

Repeated pressure and shear stress at the posterior heel following localised skin cooling: Protocol for a randomised cross-over study.

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Abstract

Background: Pressure in combination with shear forces can deform soft tissues and lead to development of pressure ulcers. The prevalence rate of pressure ulcers in the UK remains unacceptably high and can occur across the human lifespan. The posterior heel represents a common anatomical site for pressure ulcers, due to soft tissues lying adjacent to bony prominences and exposed to pressure and shear during lying postures. Localised cooling and interface materials which reduce shear may offer potentially therapeutic benefits in the development of pressure ulcers. Yet, the physiological mechanisms underpinning the potential benefits of localised cooling are not fully understood.

Objective: This study protocol aims to investigate how localised cooling influences the skin's microvascular, inflammatory, structural, and perceptual tolerance to repeated shear loading at the heel.

Methods: The protocol will be tested on individuals of different age, sex, skin tone and comorbidities, using a repeated-measure design. Three cohorts will be recruited: i) young healthy (n=35); ii) older healthy (n=35); iii) spinal cord injured (SCI, n=35). Participants will complete three testing sessions using a custom-built shearing rig with integrated thermal plate, during which the posterior aspect of the heel will be exposed to a standardised mechanical stimulus to elicit repeated pressure and shear loading. The experimental condition of each session will be determined by the temperature of the thermal plate, which will be set to either 36 °C (no cooling), 24 °C (mild cooling), or 16 °C (strong cooling). Continuous measurements will include kinetic coefficient of friction (CoF) and skin blood flow (via Laser Doppler Flowmetry; 40 Hz). Pro- and anti-inflammatory biomarkers in skin sebum (Sebutape), structural skin properties (Optical Coherence Tomography), skin conductance (μ s) and ratings of thermal sensation, comfort, and acceptance (Likert Scales) will also be assessed before and after the shear stress protocol.

Results: Recruitment began in January 2024. As of February 2025, 43 participants have been enrolled on to the study. Data collection and analysis are ongoing, published findings are expected to be available in early 2026.

Conclusions: This analysis will help identify mechanisms of skin damage following repeated shear stress at the heel, furthering our understanding of superficial pressure ulcers. It will also establish physiological and perceptual thresholds for the protective effects of cooling from shearing-induced damage at the heel.

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Repeated pressure and shear stress at the posterior heel following localised skin cooling: Protocol for a randomised cross-over study.

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Abstract

Background

Pressure in combination with shear forces can deform soft tissues and lead to development of pressure ulcers. The prevalence rate of pressure ulcers in the UK remains unacceptably high and can occur across the human lifespan. The posterior heel represents a common anatomical site for pressure ulcers, due to soft tissues lying adjacent to bony prominences and exposed to pressure and shear during lying postures. Localised cooling and interface materials which reduce shear may offer potentially therapeutic benefits in the development of pressure ulcers. Yet, the physiological mechanisms underpinning the potential benefits of localised cooling are not fully understood.

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This study protocol aims to investigate how localised cooling influences the skin's microvascular, inflammatory, structural, and perceptual tolerance to repeated shear loading at the heel.

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The protocol will be tested on individuals of different age, sex, skin tone and comorbidities, using a repeated-measure design. Three cohorts will be recruited: i) young healthy (n=35); ii) older healthy (n=35); iii) spinal cord injured (n=35). Participants will complete three testing sessions using a custom-built shearing rig with integrated thermal plate, during which the posterior aspect of the heel will be exposed to a standardised mechanical stimulus to elicit repeated pressure and shear loading. The experimental condition of each session will be determined by the temperature of the thermal plate, which will be set to either 36 °C (no cooling), 24 °C (mild cooling), or 16 °C (strong cooling). Continuous measurements will include kinetic coefficient of friction (CoF) and skin blood flow (via Laser Doppler Flowmetry; 40 Hz). Pro- and anti-inflammatory biomarkers in skin sebum (Sebutape), structural skin properties (Optical Coherence Tomography), skin conductance (μs) and ratings of thermal sensation, comfort, and acceptance (Likert Scales) will also be assessed before and after the shear stress protocol.

