below-knee amputation during resting, walking, and cooling down sessions. They discovered that diabetic patients without amputation had a faster rate of temperature change when walking.

It has been demonstrated that people with diabetic peripheral neuropathy have areas of high local shear stress, with the lateral parts of the metatarsals experiencing shear stress that is roughly two times higher than the medial and toe regions of the forefoot (Perry et al., 2002). These regions of maximum shear stress are correlated with regions of higher temperature in healthy individuals while walking (Yavuz et al., 2014), supporting the theoretical relationship between shear and temperature responses. But technical difficulties make it currently infeasible to monitor shear stress without using custom built shear plates/sensors. Although it is very challenging to measure plantar shear stress directly, this present study uses force plates to measure shear GRFs while walking at various speeds. This study aims to compare changes in foot sole temperature during walking across a range of speeds and determine the key kinetic and kinematic gait parameters contributing to the temperature change whilst walking at different speeds in healthy individuals.

3.3 Methods

3.3.1 Foot temperature and gait data collection

3.3.2.1 Participants

The sample size was determined by conducting a power analysis based on changes in foot temperature at two different cadences reported in a prior study (Reddy et al., 2017), which showed that a minimum sample size of 12 would be required for this study. Using the results of this power analysis, it was decided to recruit 21 healthy participants (*n*=42 feet) to account for dropouts and data loss caused by missing repeat testing sessions. Participant demographics (*n*=21) are detailed in Table 5. Most of the study participants were between 31-40 years (n=12), followed by 41-50 years (n=5), 51-60 years (n=2), 61-70 years (n=2).

Table 5 Participant demographics (Means & SD)

Variable	***Mean ± SD (n = 21)***
Height (m)	1.76 ± 0.07
Body mass (kg)	80.1 ± 10.9
Age (yrs)	41.6 ± 10.1

Data was collected at John Dalton tower; Biomechanics Lab (T0.18) and Human movement lab (1.04) at the Institute of Sport. 21 healthy participants were recruited, who were free of any medical conditions based on self-report and visual observations (see inclusion and exclusion criteria below). This study was approved by the University Ethics Committee (Ref No: SE171828). The participants gave their written informed consent after being briefed on the experimental study (chapter 4 & 5) protocol. The order in which participants participated was solely on their availability. Data for the main experimental study were collected throughout several visits.

Inclusion Criteria

1. Age ≥ 30 years
2. Male / Female
3. Able to walk independently without support
4. Palpable foot pulses

Exclusion Criteria

1. Recent severe lower extremity injury/surgery
2. Any loss of sensation in the feet
3. Absence of any foot pulses
4. As this study involves foot temperature measurement in healthy participants, patients with any history of chronic diseases such as diabetes, cardiovascular disease, hypertension, neuropathy (any aetiology), asthma, arthritis, foot deformities and amputation were excluded to avoid confounding factors presented by these conditions.

3.3.2.2 Customized lower body marker set for kinematic gait analysis

To collect lower body 3D joint kinematics, a custom 6 degrees-of-freedom marker set using 41 markers was placed on participant's pelvis, legs, and feet shown in Figure 7 and described in were used in this study to collection the 3D motion data. Participants wore standardised shoes and were required to wear tight-fitting shorts to allow accurate marker placement within minimum movement (markers were placed directly onto skin wherever possible).

Figure 7 Customized lower body marker placement.

Showing the placement of the 41 markers on the lower body's anterior view (left) and posterior view (right).

Table 6 Customized 6 degrees of freedom marker set.

To collect 3D motion data using Vicon system with detailed description of marker placements on each lower limb segment.

Related Segment	***Position***
Pelvis	Left anterior superior iliac spine Right anterior superior iliac spine Left Femoral Greater Trochanter Right Femoral Greater Trochanter Left Iliac Posterior Spine Right Iliac Posterior Spine End of the fused vertebra of the spine
Upper Leg	Left Thigh Left Femur Lateral Epicondyle Right Thigh Right Femur Lateral Epicondyle Left Femur Medial Epicondyle Right Femur Medial Epicondyle
Shank	Left fibula Right Fibula
Lower Leg/Foot	Lateral Ankle (Left) Lateral Ankle (Right)

	Medial Ankle (Left) Medial Ankle (Right)
Foot	Heel Heel Cuboid (Left) Medial Cuneiform (Left) Cuboid (Right) Medial Cuneiform (right) 5th Metatarsal Head (Left) 5th Metatarsal Head (Right) 1st Metatarsal Head (Left) 1st Metatarsal Head (Right)

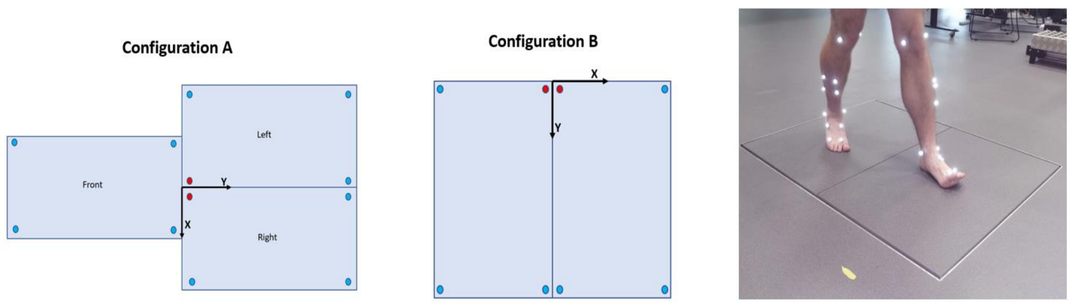
3.3.2.3 Initial walking assessment: Level Ground Walking – measurement of kinetics and walking speeds

The first visit to the Biomechanics Lab was to test level ground walking. Due to the requirement for sustained walking at a given speed to assess changes of foot sole temperature, a treadmill was subsequently required: however, to also assess ground reaction forces, and determine walking speeds for application on the treadmill, walking on level ground was first required.

Using a physician's scale, height and body mass were recorded. The force data was captured using ground-embedded force plates and the 3D motion data was recorded using Vicon motion capture system (Vicon, Oxford, UK). The above-mentioned customized six-degree marker set was used to capture the 3D motion data. The data collection for the level ground walking followed the same as the procedure explained in the pilot study (Chapter two). Walking speed manipulation, which was decided as the appropriate method to alter step length in the pilot study (Chapter two) was implemented for this study's data collection.

Participants walked barefoot at their self-selected speed (natural speed), without paying attention to the existence of force platforms. The start point of each walk was controlled to achieve clean foot strikes without overlapping the edge of the force plates during each walk, rather than instructing participants to achieve complete foot strikes (to avoid attempting to alter their gait when they walk over the force plates) on the force platforms. Timing gates were used to measure the walking speed during each walking trial for speed of feedback to participants for the need to alter speed during the subsequent trial. Participants were then instructed to walk at either a faster or a slower speed (fast/slow conditions were administered in a random order) after finishing the self-selected speed condition, the timing gaits were used to guide the participants to walk at least 0.28m/s (1kmph) faster and/or slower than their self-selected pace. Before undertaking each test, the participants were allowed to do a few practices preliminary trials, which helped to inform the participants about the start position, which enabled appropriate foot positioning on the force platform without participants ‘targeting’ the plate. On each trial of the self-selected, fast, or slow walking conditions, verbal feedback was given using data from timing gates that calculated the walking speed over a 3m distance along the path to ensure that individuals walked at the appropriate speeds and maintained consistently between trials.

Each participant was asked to complete several trials for each walking speed, to obtain at least three good trials with clean force data for both feet. For the data analysis, only trials with good foot contact were considered. For the six recorded (3 trials per foot) trials, the average walking speed for each speed condition was calculated. The timing gates during level ground walking was only used to measure the speed and the average speed for each speed condition was determined and set on the set for sustained walking measurements.



(A) (B)

Figure 8 Level ground walking – force plates configurations

(A) – Kistler force plates configurations employed in the level ground walking, Configuration A (Biomechanics lab, John Dalton tower) had three Kistler force plates with participants walking in the direction along the Y-axis, whereas Configuration B (Human movement lab,

Institute of sports) had two Kistler force plates with participants walking in the direction along the X-axis (B) – Level ground walking on a configuration B Kistler force plates with the customized six-degree marker set.

4.3.2.4 Sustained walking measurements: Treadmill Walking

Following walking on level ground, participants completed a series of sustained walking assessments on a motor-driven treadmill (Ergo ELG 70, Woodway Gmbh, Germany).

The treadmill tests involved three separate sessions to test three separate walking speeds. Within each session, participants walked for 30 minutes at the defined speed. Since each test required 30 minutes of walking, data from treadmill sessions were collected on separate occasions according to the participant's availability. On the treadmill, the average speed determined from level ground walking was set for each of the three-speed condition. The 3D motion data during each treadmill walking speed was captured through Vicon using customized marker set and 8 -12 cameras. Foot sole temperatures were recorded continuously for the duration of the treadmill walking session using the bespoke in-shoe temperature sensors and synchronized with the motion analysis data.

Experimental set up – Foot temperature assessment

A bespoke in-shoe temperature insole was designed and developed to track foot temperatures in real-time while performing dynamic activities. The sensor design was based on that developed for a previous study by Reddy et al. (2017) The insoles collected temperature data from four locations under the foot sole: Hallux, first and third metatarsal heads, and heel. Exact positions within the insoles for the sensor sites were determined that employed plantar pressure distribution to determine anatomical locations, and the temperature insole was built utilising temperature sensors and components determined in a previous study from our lab (Reddy et al., 2017).

The insoles consisted of a Plastazote® LD45 foam sheet with a thickness of 5mm. This bespoke insole comprises of four temperature sensors (TMP35, Analo device; Range 40 to 125 °C) implanted into an insole, with temperature sensors positioned at the hallux, first metatarsal head, third metatarsal head, and heel. Sensor wires were channelled through the insole and run out the lateral side of the shoe opening.

Each sensor's temperature data was captured at 100 Hz with a 0.08 °C resolution. The data from the temperature sensors was digitized and stored on a USB drive by NI myRIO, a reconfigurable input-output device from National Instruments that is controlled by LabVIEW code. The data is saved on a USB drive that is connected to the myRIO. The myRIO is powered by two battery packs that can record continuously for up to 10 hours. The insoles were placed in standardized shoes. The NI myRIO data acquisition set up was stowed in a backpack and was carried throughout treadmill walking session (Figure 9).