Results

Recruitment began in January 2024. As of February 2025, 43 participants have been enrolled on to the study. Data collection and analysis are ongoing, published findings are expected to be available in early 2026.

Discussion

This analysis will help identify mechanisms of skin damage following repeated shear stress at the heel, furthering our understanding of superficial pressure ulcers. It will also establish physiological and perceptual thresholds for the protective effects of cooling from shearing-induced damage at the heel.

Key words

Pressure ulcer, wounds, temperature, local cooling, shear stress.

Introduction

Pressure ulcers (PUs) constitute a localised damage to the skin and/or underlying soft tissue, resulting from prolonged periods of pressure or pressure in combination with shear forces [1]. In the United Kingdom (UK) alone, the annual cost of treating chronic wounds, including PUs, has been estimated to be approximately £8.3 billion [2]. Accordingly, an improved understanding of the fundamental mechanisms underlying the physiological tolerance of human skin to mechanical loading and shearing could lead to the development of cost-effective, personalised solutions to prevent these wounds and improve patient care and quality of life [3].

Sustained localised mechanical loading and shearing of the skin can arise from lying and sitting postures, particularly in individuals with mobility impairment such as spinal cord injury (SCI) [4]. Internal tissue deformations will occur as a result of sustained pressure and shear forces that can lead to changes in the physiology of skin and sub-dermal tissue, including ischemia in the blood vasculature, lymphatic impairment, and direct deformation damage [5, 6]. It has been reported that nearly 30% of pressure ulcers occur at the heel, with this region being the second most likely area for pressure damage after the sacrum [7, 8]. As opposed to the thick skin of the plantar heel, the posterior heel has thin striated skin [9], which is very susceptible to pressure- and shear-induced damage [10]. Yet, the mechanisms underlying the elevated risk of shear-induced damage at the heel remain understudied.

Microclimate conditions within and around skin tissues strongly influence the tolerance of skin to mechanical loading and shear [11]. For example, elevated temperature and humidity at the skin interface reduce the mechanical stiffness and strength of the skin [12], while also increasing its coefficient of friction [13]. These mechanisms can lead to a greater risk of tissue damage for the same mechanical stress [14, 15]. In contrast, cooling reduces skin tissue's metabolic demands and could increase the skin's physiological tolerance to mechanical loads [12, 16]. Early animal studies revealed that reduced skin temperature minimises the risk of PU formation [17, 18]. This may occur

through altered microvascular responses [18], as well as via downregulation of the expression of pro-inflammatory cytokines such as Tumour Necrosis Factor (TNF)- α , which is mediated by the stimulation of cold-sensitive TRPM8-expressing neurons in dorsal root ganglia [19, 20]. Furthermore, our preliminary proof-of-concept experimental and modelling data on a representative skin site (i.e. the finger) indicated that skin cooling to 16 °C can reduce friction by up to 35% for the same mechanical load [13]. This effect is likely due to changes in the viscoelastic properties of cooled skin tissues, which could in turn translate in reductions in shear stress. While this evidence highlights the potential therapeutic role of skin cooling for protecting tissue health, the mechanisms by which cooling enhances skin tolerance to pressure, shear, and friction remain poorly understood in humans [17-19, 21-24].

In addition to its physiological effects, localised cooling of the skin can induce cold discomfort, which can limit acceptability and adherence to therapeutic interventions that promote skin integrity, particularly for vulnerable individuals at risk of PUs [25]. However, evidence on how the absolute temperature of a surface shearing against the skin contributes to thermo-mechanical discomfort, is limited [26]. Whilst the evidence above highlights the field's limited mechanistic understanding of the effects of skin cooling on skin tissue viability, commercially available, microclimate management systems, which deliver local and full body cooling, continue to be developed and applied to support PU prevention [27-29].

It is also important to note that physiological and perceptual tolerance to pressure and shear at the skin interface may also vary as a function of age and comorbidities [30], which could in turn diminish the therapeutic efficacy of cooling. For example, ageing-induced changes in skin biophysics and morphology [31], as well as decreases in both reflex cutaneous vasoconstriction and density of thermoreceptors [32], are likely to modulate the thermoregulatory and perceptual sensitivity of the skin to localised cooling. Similarly, autonomic and sensory dysfunctions resulting from SCI manifest in impaired control of skin blood flow and lack of sensation below the injury level [33, 34].

It is based on the evidence above that this study protocol aims to investigate: 1) how different levels of localised cooling influences the skin's microvascular, inflammatory, structural, and perceptual responses to repeated pressure and shear loading at the heel; and 2) how metabolic, immunological, biophysical, and perceptual pathways underlying the effects of localised cooling on skin tolerance to shear are modulated by aging and SCI. The research that will be delivered via this protocol will be both important in improving scientific knowledge and timely to societal demands, as it will support the development of user-centred approaches to maintain skin tissue viability via evidence-based, therapeutic cooling.

Methods

Overview

Participants will attend three experimental sessions separated by a minimum of 24 hrs within the Clinical Academic Facility located at Southampton General Hospital (Southampton, UK). During the sessions, participant's will place the centre of their posterior heel on a custom-built friction rig, with integrated thermal plate, to undergo a standardised protocol eliciting repeated pressure and shear force. The study will be a randomised cross-over design, involving three plate temperatures, which will be set to either 36 °C (no cooling), 24 °C (mild cooling), or 16 °C (strong cooling). Microclimate conditions at the interface between a loaded skin site at risk of PU (e.g., the sacrum) and a support surface (e.g., a mattress) are commonly associated with ~38 °C skin temperatures. Following pilot testing, some participants (n=2) found a 38 °C plate temperature to be borderline uncomfortable, we therefore decided to reduce the plate temperature to 36 °C to improve thermal tolerability in the no cooling condition. The rationale for using two levels of cooling is twofold: firstly, prior research investigating localised cooling on tissue viability in animal [17, 18] models utilised cooling interventions at 25 °C, demonstrating the benefit of reduced skin temperature in preserving tissue viability. Second, one of the main aims of the study is to examine how different levels of cooling may influence the biophysical properties of the skin and perceptual thermal

tolerances of both mild (24 °C) and strong (16 °C) cooling.

Participants

Three participant cohorts will be recruited: i) young healthy (n =35); ii) older healthy (n =35); and iii) SCI (n =35). The current study protocol is being supported by a Medical Council Research grant (MR/X019144/1). As part of this grant, two distinct experimental protocols have been designed: 1) the present study protocol, which aims to investigate temperature modulation of shearing forces at the heel; 2) our companion study protocol (see Gordon et al., [35]), which aims to investigate temperature modulation of sustained mechanical loading at the sacrum [35]. The separation of the protocols is motivated by their intrinsic conceptual differences (i.e. the pathophysiology of shearing-induced vs. loading induced mechanical damage) as well as by different experimental challenges associated with their delivery (i.e. the development of a large, shearing-inducing, and thermally controlled friction rig for the heel vs. a small thermo-mechanical indenter for the sacrum). By design, the same participant cohort that will be recruited to evaluate the regional differences in response (sacrum vs. heel) and assess how the addition of shear force may impact local tissue physiology and the efficacy of cooling.