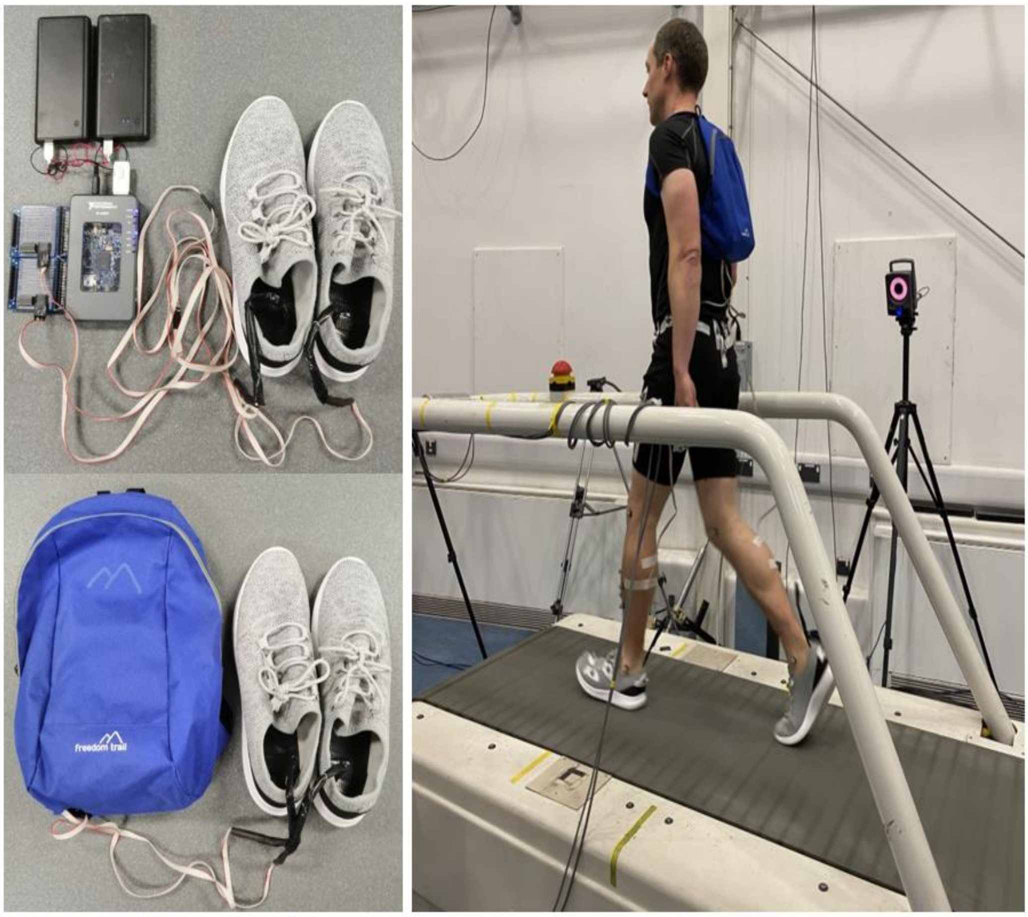


Figure 9 Temperature assessment set up while walking on the treadmill

Temperature measurement device used in the study connected to the myRIO, which was worn in a small backpack. Temperature insoles inserted into the shoe were digitized, stored on a USB drive, and connected to the NI myRIO device, and powered by battery pack. This set up was held in a backpack while walking on the treadmill.

3.3.2 Determining the sensor locations

The positioning of temperature sensor locations of the shoe sole were determined by the following methods.

- The hallux, MT1, MT3, and heel were identified as the prime anatomical regions for the positioning of the temperature sensor based on the previous studies demonstrating them as common ulcer locations in diabetic patients.
- These locations are associated with high plantar pressures in diabetic patients, therefore pressure mapping was used to determine these high-pressure locations to identify the correct positioning of temperature sensors within the shoe sole for a range of different shoe sizes.
- To determine the location of these anatomical landmarks the pressure distribution was measured whilst standing and walking across the pressure platform. Plantar pressure is a quantitative measurement and importantly for this purpose, indicates precisely where the highest pressures are located across the plantar surface. Using pressure measurements is a much more precise method for determining anatomical locations projected onto an insole than palpation and tape measures.

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This mini-study involved 26 participants (shoe sizes: 7 (*n*=7), 8 (*n*=5), 9 (*n*=7), 10 (*n*=5), and 11 (*n*=2)) between the age of 18 to 55 years with a mean body mass (81.2 kg) and height (169.5 cm). The participants enrolled were staff, students from the Manchester Metropolitan University, and other individuals by word of mouth, as a form of convenience sampling.

The overall length and width of their feet were measured with a measuring tape (Chaiwanichsiri et al., 2008).

The pressure map of the foot was created while standing and walking using the P-WALK pressure platform (BTS bioengineering, Italy, Europe), which displayed the pressure distribution in both static and dynamic phases (**Error! Reference source not found.**). In the standing trial, participants were requested to stand on the pressure plate barefoot for a minute while those in the walking trial were asked to walk across the pressure plate (the plate captures one foot at a time), recording three walking trials per foot. The following three parameters were assessed from the walking trial: (i) shoe size, (ii) foot length, (iii) foot width and also foot pressure distribution (foot contact area) was assessed in both standing and walking trials (**Error! Reference source not found.**).

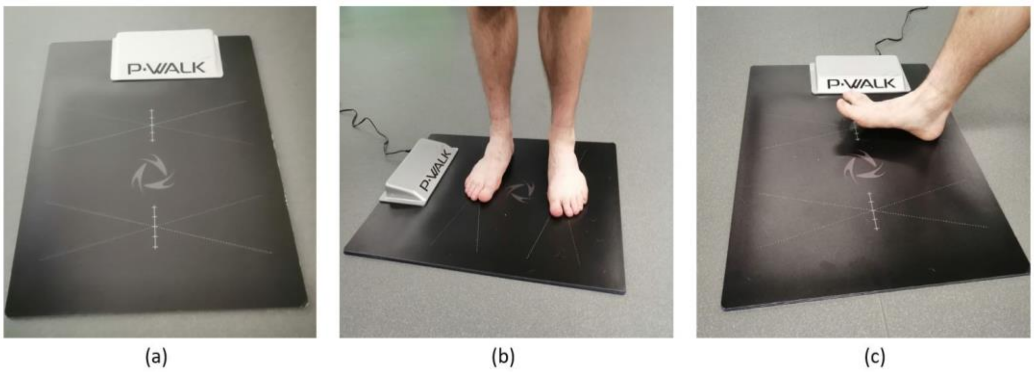
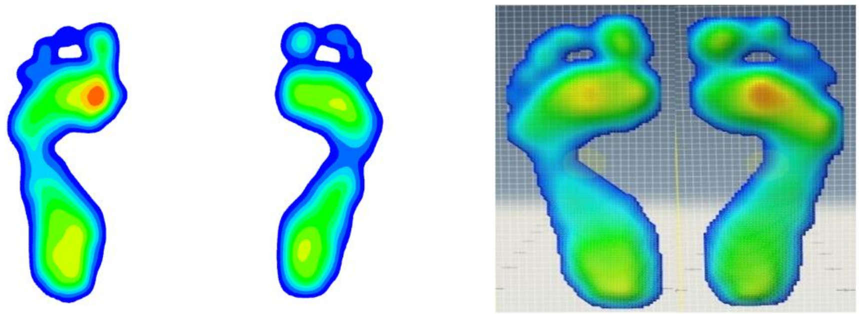


Figure 10 – Pressure assessment equipment.

(a) BTS P-walk to measure the plantar pressure distribution (b) Plantar pressure recorded during standing (c) during walking



(a) (b)

Figure 11: Pressure distribution: Standing and walking

(a) showing the pressure distribution of the feet while standing over BTS pressure platform (b) showing the pressure distribution of the feet during walking

From the plantar pressure distribution, the hallux, metatarsal 1(MT1), metatarsal 3 (MT3), and heel, locations were measured in each foot relative to the heel (Figure 9). The measured distances were converted to a percentage of the length of the foot.

The back of the heel was considered the origin of the foot to draw the axis. The X-axis, which is the midline of the foot, was defined from the origin back of the heel to the third toe (along the length of the foot). The length of the foot was measured as the most forward-projected point on the head of the larger of the first or second toe and the heel's most backward-projecting point while standing (Krishan et al., 2011).

The Y-axis was considered perpendicular to the midline. The width of the foot was measured as the distance between the point on the metatarsal bone (metatarsal-tibiale) with the greatest medial projection and the point on the head of the fifth metatarsal bone (metatarsal- fibulare) with the greatest lateral projection (Krishan et al., 2011). A series of co-ordinates to determine the four sensor locations were measured using the plantar pressure distribution during walking.

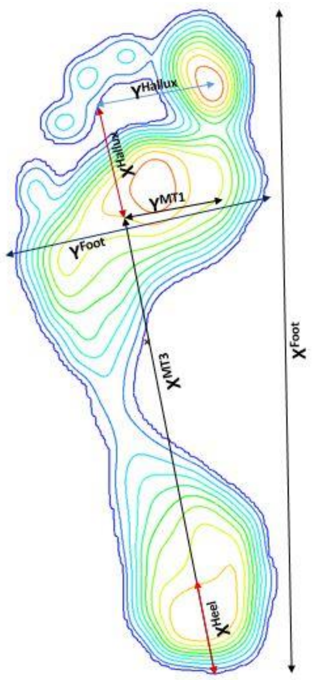


Figure 12: Coordinates of sensor locations of the foot showing length and width of the foot and length and four anatomical locations (hallux, MT1, MT3 and heel).

Table 7 The coordinate definitions for the anatomical locations

As shown in ***Error! Reference source not found.*** *are explained below.*

Variable	Description
X^{Foot}	Length of the foot from the back of the heel to the hallux
Y^{Foot}	Width of the foot
X^{Heel}	Length of heel from back of the heel along the midline
X^{MT3}	Length of MT3 from back of the heel along the midline
Y^{MT1}	Width of MT1 from the medial plane
X^{Hallux}	Length of hallux from MT3 along the midline
Y^{Hallux}	Width of hallux from the midline

To obtain percentage co-ordinates relative to the back of the foot and therefore be able to apply these relative coordinates to the range of foot sizes, the co-ordinates were normalised by foot length and width. The length and width of the defined anatomical locations were calculated and measured on both feet for every participant across the range of foot sizes investigated, and the average for each foot size was used to establish the four primary anatomical locations for sensor placement for each foot size. Mean distances/coordinates for each anatomical location were calculated and **Error! Reference source not found.**.