The sample size justification for the current protocol is based on the power calculations from Gordon et al., [35], using changes in the peak hyperaemic response, which is a robust repeatable response. Specifically, we will recruit a minimum of 18 participants per group, with target recruitment of 35 individuals, to allow for sufficient statistical power and to account for up to 50% dropout. Participants will be screened for study participation using a set of inclusion/exclusion criteria. Participants will be recruited into three groups; younger healthy (18-35 years old); older healthy (55-70 years old) and individuals presenting with SCI (injury level within T1-S1). The younger and older healthy groups will be undertaking regular physical activity (1-3 times per week), non-smokers or vapers, and free from comorbidities that would preclude them from taking part e.g., suffering from hypertension or Raynaud's disease. Both males and females will be recruited for sub analysis on the

influence of sex, and individuals with different skin tones, ranging from light to dark as assessed by the Fitzpatrick Scale[36]. The stratified skin sampling will be used to determine whether there is an influence of skin tonality on pressure and shear tolerance at the skin of the heel.

Ethical considerations

Healthy individuals aged 18 to 70 years, and those with a SCI will be recruited and tested for the project and will be conducted in line with Southampton University Code of Practice for Research, complying with the *Declaration of Helsinki*. Written informed consent will be obtained from participants, and relevant personal information (e.g. skin's perceptual sensitivity to cooling). Participants will have the unconditional right to withdraw from the study at any point. Data management will adhere to the University of Southampton's policy on data quality, the requirements of the Data Protection Act 2018 and the University of Southampton's Ethics Committee (ERGO) policies (see *Availability of data and materials*). Participants will be eligible for compensation of their time upon successful completion of an experimental trial, in the medium of retail vouchers (maximum compensation value £576). All experimental methods and measurements will be non-invasive, posing low risks to participants. However, mitigation measures are in place to manage any risks that may develop, including on-going skin temperature monitoring, checks of subjective wellbeing, and active skin re-warming following the cooling stimuli. The skin will also be checked for blanching erythema at regular intervals. Ethical approval for the stated measurements and procedures has been granted by the University of Southampton's Ethics Committee (ERGO 88984).

Experimental procedures

The study is a repeated-measures cohort design. Once participants have been screened and recruited, they will be invited to their randomly-allocated experimental sessions [37]. They will come to the laboratory wearing comfortable, loose-fitting attire. Upon arrival, participants will be seated whilst they acclimatise to the ambient conditions of the laboratory (21-24 °C; 50% RH) before recording height and body mass (Model 874; Seca GmbH, Hamburg, Germany).

Following the pre-experimental checks, participants will be seated on a hospital bed in a semi reclined position supported by pillows and a back rest. An elevated ankle cushion (20 x 11 x 10 cm) will then be positioned under the right leg and placed under the gastrocnemius muscle belly. To standardise the position of the foot and ankle, and minimise movement during the repeated shear movements, an adjustable orthotic ankle foot brace will be strapped on to the right foot and ankle angle set to a neutral plantar grade position (90°). This will ensure the skin over the calcaneus is consistently in contact with the surface of the thermal plate when the heel is placed on the friction rig and provide a constant relative tension in the local skin site (Figure. 1). The axial load will then be standardised to exert 15 N of normal force on the thermal plate.

Insert Figure 1 here.

Figure. 1. Experimental set up. The foot and ankle are supported by an orthotic brace and ankle support to standardise positioning whilst minimising movement during the shearing protocol. A series of measurements that run continuously or during discrete time points will be taken (Figure 2). First, baseline assessments including structural, and functional imaging of the posterior heel skin will be captured using Optical Coherence Tomography (OCT). This will be followed by sampling of skin sebum at the heel for subsequent biomarker analysis, using an established methodology involving a 2-minute application time and tweezer extraction to avoid cross-contamination [38]. To provide an index of baseline local skin hydration, a capacitance meter will then be placed on the heel to measure skin conductance (in μs). After the baseline measurements are completed, participants will place the heel on the thermal plate of the shearing rig [13]. Temperature of the aluminium thermal plate (22 x 16.7 cm) is controlled by a set of water-perfused Peltier elements and when applied to the skin, allows for the manipulation of local skin temperature (range: 0 °C to >50 °C; variable temperature rates under PID control (DaisyLab, MC computing, USA)). An optic fibre is integrated in the centre of the plate through a 1 mm hole, flush to its surface, allowing for the monitoring of skin blood flow via Laser Doppler Flowmetry (LDF) when the heel is static. An integrated force plate and low resistance trackway allow the recording of both normal and tangential

forces (N), respectively. The friction rig is interfaced with an A-to-D data acquisition unit (MC computing, USA), sampling plate surface temperature ($^{\circ}\text{C}$), normal and tangential forces at 33 Hz. The kinetic coefficient of friction (CoF) according to Amonton's law [39] can be estimated as the ratio of tangential (F_t) to normal force (F_n) (F_t/F_n) and defined as the resistance generated from two surfaces rubbing against each other [40].

The friction rig has been modified to be situated on a linear rail system that allows bidirectional linear travel. The travel is achieved by a servomotor (drylin[®] SAW-0630 linear module with motor, Igus, UK), which is fixed to the rig and causes 10 cm of displacement at the heel at a velocity of ~ 3.3 cm/s. The servomotor is equipped with a linear strain gauge (Loadstar[®] RAS1 S-Beam Load Cell, LoadStar, USA) providing measurements on the tangential pull (N) of the shearing rig during the prescribed displacements. Participants will be asked to provide subjective ratings of thermal sensation, comfort, and acceptability, using Likert scales (detailed below). At this point, the standardised protocol to cause repeated shearing stress will commence (Figure. 2).

Insert Figure 2 here.

Figure. 2. Standardised repeated shear protocol delivered at the heel. The friction rig will be used to deliver a standardised protocol to evoke repeated shear stress under 3 thermal conditions, i.e. a control skin temperature evoking no cooling (i.e. 36°C) and two cooling temperatures of 24°C and 16°C . During the protocol, a series of non-invasive measurements will be conducted [i.e. estimation of skin friction from the ratio of tangential and normal force, skin blood flow via LDF; inflammatory biomarker sampling from skin sebum; structural and functional imaging via Optical Coherence Tomography (OCT); perceptual assessment of subjective thermal sensation, comfort, and acceptance, and measurement of skin conductance to be used as an index of local skin hydration] at different time points (identified in the diagram by \uparrow).

The protocol starts by participants placing the heel in the centre of the thermal plate over the hole where the LDF optical probe is located flush to the surface. Positioning of the bed and lower limb will be modified to provide a standardised 15 N axial load on the plate. Skin blood flow will be measured intermittently (accounting for displacement of the heel following the static loading phases) throughout the protocol via LDF (Moor Instruments, moorVMS-LDF laser Doppler monitor, UK). The heel will remain in place for a 60 s thermal preconditioning period to allow for temperature adaptation at the skin interface (i.e., 36 , 24 , or 16°C). The repeated shearing sequence will then commence (Figure 2), initially with a 10 s pause, before the servomotor travels in one direction

pulling the rig and displacing it by 10 cm, pausing for 1 s then travelling in the opposite direction pushing the rig back to the original starting point. This sequence completes one repetition, which is repeated 10 times. After completing the 10 shearing repetitions, participants thermal perceptions will be recorded, followed by post- OCT, skin sebum and skin conductance measurements.

The sections below provide a description of the measurements to be used during the protocol.

Measurements

Skin blood flow

Skin blood flow will be monitored via LDF using a non-invasive optical probe, sampling at 1mm tissue thickness [41]. LDF has been validated [42] and been widely used to assess changes in blood flow velocity (as an index of changes in flow) over bony prominences, such as the sacrum [21, 22, 24, 43]. The optical probe is integrated within the custom-built friction rig, allowing concurrent manipulation of skin temperature whilst monitoring changes in skin blood flow prior to the repeated shearing protocol (i.e. thermal pre-conditioning phase). LDF values during the thermal preconditioning phase will be used to calculate the baseline skin blood flow (taken as the mean average during the 60 s period) and subsequently compared across test shearing repeats.