Although pressure measurements were taken while standing and walking, only data taken while walking were used to derive the results since standing revealed an inconsistent pressure distribution compared to walking.

Table 8 The coordinates anatomical sites of the foot with mean (SDs) and percentage distances calculated from means for UK shoe sizes.

The coordinates anatomical sites of the foot (X^{Heel}, X^{MT3} Y^{MT1}, X^{Hallux} and Y^{Hallux}) and the length and width of the foot (X^{Foot} and Y^{Foot}), measured in centimetres.

Foot Size	***X^{Foot} (cm)***		***Y^{Foot} (cm)***		***X^{MT3} (%)***	***Y^{MT1} (%)***	***X^{Hallux} (%)***	***Y^{Hallux} (%)***	***X^{Heel} (%)***
	R	**L**	**R**	**L**					
7	26.1(0.4)	26.7 (0.8)	10.6 (0.6)	10.8 (0.6)	72	30	90	34	18
8	27 (1.1)	27.7 (0.8)	10.8 (0.4)	10.9 (0.5)	71	30	87	33	17
9	28.5 (0.5)	28.6 (0.5)	11.4 (0.4)	11.2 (0.4)	71	30	89	35	16
10	29 (0.5)	29.3 (0.7)	11.6 (0.3)	11.6 (0.5)	70	31	89	36	16
11	29.6 (0.2)	29.9 (0.6)	11.6 (0.3)	11.2 (0.2)	72	30	91	34	15

(a) (b)

Figure 13: Custom made insoles design.

Photograph showing (a) custom made insoles designed using this study results. Grooves have been made to allow for embedding sensors and channelling cables. Photograph (b) showing temperature sensors embedded into the grooves and fixed with insulation tape.

These measurements of the anatomical sites relative to the length and width of the foot were then translated onto the insoles in order to match the sensor placement with these locations.

Temperature Assessment Protocol

The protocol for temperature assessment is shown in Figure 14. At their arrival to the Biomechanics lab for the treadmill data collection, foot temperature at the sensor locations were measured using an infrared temperature gun. The acclimatisation period of 10 mins then started where the participants sat with their shoes off and legs stretched out. This was done to allow the temperatures of the feet to return to their normal state after walking to reach the lab. This is the acclimation phase, during which the participant's foot temperature was allowed to stabilize.

After the acclimation period, barefoot temperature at the four sensor locations was measured on each foot using an infrared temperature gun.

After the acclimatisation period, participants then wore the shoes with the temperature insoles (without socks). The in-shoe foot temperature was measured starting with sitting (10 mins), followed by standing (15 mins), walking (30 mins) and recovery (10 mins) as shown in Figure 14. This protocol was followed for all three speed conditions. Sitting and standing temperature data are presented in Chapter 5, while all walking and recovery data are presented here in Chapter 4.

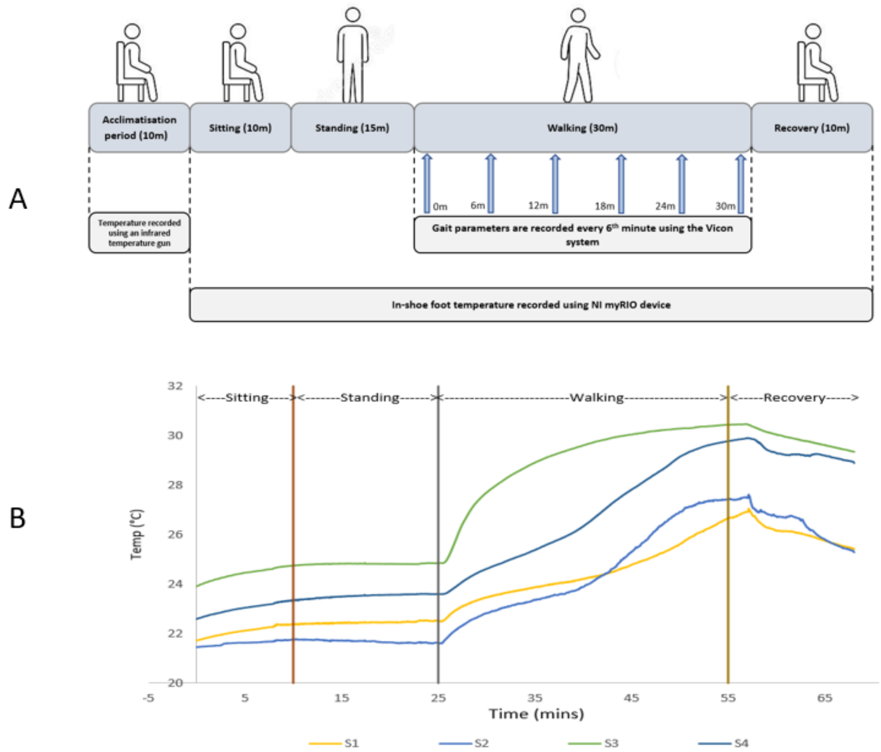


Figure 14 Schematic diagram showing the study protocol and timeline of the foot temperature measurement during treadmill sessions which consists of different activities

A *- Acclimatisation period (10min) before treadmill sessions, in-shoe foot temperature measured starting from sitting (10min), during standing (15min), walking (30min), and recovery (10min). Gait parameters were recorded for 1 minute at every 6th minute of treadmill walking.* ***B*** *– Example temperature data from a single participant showing the foot temperature at the four sensor locations (S1-S4) during the different activities.*

3.4 Outcome gait variables

3.4.1 Gait data processing and analysis

The 3D motion data for each walking trial was labelled (Plug-in-gait model) and gap filled - small gaps using a Woltring filter (less than 10 frames) and larger gaps were pattern filled in using Vicon Nexus. The recorded kinematic (movement) and kinetic (force) data were processed using Visual 3D (C-motion, Maryland, USA).

For data analysis, the treadmill sessions were broken up into intervals, with one minute of 3D motion data being collected every 6th minute for the whole 30-minute walking duration. The treadmill data was averaged across 60 seconds of data collection for each timepoint, and the mean and SD for each walking session was calculated, and the data was averaged across all participants, where the data was obtained for each foot (i.e., *n=42* datasets). The above-mentioned kinematic variables were determined from the motion data.

Gait variables

Gait variables relating to step spacing and stride lengths can be measured by considering gait from a spatial perspective. Stride occurs between the first contact of the foot and the subsequent first contact of the ipsilateral (same) foot. Step occurs between the first contact of a limb and the first contact of the contralateral (opposite) limb. The distance between these steps is referred to as step length and it is measured parallel to the body's line of progression. The variables mentioned below are determined from the 3D motion data using Vicon and processed in Visual 3D. The peak force and integrated force overtime (Force-time integral) of the GRF components were quantified for all three walking speeds whilst walking on the level ground.

Temporal-Spatial parameters

Step length is the distance between the posterior heel contact of the previous footfall and the posterior heel contact of the current opposing footfall. It describes the distance for a given step. The step length is on average ~70 cm.

Stride width is the distance between the centres of the feet during the bilateral support of the limbs in the gait cycle when both feet touch the ground. The average stride width is 8 to 10 cm.

Cadence is the number of steps made over a specific period (one minute). Adults walking at a comfortable pace have a cadence of between 90 to 120 steps per minute.

Velocity is the walking speed in the given direction. The average self-selected walking velocity is 1.34 m/s (Braden, 2012).

Stance Phase

The foot loads during the stance phase, which increases force and can generate heat under the foot. Therefore, the stance phase is divided into smaller phases and measured to see if it correlates with the temperature changes whilst different walking speeds.

Heel Strike – Dorsiflexion angle & Speed

This is when the first foot's heel first contacts the ground. Dorsi flexors are the primary muscles involved in the heel strike (the ones that pull your toes up). The phase of heel striking is when the walker is the most stable. The foot dorsiflexion angle and the posterior heel speed prior to heel strike are measured as one of the gait parameters that can influence foot temperature changes.

Rockers during Stance

The foot remains in static contact with the ground throughout the stance phase of gait while the body moves forward. A balance between stability maintenance and progression is important to facilitate the body's forward movement. This is made possible by a series of rockers in the ankle and foot that permit the forward rotation of the stance limb while the foot is remaining stable. This sequence was broken into separate rockers.

Rocker 1 (Heel rocker) Involves the heel serving as a rotation point for the foot to transition from a neutral position at first contact to 10 degrees of plantarflexion during loading response. This action causes the tibia to begin moving forward by translating momentum created during weight acceptance.

Rocker 2 (Forefoot rocker) occurs as the heel leaves the ground, and the rotation point moves to the forefoot and the metatarsal heads. This change takes place as the limb transitions to the terminal stance. As the body weight moves past the foot support area, this movement quickens the forward motion.

Rocker 3 (Toe rocker), which happens during pre-swing, is the final rotational point for the body's forward motion before entering swing phase.

3.4.2 Temperature data processing and analysis

The in-shoe temperature data was pre-processed using MATLAB (2014a; MathWorks Inc.). This process filtered the data using a moving average filter with a window of 1s and down sampled by a factor of 20.

Temperature rise curves for the treadmill speed conditions were obtained (Figure 14B). The temperature difference for each activity (sitting, standing, walking and recovery) was determined from the starting and ending temperature during each activity. While analysing the temperature changes, it was found for the treadmill sessions where more than one speed session was conducted on the same day that notably higher end of standing temperatures was identified in cases where multiple sessions were recorded consecutively. As change in temperature during walking was calculated by the difference between peak temperature during walking and the start of walking (end of standing), these elevated values at the end of standing due to insufficient time for the temperatures to return to their base level would underestimate the temperature change during subsequent sessions. Therefore, where multiple speeds were collected consecutively on the same day the adjusted temperature changes during walking were calculated using the first reference values of that day only.

Thus, 3 key temperature variables calculated were:

- Change in temperature: 30 mins walking – Difference between initial temperature (end of standing) before walking and peak temperature during walking.
- Change in temperature: Total – Total range in temperature during the whole session (start of seated to the peak measured during session)
- Change in temperature: Recovery – Difference between temperature at the end of the recovery period and the end of walking trial.

3.6 Results

Gait parameters

Temporal spatial gait results are shown in Table 9, which show a significant difference between self-selected and slow, except for rocker time 3, foot angle at heel-strike and posterior heel speed prior to heel-strike. Similar differences were seen between self-selected and fast speeds, except rocker time 1 did not show significant differences either between these speeds. Faster walking speed influenced step length, cadence, foot angle during heel strike, vertical and shear (anterior-posterior and medial-lateral) peak forces and vertical force-time integral. These gait parameters increased with increase in walking speed.

The heel speed prior to heel strike in the posterior direction showed a significant ANOVA effect, but no post-hoc differences were found within speeds. While the body as a whole is still moving forwards throughout the cycle, heel-clawing upon initial contact (as seen by the common momentary anterior spike in the AP GRFs during normal walking GRF profiles) is common and results in a posterior heel velocity.

Anterior-posterior force-time integral increased with walking speeds to an extent but not beyond the self-selected speed and did not reach significance, whereas the anterior-posterior peak component of the shear force increased progressively with increasing walking speed. Vertical peak forces increased progressively with increasing walking speed, whilst conversely vertical force-time integral decreased progressively with increasing walking speed.

Table 9 Temporo-spatial and kinematic parameters with Means, SDs, and significance between different speeds

Using repeated measures ANOVA [abc denotes the significance between speeds: a – slow and self-selected speeds; b – Slow and Fast speeds; c – Self-selected and fast speeds]

Variables	***Speed (n=42)***			***ANOVA (n=42)***
	Slow	***Self-selected***	***Fast***	
Temporal - spatial parameters				
Velocity (m/s)	1.14 ± 0.19	1.39 ± 0.02[a]	1.72 ± 0.03[bc]	< 0.001
Step length (m)	0.67 ± 0.01	0.73 ± 0.01[a]	0.84 ± 0.01[bc]	< 0.001
Cadence (steps/min)	103.18 ± 1.27	113.77 ± 1.21[a]	127.21 ± 2.26[bc]	< 0.001
Step Time (sec)	0.59 ± 0.01	0.52 ± 0.01[a]	0.48 ± 0.01[bc]	< 0.001
Swing Time (s)	0.39 ± 0.02	0.36 ± 0.03[a]	0.35 ± 0.02[bc]	< 0.001
Stride width (m)	0.09 ± 0.01	0.1 ± 0.03	0.09 ± 0.02	0.15
Rocker time 1 (sec)	0.13 ± 0.13	0.12 ± 0.12[a]	0.11 ± 0.09	0.25
Rocker time 2 (sec)	0.47 ± 0.14	0.40 ± 0.11[a]	0.32 ± 0.11[bc]	< 0.001
Rocker time 3 (sec)	0.21 ± 0.09	0.21 ± 0.09	0.21 ± 0.08	0.87
Posterior Heel speed prior to heel strike (m/s)	0.61 ± 1.36	0.96 ± 0.14	1.15 ± 0.11	**0.03**
Kinematic parameter				
Foot dorsiflexion angle during heel strike (degrees)	8.96 ± 19.43	11.39 ± 19.4	13.26 ± 21.87	0.28

Table 10 Kinematic parameters with Means, SDs, and significance between different speeds

Using repeated measures ANOVA [abc denotes the significance between speeds: a – slow and self-selected speeds; b – Slow and Fast speeds; c – Self-selected and fast speeds]

Variables	***Speed (n=42)***			***ANOVA (n=42)***
	Slow	***Self-selected***	***Fast***	
	Force time integrals (Ns)			
Medial – Lateral	23.24 ± 17.7	24.26 ± 20.7	24.14 ± 21.56	0.45
Anterior – Posterior	26.81 ± 16.06	30.14 ± 18.52	30.24 ± 21.29	0.16
Vertical	831.12 ± 696.1	751.69 ± 638.96	642.04 ± 540.39	< 0.001
	Peak forces (N)			
Medial – Lateral	89.97 ± 69.13	104.79 ± 77.11[a]	130.52 ± 102.75[bc]	< 0.001
Anterior – Posterior	41.67 ± 31.69	46.07 ± 34.21	54.82 ± 41.63[bc]	< 0.001
Vertical	1621.81 ± 1386.09	1727.86 ± 1493.43[a]	1901.83 ± 1624.81[bc]	< 0.001

Temperature Assessment

The foot temperature changes during walking, recovery and total period were assessed described in the methods (Figure 14). Mean foot temperature changes were determined for these periods and are shown in Table 11. The mean temperature increase during the 30 minutes walking activity was highest with the fast speed. The range of temperature changes across participants was highest during the fast speed. The total temperature change across the protocol activities ranged between 4.1 to 5.4°C and was similar at slow and self-selected speeds, but higher at the fast speed compared to slow speed.

Gait parameters and Walking temperature correlation

There were significant positive correlations identified between the change in temperature during walking with walking speed, step length, and walking cadence, which agrees with the study hypothesis. Inverse correlations were found between step (stance and swing) time, rocker time 2, anterior-posterior force-time integrals and walking temperature. The peak and vertical force-time integrals had significant correlation with walking foot temperature.

Table 11 Temperature changes during treadmill sessions at different speeds

(Means, SDs, and repeated measures ANOVA) [abc denotes the significance between speeds: a – slow and self-selected speeds (SS); b – Slow and Fast speeds; c – Self-selected and fast speeds]. Ranges of temperature changes within the participant group are shown for 2 of the variables below the means and SDs.

Change in temperature		***Treadmill session (n=89 feet)***			***ANOVA (p value) (n=89)***
		Slow	***SS***	***Fast***	
30 mins walking (°C)	*Mean ± SD*	2.8 ± 1.4	2.8 ± 1.3	3.8 ± 1.9[bc]	0.07
	Range (Min to Max)	5.0 (0.4 to 5.5)	5.2 (0.7 to 5.8)	6.5 (0.7 to 7.1)	
Total (°C)	*Mean ± SD*	4.1 ± 1.4	4.4 ± 1.4	5.4 ± 1.8[b]	**0.02**
	Range (Min to Max)	4.6 (1.9 to 6.6)	4.8 (2.2 to 7.0)	6.5 (1.5 to 8.1)	
Recovery (°C)	*Mean ± SD*	-0.31 ± 0.44	-0.27 ± 0.93	-0.37 ± 0.81	0.7

*Table 12 Spearsman Correlation between gait parameters and the change in temperature during 30 mins walking the Rho values and significance by * (p < 0.05) or ** (p < 0.01)*

Variables	***Change in in-shoe temperature: 30 mins walking (n=89), Rho values***
Basic measures	
Height (cm)	*0.05*
Body mass (kg)	*0.004*
Age (yrs)	*0.13*
Temporal-spatial parameters during treadmill sessions	
Speed (km/h)	***0.30****
Step length	***0.26****
Cadence (steps/min)	***0.30****
Step time (s)	***0.27****
Swing Time (s)	***0.28****
Stride Width (m)	*0.09*
Rocker time 1 (s)	*0.12*
Rocker time 2 (s)	***0.28****
Rocker time 3 (s)	*-0.02*
Foot dorsiflexion angle during heel strike (degree)	*0.12*
Posterior Heel speed prior to heel strike	*0.21*
Force time Integrals (Ns)	
Medial – Lateral	*0.03*
Anterior – posterior	***0.26****
Vertical	***0.34****
Peak forces(N)	
Medial – Lateral	***0.23****
Anterior – posterior	*0.14*
Vertical	***0.33****

3.5 Statistical analysis

All the analysis was carried out using Statistical Package for the Social Sciences (SPSS) (released 2016. IBM SPSS Statistics for Windows, Version 24.0. Armonk, NY: IBM Corp). Normality test was performed for all the gait and temperature data, Pearson's correlation coefficient was used for the normally distributed data and Spearman's correlation was used for the non-normally distributed data. Differences between speeds were assessed using a one-way repeated measures ANOVA and Bonferroni post-hoc analysis, with statistical significance accepted at $p < 0.05$.

3.7 Discussion

Foot temperature changes during walking are a consequence of the mechanical interaction between the foot and the ground. Peak forces (vertical and shear) were found to increase as walking speed increases in the present study, which agrees with a previous report (Fukuchi et al., 2019). Higher forces are thought to load the foot sole's tissue more, leading to increased deformation of the tissue and increasing the work required by the muscles, especially the small intrinsic foot muscles, in order to stabilize the foot. But also, the physical act of compressing soft tissue itself generates heat. As more temperature is generated due to the deformation and activity of the muscles, and if this heat cannot dissipate, it will raise the local temperature. In the current study, foot temperature increased the most with fast walking compared to self-selected speed and slow speeds. There was a 1°C higher temperature rises during fast walking compared to self-selected and slow walking (Table 11), supporting the observation of higher temperature rises with faster walking speeds. Shorter step times and greater peak vertical and shear (anterior-posterior and medial-lateral) forces were associated with increased walking speed. The temperature increase over 30 minutes of walking in slow and self-selected walking were similar (2.8°C rise). Slow walking increases contact duration while decreasing peak forces (vertical and shear), while the faster self-selected speed would have longer contact duration but higher peak forces. Decreased forces would probably result in less heat build-up, whereas longer loading periods would result in more heat build-up, cancelling each other out to produce increases to self-selected speeds that are similar. This reflected on the results and there was no difference noted in the post hoc tests between self-selected and slow speed walking. As a result, it may not have had a substantial effect to considerably change the temperature differentially between speeds. This indicates that walking more slowly had a lesser effect on temperature changes than walking fast. As hypothesised, when assessing the different walking speeds numerous kinetic and kinematic characteristics, including step length, cadence, foot angle altered (Table 9)

These were to be expected as they are well demonstrated by previous studies showing differences between walking speeds in temporal spatial data and kinematics(Allet et al., 2011, Allet et al., 2008). As the speed increased both step length and cadence increased, confirming that manipulating speed was a successful method of altering step length as previously demonstrated within Chapter 2 as this chapter's mechanism of manipulating forces experienced under the foot. The change in temperature during walking had correlations with speed, step length, and cadence, indicating that these were key gait variables modulating temperature changes during walking. Both cadence and step length are driven by speed, which is correlated with temperature change, higher cadence will result in the tissue being compressed more frequently per minute, where compression of the tissue causes heat. While greater step lengths cause greater peak forces (Martin and Marsh, 1992)Therefore it is clear that the temporal-spatial parameters have an impact on foot temperature through alterations to foot loading. Previous studies have shown increase in foot temperature with walking speed (Fukuchi et al., 2019, Nilsson and Thorstensson, 1989, Taylor et al., 2004).

Vertical forces were found to have a strong impact on foot temperature changes through the significant positive correlations found with peak vertical forces and vertical force-time integral. In contrast, foot temperature change was inversely correlated with anterior-posterior peak and shear force-time integral, which is contrary to the initial hypothesis that increasing shear forces acting on the soft plantar tissue would generate heat. The inverse correlation seen between temperature increase and shear anterior-posterior force time integral suggest that foot contact time is relatively less important to temperature increase than peak force (as shown by force-time integrals). This contrasts with the way that force-time integral and loading time are thought to be significant when discussing pressures and foot ulcers. However, as this is the loading time per stance, as stances are evaluated cumulatively over time, these greater forces may still be applied for extended durations. Plantar pressures result by dividing the vertical force that the foot is subjected to while walking by the contact area. Despite the fact that Reddy et al. (2017) demonstrated that vertical pressure was unrelated to temperature increases. As a result, either an increase in the vertical ground response force or a decrease in the total contact area is required for an increase in plantar pressure (Cavanagh et al., 2000). It was discovered to have higher plantar pressures and wider contact areas in DFU patients, which indicate that DFU patients are certainly to experience higher vertical GRFs (Fernando et al., 2016).

Other temporal-spatial results from this study showed inverse relationships between foot temperature and step time, swing time, and RT2 (forefoot rocker). According to Segal et al.

(2004), an increase in walking speed has less of an impact on the forefoot loading patterns. This appears to be reflected in the lack of changes seen in rocker time 3 (forefoot rocker). Similarly, the amount of foot-ground contact reduces as the speed increases. Step and swing times increase when walking speed decreases, hence lower forces may be more responsible for temperature rise than loading times. Swing time may provide more time for heat dissipation and recovery, or it may likely be related to the relationship between slower walking and greater swing times.

The in-shoe temperature followed an upward trend and plateaued within 30mins of walking for every speed. This is in agreement with the findings of (Reddy et al., 2017). Given the physiological mechanics underlying heat creation and the factors regulating heat loss, the concept of a foot temperature plateau appears reasonable. Muscle contractions, frictional forces, and viscoelastic heating may all be contributing factors to heat build-up in the foot. The increases seen in temperature during walking among participants ranged between for slow – 0.4 to 5.5°C, self-selected – 0.7 to 5.8°C, and fast – 0.7 to 7.1°C, therefore the faster speed was associated with more variance (SDs: Slow – 1.4°C, self-selected – 1.3°C, fast – 1.9°C) in foot temperature response, perhaps reflecting the different gait strategies that participants adopt to meet the demands of faster walking.

Over the course of the whole testing session, with temperatures increasing steadily following the acclimatization period, during sitting, standing, and then walking. Depending on the speed walking contributed 60 -70% of the total temperature change over the period of the different activities. As perhaps expected, the total temperature change was larger for fast (5.4 ± 1.8) than for self-selected or slow walking speed. In the literature, for static temperature changes acquired at a single point in time and measured in the resting state, the temperature threshold for a difference between is given as 2.2°C, which is considered pathological. However, during continuous real-time temperature measurements we demonstrated here that the temperature changed by at least 3°C with walking for 30 minutes. Because of these significant temperature changes, using dynamic temperatures to determine pathology is likely to be much more challenging and justifies the approach of this thesis to first establish ‘typical’ foot temperature fluctuations with daily activities in healthy individuals to underpin application of ‘pathological thresholds’ in clinical populations.

The foot temperature decreased during the recovery period after walking, but it was shown that the temperature kept increasing to an extent during the first 3 minutes of the recovery period and only decreased by -0.27 to -0.37°C over the 10 min recovery period (compared to an increase of ~3°C over 30 mins of walking). It was therefore demonstrated that the in-shoe temperature did only reach 10% of the pre-walking temperature after 10 mins of recovery with any walking speed conditions, suggesting that temperature dissipation takes longer than was recorded within this study. Similarly, after 45 minutes of walking,(Reddy et al., 2017) noted a 2°C temperature drop during the 20 minutes of recovery, but the temperature did not drop to the initial walking temperature. This has implications for dissipation of foot temperature as it is likely that it will take a substantial time for temperatures to dissipate following heat generation. In diabetes, footwear is currently designed with offloading properties as the primary factor, whereas this research shows that more emphasis should be placed on understanding heat dissipation properties to enhance cooling following periods of walking activity.

3.8 Conclusion

This study has shown that foot temperature changes markedly when measured in real-time during walking by over 3°C and exceeds the current threshold of 2.2°C used to indicate pathological changes during static resting measurements. Fast walking causes the greatest rise in foot temperature compared to slower speeds. Longer steps and higher peak vertical and shear GRFs may be factors contributing to foot temperature rises. Foot temperature was very slow to recover towards initial values during recovery after walking, indicating temperature dissipation is slower than temperature generation due to foot loading and should be a consideration for future research.

Chapter four: *Intrinsic physiological and anthropometric factors contributing to changes in plantar temperature during sitting and standing*

4.1 Abstract

Objective: Fat pad thickness, blood flow, plantar stressors, intrinsic muscle activity are among the factors that result in physical activity-induced increases in plantar temperature. This chapter aims to examine the anatomical information of the foot including plantar fat pad thickness, blood flow, and their relation to the temperature change during sitting and standing.

Methods: The plantar thickness at four anatomical sites (hallux, heel, first and third metatarsal heads) was measured, along with blood flow to the lower extremities from healthy individuals (n=21). The plantar skin temperature was assessed at the anatomical areas prior to and after the acclimatization period and the in-shoe temperature was monitored while sitting and standing.

Results: The fat pad thickness at the heel was greater (1.91cm) than the other metatarsal or hallux regions. After the acclimatization time, the foot temperature at the anatomical regions decreased by 2°C. Over the course of sitting and standing, the in-shoe temperature increased by an average of 1.24°C. The in-shoe temperature change was significantly correlated with the thickness of the fat pads at the first and third metatarsal heads during sitting and standing. The absolute plantar skin temperature was inversely correlated with the first metatarsal head and heel. Fat pad thickness at first and third metatarsal heads showed a positive correlation with body mass.

Discussion: Body mass and plantar fat pad thickness have clear associations with changes to the temperature of the foot sole, so should be considered when investigating differences between individuals. The 2°C temperature drop experienced throughout the acclimatization period highlights the potential fragility of the generally recognized threshold of 2.2°C used to identify pathology in diabetic foot.

4.2 Introduction

A fat pad is essentially a group of adipocytes surrounded by a regular pattern of fibrous tissue septa, which in addition to providing insulation and protection, mainly serves as a shock absorber. Particularly the plantar fat pad has distinct qualities that allow it to function as a shock absorber. It is possible for the fat pads of the heel and the metatarsals to take on the weight-bearing role that is a fundamental element of the human foot because of interactions between neurons, blood vessels, and adipocytes. The majority view was based on the idea that diabetic patients' foot ulceration was contributed to by loss of their plantar fat pad thickness. The plantar tissues of the foot change structurally in patients with diabetes mellitus (DM) as a direct result of hyperglycemia and non-enzymatic glycation, where the build-up of advanced glycation end-products aids in the pathogenesis of numerous diabetes-related illnesses. It is believed that reduced perfusion to the fat pad caused by microangiopathy causes the fat pad cells to start to decreasing in size (Waldecker and Lehr, 2009). As a result, the fat pad would become thinner, increasing plantar pressure, and leading to the development of foot ulcers. Diabetic peripheral neuropathy, a major contributing factor to diabetic foot ulceration, is driven by this end-product accumulation in the foot, which causes endothelial dysfunction, wall stiffness, and degenerative changes in the connective tissue structure (Brownlee, 1995).

The human fat pad is made up of connective and adipose tissues located on the lateral and lower side of the foot. Due to its complex structure, the plantar skin and fat pad reduce ground impact, dissipate plantar pressures, and protects the foot from mechanical stresses that occur during locomotion (Jahss et al., 1992). The anatomy of the plantar skin and fat pad can be determined using ultrasound imaging and the severity of any structural changes or pathologies.

Reduced mechanical efficacy and structural integrity are the end results of structural tissue alterations that include soft tissue and joint stiffening, skin and fat pad atrophy, and mechanical displacement of the sub-metatarsal head fat pads (Gerrits et al., 2015, Andersen et al., 2004, Chao et al., 2011). Greater peak plantar pressure, increased tissue stress, and quicker tissue deterioration are all consequences of subsequent changes to the thickness or elasticity of the plantar skin or fat pad. Particularly in cases with limited joint mobility, foot deformities, and peripheral neuropathy, the foot becomes susceptible to diabetic foot ulcers (DFU) (Alavi et al., 2014). Regular clinical screening has been shown to reduce the difficulties associated with diabetic feet and in addition ultrasound screening may have an even greater positive effect (Morrison et al., 2021, Boulton et al., 2006).

The fatty tissues and muscle fibres make up the plantar fat pad, this soft-tissue detail may be seen using ultrasound imaging, and studies have indicated that determining the soft-tissue thickness through ultrasound could help determine a person with DFU development (Ledoux et al., 2013, Kumar et al., 2015, Abouaesha et al., 2001). According to several studies, people with and without diabetes have varied plantar soft tissue thickness measurements, which increases the possibility that these measurements could be used to detect or anticipate changes in the feet of diabetics. The accuracy of ultrasound measures of the thickness of the plantar skin and fat pad, however, is not well documented (Morrison et al., 2018). Due to the perceived subjectivity of such assessments, especially those of the plantar foot in diabetic patients, ultrasound can also be used to depict tissue features other than the thickness (Castro et al., 2019, Naredo et al., 2006). Using ultrasound imaging Kumar et al. (2015) studied the thickness of the sub-metatarsal head fat pad in individuals with and without diabetes. They discovered that diabetic patients' fat pad thickness had decreased and were advised to use ultrasound to check diabetic feet to identify any foot complications.

The foot deformities such as hammer/claw toes in diabetic neuropathy patients lead to sub phalangeal fat displacement at the metatarsal heads, which results in a 65% reduction in the thickness of the fat pad (Bus et al., 2004). The heel pad has long been recognized as a key component in dissipating the impulsive vibration produced by heel strike (Jørgensen, 1985). Heel fat pad is made of micro and macro chambers and they are believed to decrease in diabetic neuropathy patients which in turn reduces the compressibility of heel fat pad (Tong et al., 2003) Compressibility index (ratio of unloaded to loaded of fat pad thickness) of these chambers has been utilised in studies to describe the characteristics of heel pads (Tsai et al., 2000, Turgut et al., 1999). Even if they are useful, such measurements fall short of accurately replicating the loading conditions that the heel pad encounters during the dynamics of gait, which is critical when assessing the mechanical characteristics of viscoelastic structures. Also, due to adipose tissue atrophy and collagen degeneration in this area, diabetic peripheral neuropathy has also been linked to higher incidences of heel pad syndrome. Since they have decreased sensation in their feet and are therefore unable to feel pain, they continue to place excessive pressure on their heels, which exacerbates the atrophy of the heel fat pads (Hsu et al., 2009).

Diabetic neuropathic foot frequently has raised skin temperature which is contributed to by arteriovenous shunting (Boyko et al., 2001). Previous research focused on well-known principal weight-bearing areas, such as the metatarsal head and heel, for temperature monitoring. Their findings showed that localized tissue injury was the main factor of elevating plantar temperature. Sun et al. (2005) separated the entire sole into regions of interest based on typical anatomic classification, including secondary weight bearing regions like the toes and midfoot, in order assess the foot temperature. They observed that the forefoot and heel were hotter than the hallux, and that the overall plantar temperature remained a consistent 27.8 1.0 °C for a period of 15 minutes.

Through cutaneous vasodilatation, increased sweat, and the release of piloerection, convective heat is dissipated (Ganong, 1995). Thermoregulatory shunt flow is generally perceived to play a significant role in the skin temperature changes (Jones and Plassmann, 2002). The posterior tibial artery, which separates into the medial and lateral plantar arteries beneath the flexor retinaculum, is the main source of blood flow for the plantar foot. A deeper layer of the lateral sole is reached once the blood flow passes through the medial foot arch region between the quadratus plantae and flexor digitorum brevis muscles. The lower extremities' small blood arteries have increased blood flow and velocity in diabetic peripheral neuropathy patients (Zhou et al., 2022). The relationship between blood flow and foot skin temperature in diabetic patients was first investigated by (Chatchawan et al., 2018), where the blood flow demonstrated to positively correlate with the plantar temperature. The plantar temperatures of diabetic neuropathy patients were considerably higher than those of diabetic patients without neuropathy, indicating that monitoring foot temperature is a significant potential tool for assessing the risk of diabetic foot in DM patients (Bagavathiappan et al., 2010).

However, no studies have addressed the relation between plantar temperature and plantar fat pad thickness. This study chapter aims to determine the intrinsic physiological and anthropometric contributing to foot temperature change during sitting and standing.

4.3 Methods

As part of the study protocol, the intrinsic physiological components and anthropometric factors were determined and presented in this chapter. Data on twenty-one healthy individuals (height: 1.76 ± 0.07m; body mass: 80.1 ± 10.9kg; and age 41.6 ± 10.1 years) were acquired at John Dalton Tower, the Biomechanics Lab (T0.18), and the Institute of Sports Human Movement Lab (1.04). Participants were chosen based on the inclusion and exclusion criteria outlined in Chapter 4. The ethics committee of the university approved this research (Ref No: SE171828). The participants gave their signed informed consent after understanding the study's protocol.

4.3.1 Ultrasound Imaging and Ankle Brachial Pressure Index

Fat pad thickness of the foot corresponding to the sensor locations: hallux, first metatarsal head (MT1), third metatarsal head (MT3), and heel in each foot were measured using B-mode ultrasound imaging with a linear array transducer (MyLab25, Esaote, Genoa, Italy) placed on the plantar surface of the foot and along the longitudinal plane for all sites. All thickness measurements were made from static images of the sensor locations. The ultrasound imaging parameters were optimised for each site and minimum pressure was applied to the skin’s surface with the transducer to avoid any compression of the underlying skin tissue and fat pad.

To acquire the image of the heel, the transducer was positioned above the plantar fascia origins at the medial calcaneal tubercle and positioned so that its long axis was aligned perpendicular to the skin surface. To acquire the images of MT1 and MT3 over the plantar forefoot, the transducer was positioned so that the longitudinal axis of each metatarsal was aligned. The metatarsal head was profiled at its maximum convexity with the transducer positioned perpendicular to this. To acquire the images at the hallux, the longitudinal imaging plane was used to identify the phalangeal bone.

The ankle brachial pressure index ABPI, assessing arterial blood flow to the lower limb was measured using a sphygmomanometer and Doppler ultrasound (Huntleigh, Cardiff, UK). The brachial systolic pressure from the upper arm and the ankle systolic pressure from the lower arm were obtained with the participant resting in the supine position. These indicators were measured to comprehend the components responsible for the behaviour of the rise in plantar foot temperature and peak temperature.

4.3.2 Foot Temperature Assessment

The temperature of both feet was measured according to methods as described below and shown schematically in Figure 15.

Plantar skin temperature

At their arrival to the Biomechanics lab for the treadmill data collection, foot temperature at the sensor locations (hallux, MT1, MT3, and heel) were measured using an infrared temperature gun. The acclimatisation period of 10 mins then started where the participants sat with their shoes off and legs stretched out. This was done to allow the temperatures of the feet to return to their normal state after walking to reach the lab. This was defined as the acclimation phase, during which the participant's foot temperature was allowed to stabilize. After the acclimation period, barefoot temperature was again measured at the four sensor locations on each foot using an infrared temperature gun.

In-shoe foot temperature

After the acclimatisation period, participants then wore the standardized shoes with the temperature insoles (without socks). As a part of the study protocol, the in-shoe foot temperature was measured starting with sitting (10 mins), followed by standing (15 mins).

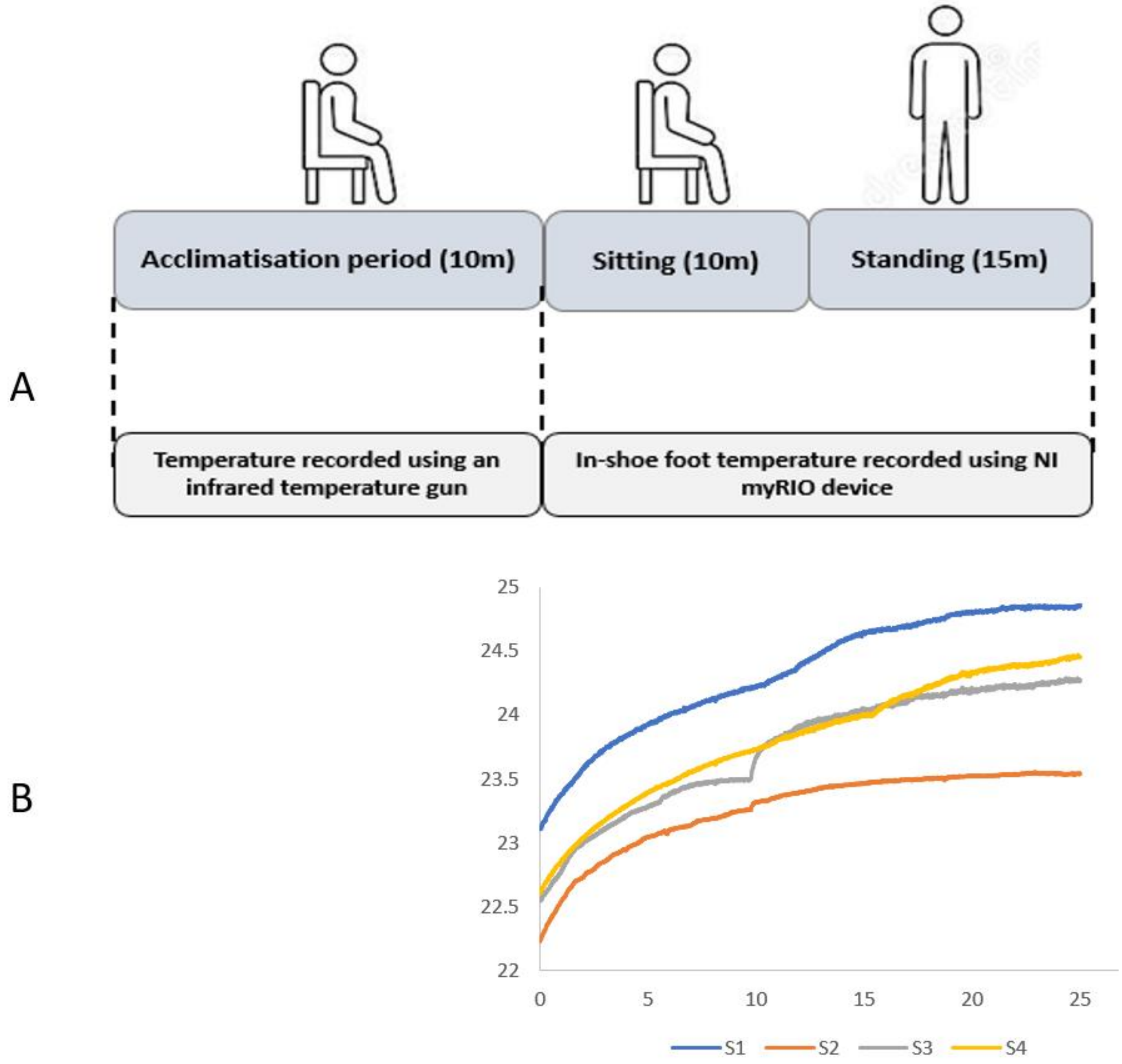


Figure 15 Schematic diagram showing the study protocol of the foot temperature measurement – acclimatisation period, sitting and standing

Acclimatisation period (10min), measured with an infrared temperature gun followed by in-shoe foot temperature measured starting from sitting (10min), during standing (15min)

4.4 Temperature assessment

Measured using insole temperature assessment:

- In-shoe foot temperature: sitting & standing – Absolute temperature during start and end at each time

- Change in temperature: sitting & standing – Change in in-shoe temperature between start of sitting and finish of 15 minutes standing.

Measured using infrared thermometer:

- Absolute plantar skin temperature pre-post acclimatisation period: Temperature at arrival and again at post 10-minutes acclimatisation.

4.5 Data Processing and Analysis

Using the images generated from B-mode ultrasound scanning, the fat pad thickness at each sensor position on both feet were assessed. The ultrasound system's straight line measurement function was used to measure the fat pad thickness. The thickness at these sensor locations were measured as follows: heel was measured from the plantar skin to the periosteum at the medial calcaneal tubercle, MT1 and MT3 was measured from the plantar skin to the periosteum of the metatarsal heads, and hallux from the plantar skin to the periosteum of the phalangeal bone. The systolic pressure values were obtained from the upper and lower arm, and the ABPI was determined using the formula:

ABPI = Ankle systolic pressure/ Brachial systolic pressure.

Using Spearman's correlation in SPSS (released 2016. IBM SPSS Statistics for Windows, Version 24.0. Armonk, NY: IBM Corp) these intrinsic characteristics were correlated with the absolute temperature at the sensor locations and the in-shoe temperature when sitting and standing. Differences between the fat pad thickness and absolute plantar skin temperature, and the in-shoe foot temperature whilst sitting and standing were assessed using a one-way repeated measures ANOVA and Bonferroni post-hoc analysis, with statistical significance accepted at $p < 0.05$.

4.6 Results

The mean and SDs of the intrinsic physiological and anthropometric factors and the foot temperature whilst sitting and standing are presented Table 13 and Table 14. The fat pad thickness was found to be significantly greater at the heel compared to the other measurement pad sites. Although the foot temperature measured at the heel was lower compared to other sites (Table 13), this did not reach significance ($p>0.05$).

Table 13 - Means, SDs of Intrinsic physiological and anthropometric factors, and skin and in-shoe foot temperatures

ABPI, fat pad thickness at the different anatomical locations and pre-post temperature measured using temperature gun at the four sensor locations after the acclimatisation period before sitting [[a] denoting significant difference between Hallux, MT1 and MT3]

Anatomical location	Fat pad thickness (cm)	Mean foot temperature °C	
		Pre acclimatisation period	Post acclimatisation period
Hallux	1.03 ± 0.18	28.18 ± 2.81	26.29 ± 2.89
MT1	1.09 ± 0.27	29.25 ± 2.07	27.26 ± 1.85
MT3	1.06 ± 0.22	28.87 ± 1.96	26.87 ± 2.02
Heel	1.91 ± 0.33[a]	27.65 ± 2.34	25.53 ± 2.51

Table 14 – In-shoe foot temperatures and ABPI data.

Means ± SD for in-shoe foot temperatures at each time point, and ABPI.$^{\alpha}$ denote a significant difference from start of sitting ($p<0.05$), $^{\beta}$ denotes a significant difference from end of sitting ($p<0.05$), $^{\gamma}$ denotes a significant difference from start of sitting ($p<0.05$).

In-shoe foot temperature (°C)			ABPI
Start of sitting	End of sitting	End of standing	
$24.51 \pm 1.68^{\beta\,\gamma}$	$25.25 \pm 1.60^{\alpha\gamma}$	$25.94 \pm 1.79^{\alpha\,\beta}$	1.28 ± 0.13

Table 15 Correlations between foot temperature and intrinsic physiological parameters

*Correlations between temperatures measured using the in-shoe system during sitting and standing with the internal physiological factors and demographic characteristics, r values and significance by * (p < 0.05) or ** (p < 0.01)*

Variable		***Absolute plantar skin temperature after acclimatization period (r value)***				***Change in In-shoe temperature during sitting and standing (r value)***
		Hallux	***MT1***	***MT3***	***Heel***	
Height (cm)		0.12	**0.19***	0.13	0.1	-0.11
Body mass (kg)		0.05	**0.23****	**0.22***	0.12	-0.09
Age (yrs)		0.13	**.32****	**.29****	**0.34****	**0.29****
ABPI		-0.11	-0.04	0.02	**.214***	-0.09
Fat pad thickness (cm)	*Hallux*	**0.23****	-	-	-	-0.04
	MT1	-	**-0.21***	-	-	**-.21***
	MT3	-	-	0.01	-	**-.30****
	Heel	-	-	-	**-0.20***	-0.18

The skin temperature and in-shoe temperature changes at various stated levels were correlated in the bivariate analyses with a range of intrinsic characteristics. There is a modest inverse (negative) correlation between the plantar skin temperature and the thickness of the plantar fat pads at the MT1 and heel, as well as between the in-shoe temperature and fat pad thickness at the MT1 and MT3 locations. Age showed a significant positive correlation with the in-shoe temperature, and skin temperatures at all sensor locations, except for the hallux. There were also low-moderate significant positive correlations between temperature at selected sites with height and body mass.

4.7 Discussion

The primary soft tissue on the sole of the foot is the fat pad, and it is the first to deform when the foot strikes the ground during gait. The fat pad provides protection by absorbing the pressures, shear forces, and impacts that occur with almost every weight-bearing activity, including walking, running, and even standing still. As a result, it is a crucial medium for producing and insulating heat.

In the present study, the mean fat pad thickness at the heel was 1.91cm, which is within the normal thickness (1-2cm) expected for healthy individuals (Özdemır et al., 2004). The heel fat pad was greatest compared to all other measurement sites with similar fat pad thickness at first (1.09cm) and third (1.06cm) metatarsal heads, which were lined up with the generic reference value of 1-2cm of metatarsal fat pad thickness (Health, 2023) and the hallux (1.02cm) (Table 13), but no prior studies were found with comparative values for hallux and specific metatarsal heads for healthy individuals. Although the heel showed the greatest fat pad thickness, the heel showed the lowest initial temperature of all the sites (25.5°C). The heel and MT1 fat pad thickness demonstrated negative correlations with temperature while the hallux exhibited a positive correlation between initial temperature and fat pad thickness. This indicates that in the case of the heel and MT1, a thicker fat pad is associated with a lower temperature. The hallux differs (positive correlation) from MT1 and heel (negative correlation), which may be due to the different physiology between the regions (Table 15). In contrast to MT1 and the heel, which have fat but also a thicker layer of non-vascularized skin as part of the measured thickness, the hallux may contain a greater percentage of vascularized tissue (tissue with blood vessels to provide heat).

The same holds true for other sites, with the metatarsal head (MT1 and MT3) fat pad thickness showing a significant negative correlation with the temperature change during sitting and standing. This may represent need to dissipate high ground reaction forces upon landing (I.e., heel strike) during gait, with thicker fat pads helping to dissipate forces and temperature more effectively.

Our measurements show that the foot temperature at the initial measurement when first presenting at the laboratory were higher, and the plantar skin temperature at each sensor location dropped by about approximately 2°C after a 10-minute acclimation period. This reflects the fact that participants had been undertaking foot loading activities before coming into the lab leading to foot temperature being elevated and the reduction of 2°C after 10 minutes of acclimation reflects a 'normalisation' of temperature. This change in foot temperature during the acclimation phase highlights the potential fragility of the currently accepted threshold of 2.2°C used to define pathology in diabetic feet (Frykberg et al., 2017a). The present results highlight that this threshold is susceptible to the confounding effect of prior foot loading/activity and that a period of acclimation is required before any measurements are acquired.

In-shoe temperature during sitting and standing increased by an average of 1.24°C over the course of the two periods (Table 14). This is suggested to result from the progressively increasing foot loading that occurs with sitting and standing. In Chapter 4, it was shown how walking significantly increases foot temperature by over 3°C and furthermore here it is shown that sitting and standing increase foot temperature by up to 0.8°C. Sitting and standing activities load the foot below and at body weight levels respectively, which is sufficient to cause temperature rises of up to 0.8°C. This type of activity also varied from walking in that it is not intermittent foot loading, but rather continuous sustained loading for 25 minutes.

Age showed a significant positive correlation with the temperature changes at all sites with exception of the Hallux. This indicates that with increasing age the plantar skin temperature is higher. Studies have shown that the fat pad decreases with increasing age (HEALTH, 2012) and may be reduced by 50% by the age of 50 years. This is consistent with the negative correlations between fat pad thickness and temperatures seen at the first metatarsal head and heel; indicating thinner fat pad is associated with high foot temperature. Similar to ageing, diabetes is also associated with a reduction in fat pad thickness (Dalal et al., 2015) and may indicate a link with higher foot temperatures if the same logic is followed. This is essential due to the current interest about how foot temperatures relate to ulceration (Beach et al., 2021, Yavuz et al., 2019). The medial forefoot and heel plantar skin temperature showed a significant positive correlation with the basic physical measures. Including that higher body mass correlated with higher initial foot temperature at these sites. People who are overweight or obese are also more prone to fat-pad loss and subsequent displacement, where increased pressure can particularly cause heel fat pad displacement. Additionally, extra body weight might increase the physical strain on the fat pads, reducing their ability to provide protection, being linked with thinner fat pads and higher foot temperatures, these factors combined demonstrate a variety of factors to reinforce consideration of body mass when researching, or attempting to account for foot temperatures.

ABPI also correlated with the initial temperature at the heel, which indicated increased blood flow to the lower limb correlates with plantar foot temperature, where initial temperature at heel is associated with diminishing blood circulation. Reduced blood flow could prevent heat build-up, but it could also make it harder for heat produced mechanically to dissipate. This is related to ABPI, which demonstrates that higher temperatures are associated with improved circulation at the ankle.

4.8 Conclusion

Intrinsic and anthropometric parameters and how they related to changes in foot temperature during static activities were investigated in this chapter. It was discovered that the plantar fat pad did influence foot temperature, but it varied at different anatomical location depending on the physiological structure. Although the correlations presented and discussed in this study are significant, they might be considered weak-to-moderate. However, foot temperature is not dependent upon a single factor and therefore it should be kept in mind that each of these single factors would not be expected to be contributing on its own, so significant correlations of temperature with single variables would likely be unusual.

Chapter five: *Conclusion and Future Directions*

51 Summary of main findings

The main aim of this thesis was to measure foot sole temperature continuously in real-time during different activities in healthy individuals and to understand the extrinsic factors and internal physiological factors contributing to these temperature changes. Achieving this aim will enable understanding of typical foot temperature changes for translation to the diabetic patient population for determination of pathological foot temperature changes. In order to achieve the thesis aim, several sub-studies were undertaken.

In Chapter two a pilot study was undertaken to determine the most appropriate method to manipulate shear force while walking. The aim of the study was to pilot two alternative approaches to the walking protocol of the experimental study (Chapter four) and to determine how effectively shear forces may be changed during a sustained walking session utilizing a manipulated walking pattern. This pilot study found that step length and walking cadence increase with walking speed and was the best approach for manipulating shear force. A metronome was used to manage the walking cadence on both level ground and the treadmill. However, anecdotal observations showed that the participants were aware of the metronome sound, which led to more forceful foot strikes on the force platforms, which caused shorter step lengths as the metronome count increased. This demonstrates that while walking without a metronome, the results were more natural and compatible with a normal gait, however, when walking with a metronome, the results were unnatural. Whilst non-significant, the manipulation of walking speed, did demonstrate tendencies that were consistent with previous research, and individuals were able to perform more naturally. The findings identified varying walking speeds as the best way to manipulate shear force, through alterations to step length. A novel finding which subsequently informed the protocol design of Chapter four of this thesis.

Chapter three aimed to measure plantar foot morphology and sizes to determine appropriate sensor locations for the temperature insoles to be used in Chapters four and five of this thesis. A wide age range of 18 to 55 years was selected based on their shoe sizes being within the range of 7-11 (UK sizes). Most members were male due to the range of foot sizes selected (7-11 UK), but a small number of females with larger feet were recruited. A BTS P-walk pressure platform was used to evaluate the plantar pressure distribution while standing and walking. Mean distances between each sensor were calculated and measured on both feet for every participant, and the average for each foot size was used to establish where the four primary anatomical spots on the insoles should be placed for each foot size. Custom-made temperature insoles were designed for each foot size which helps to find the relation between plantar foot temperature and shear force for the data collection in Chapters four and five.

Following the establishment of both an appropriate method to modulate shear force during walking, and the development of the in-shoe temperature sensors, a study was undertaken (Chapter 4) examine the external predictors contributing to temperature increase during walking in order to better understand the temperature during sustained walking. The findings from the pilot study were applied in this investigation, where step length was altered by changing walking speed. According to studies, men are more likely than women to develop diabetic foot ulcers (Banik et al., 2020, Alhubail et al., 2020). Due to this, the temperature insoles (designed from Chapter three results) were primarily designed for UK men's shoe sizes 7 to 11, and the in-shoe foot temperature was measured while walking at three different speeds for 30 minutes on the treadmill.

Accordingly, the rise in foot temperature may be caused by the repeated stresses generated during walking, which were reflected in the foot temperature. Based on this theory, in this study, it was noticed that sustained walking was associated with an increase in foot temperature. Whilst walking fast, the heat generation was higher compared to other walking speeds. Reddy et al. (2017) previously found that walking increased foot temperature by about 5 °C, and that the rate of temperature change was influenced by walking cadence, but that the final temperature was unaltered. This present study investigated how the kinetic and kinematic factors are related to foot temperature. After examining a number of kinematic factors, it was discovered that the change in foot temperature during walking was significantly correlated with walking speed, step length, and cadence.

The change in foot temperature has previously been linked to mechanical stress, which tends to compress the foot vertically (Houghton et al., 2013). Similarly, there was a substantial association between peak and force-time integral vertical forces and temperature change in this study. According to studies, shear pressure may be important in controlling foot temperature and in treating certain foot pathologies, such as diabetic foot ulcers (Yavuz et al., 2015b, Yavuz et al., 2014, Yavuz, 2014). Force-time integral of anterior-posterior shear was shown to be inversely correlated to temperature change in this study, which means the foot temperature reduces with higher shear forces. This gives us an understanding that the magnitude of the forces is more essential than the foot contact time.

In screening the diabetic foot for complications, a temperature threshold for a clinical difference between feet is stated as 2.2°C (Lavery et al., 2007, Lavery et al., 2004) in the literature for static temperature variations obtained at a single time point and measured in the resting state. This difference of 2.2°C is regarded as pathological. In this present thesis however, it is shown that with walking for 30 minutes, the temperature changed by at least 3°C during continuous real-time temperature readings. This thesis uses the method of first establishing "typical" foot temperature fluctuations with daily activities in healthy individuals for application to clinical populations to support establishment of "pathological thresholds". Because of these significant temperature changes, using dynamic temperatures to determine pathology is likely to be much more difficult and justifies this thesis's approach. However, the large changes in temperature during different activities highlight care should be taken when comparing temperatures between feet in respect to the 2.2°C pathological threshold.

The foot temperatures were measured during different activities. The foot temperature dropped to 2°C after the acclimatization period. The temperature was expected to drop during the sitting and standing activities of the protocol. However, the temperature change during sitting +0.63°C, and in standing was +0.54°C. This provides substantially to the theory that individual differences brought on by physiological factors may be reflected in the variation in early foot temperatures. Temperature increases of 2.8-3.8°C were seen during walking at three different speeds. During normal walking, the footwear provides foot insulation. As heating of one area of the foot raises the temperature of the entire foot by raising the environment inside the shoe, this insulation probably lowers the variations in temperature between different locations of the foot. The greater temperature variations in the foot temperature response were associated with faster walking speeds, which may be an indication of the various gait strategies participants used to adapt to faster walking. Comparing pathological thresholds also becomes more challenging since walking involves greater variability than standing. In order to account for temperature variation, assessments of dynamic activities would probably be required to be made across longer time periods. Following walking, temperature decreased by 0.27-0.37°C throughout the 10-minute recovery time, indicating that temperature dissipation may take longer than the period over which temperature increased.

It is believed that the fat pad thins down in diabetic neuropathy patients and causing increased pressure on the plantar surface of the foot (Brownlee, 1995). Physical activity-induced increases in plantar temperature are thought to be triggered by a combination of factors including plantar stressors, intrinsic muscle activity, blood flow, and viscoelastic heat production by fat pads or other tissues. In Chapter five, based on this theory an investigation of the relationships between temperature variations during sitting and standing and the thickness of the plantar fat pad and blood flow was conducted. The fat pad at four anatomical locations were assessed, where the thickness of the fat pads on the first and third metatarsal heads significantly correlated negatively with the change in foot temperature during sitting and standing. This might indicate the necessity to properly dissipate high-ground reaction forces during heel strike, with thicker fat pads contributing to this. Whereas, the hallux was positively correlated but the first metatarsal head and the heel were negatively correlated to plantar skin temperature, this may be due to the distinct physiology between these locations. The hallux may have a higher proportion of vascularized tissue compared to MT1 and the heel, which have fat but also a thicker layer of non-vascularized skin as part of the measured thickness. The ankle-brachial pressure index is substantially correlated with the temperature of the heel skin, showing that greater temperatures are associated with improved ankle circulation.

5.2 Implications for diabetic foot ulceration

One of the main findings of this thesis is that foot temperature increases with daily activities but particularly with walking speed. As previously proposed, if foot temperature is a contributing factor in diabetic foot damage that results in ulceration, then lowering foot temperatures by either decreasing heat generation or increasing heat dissipation may be a good strategy to lower the risk of diabetic foot ulceration (Armstrong et al., 2005). This could be achieved by altering the walking speed, step length and cadence (Reddy et al., 2017). The foot temperature increased at least by 3°C with walking, this illustrates that while walking, there is a substantial increase in the physiological demand on the feet. The tissue may sustain ischemic injury if the demand for blood flow is not met. Decreased peripheral blood flow may result in less heat dissipation during walking and lower the starting and ending foot temperatures. Also, muscle deficit in diabetic neuropathy patients causes nerve conduction to degenerate, which reduces heat generation during walking (Bansal et al., 2006). Additionally, people with diabetes who have deformed feet experience stiffness and displacement of the fat pads, which can alter the mechanical properties of foot and heat dissipation. In addition to its primary function for pressure offloading, footwear should be designed to dissipate heat and prevent the foot from getting warm. At the end of the walking conditions, it was seen that the participant's feet were sweaty. Further research is needed to determine how sweating affects foot temperatures, particularly in diabetic neuropathy patients, many who may have autonomic neuropathy and an impaired sweating response. Thus, clinical knowledge that could support the treatment and management of diabetic patients' feet could be gained by understanding normal and physiological patterns of change in foot temperature in diabetic patients. However, supporting such improvements necessitates continuous monitoring of foot temperature changes.

5.3 Further findings of interest and future directions

This study found that walking results in significant temperature increases that take relatively longer to recover. Therefore, in longer and home-based investigations, the actual range of foot temperature changes can be evaluated during daily life. A slower recovery/return of foot temperature to resting levels following walking, has implications for the design of footwear to facilitate foot cooling. Particularly for people with diabetes foot cooling following prolonged walking will be important to avoid thermal-induced skin damage that could precipitate foot ulceration. The evaluation of foot temperature could be expanded to determine whether the same temperature patterns are seen in clinical populations and to identify how temperature changes under the feet of people with a clinical condition. It is also, important to do a separate study on temperature changes in diabetic feet in different risk groups.

The foot temperature in the study was measured in a lab environment; more investigation into how temperature changes in healthy people during the daily life can aid in understanding temperature variations. Additionally, it is also important to compare the temperatures of pathological and healthy feet to determine whether a dynamic temperature difference can reveal any additional signs of pathology.

5.4 Limitations and consideration

Since the experimental study involved 30 minutes walking at different speeds on the treadmill, most participants were between the age group of 31 - 40 years. However, the participants did range from 31 to 70 years, given correlations were observed with age, future studies including increased older participants might allow these correlations to be assessed further to see whether they alter further with older generations.

Since this study involved more male participants than females, there were no apparent gender differences in foot temperature in foot temperature were assessed.

There were instances of data loss from some of the sensors, with individual sensors failing to record during sessions, therefore rather than assessing the individual sites under the foot, the in-shoe foot temperature data for each foot were consistently determined using a minimum of two of the four sensors for the walking data in Chapter four. Future studies could expand the results of the current thesis to assess inter-site differences under the sole.

It might be interesting to see in future studies as how long it takes for the foot temperature to return to pre-walking/activity levels since the temperature did not drop to the initial walking temperature after the 10-minute recovery period. However, this decision to use this approach in this thesis was chosen for logistical and practical reasons, as each temperature assessment session already lasted 1.5 hours. This was accounted for in cases of repeated sessions, by always using the first sitting/standing period as the baseline for assessing the temperature differences.

5.6 Conclusion

Considering the findings from the body of the research included in this thesis. It is evident that healthy individuals' foot temperature increases whilst walking at different speeds. Various gait parameters such as step length, cadence, peak vertical, and shear components of the ground reaction force increase with the increase in walking speed. The foot temperature at each walking speed reached a plateau at some point. Walking temperature change is significantly correlated with the extrinsic gait parameters walking speed, step length, cadence, force-time integral, and peak vertical forces. During sitting and standing, the plantar fat pad affects the foot temperature, but this effect varied at different anatomical sites because of the locations' physiological structure. However, it should be noted that each of these individual factors would not be anticipated to contribute on its own because foot temperature is not dependent upon a single factor. The foot temperature variations reported with daily activities in this thesis provide caution to the current 2.2°C threshold currently used to define pathology in the diabetic foot. With a better understanding of pathophysiology and the potential creation of evidence-based healthcare guidelines for treating diabetic foot ulcers, this work offers insight into how foot temperature changes in healthy individuals throughout different activities.

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