Biomarkers

Pro- (IL-1 α , IL-1 β , TNF α , IL-6, IL-8, IFN γ) and anti-inflammatory biomarkers (IL-1RA) will be extracted from skin sebum via the application of Sebutape (Cuderm, USA). This approach has been optimised [44], to ensure both low abundance and high abundance proteins can be quantified. In summary, Sebutape is applied to the heel for 2-minutes before the samples are extracted using tweezers and a gloved hand to avoid cross contamination. Stored samples will be coded and stored at – 80 °C prior to analysis using standard ELISA plates for targeted proteins. The extraction of skin inflammatory biomarkers will use chemical and mechanical stimuli for maximal extraction efficiency. Chemical extraction will involve 0.85 mL of extraction buffer, which consisted of PBS + 0.1% surfactant Dodecyl Maltoside. The tapes will then be shaken with the buffer for 1 hour

followed by 5 minutes of sonication. A 0.35 mL aliquot will then be used for total protein analysis. The remaining 0.5 mL will be centrifuged for 10 minutes at a speed of 15 000g at 4 °C. The supernatants will be discarded and the remaining solution with the pellet briefly vortexed and used for the immunoassay analysis, as prescribed by the manufacturer using MSD U-Plex kits (MesoScale Diagnostics).

Skin imaging

Skin imaging will be conducted using an OCT system (VivoSight®, Michelson Diagnostics Ltd., Maidstone, Kent, UK) which utilises a laser source of near-infrared wavelength (1305 nm with a Class 1M (EN 60825-1). The system includes a dynamic mode whereby the principles of speckle variance OCT are used to visualize the microvasculature in the superficial dermis. A total of 120 images with 50 µm spacing will be acquired as a $6 \times 6 \times 2 \text{ mm}^3$ (width \times length \times depth) stack. This technique will allow non-invasive characterisation of the skin's epidermal and blood perfusion properties prior to and following the thermomechanical manipulations [45]. Using OCT is non-inferior to punch biopsy for skin characterization [46]. The OCT probe will be placed gently on the skin, maintaining a static position during acquisition. Spacers at the probe interface will be used to optimise the focal point of the epidermis during scanning.

Perceptual assessments

Participants' local thermal and comfort sensations will be assessed via Likert scales, to establish time-dependent changes in subjective perceptions of cooling [47]. The Likert scales for thermal sensation, thermal comfort, and thermal acceptance were created based on the recommendations of Schweiker et al., [48], i.e. using a ruler to draw a 100 mm horizontal line, with evenly spaced anchors. Thermal sensation consisted of a 7-point scale from 1 (cold) to 7 (hot) with 4 as neutral. Thermal comfort used a 5-point scale ranging from 1 (comfortable) to 5 (extremely uncomfortable) and thermal acceptance used a 4-point scale ranging from 1 (clearly acceptable) to 4 (clearly unacceptable). Perceptual sampling will occur at pre- and post- the shearing protocol (Figure. 2).

Statistical analyses

Data will be assessed for normality of distribution (Kolmogorov–Smirnov test). Within- and between-subject mean differences in (N=35 with 95 % Confidence Intervals) as a function of mechanical stimuli temperature (i.e. 3 levels: 36, 24, 16 °C), time (i.e. varying levels depending on variables' sampling rate), and of participant group (i.e. 3 levels: young, older, SCI) will be analysed. These independent and interactive effects will be assessed by means of 3-way mixed model analysis of variance (or Friedman) in biomarker expression, skin structural and biophysical properties (i.e. imaging parameters), subjective thermal perceptions and CoF. Post-hoc analyses will be performed between shearing stimuli temperatures, time, and participant groups based the presence of main effects and using Tukey's test. Group-related co-variables associated with sex, skin tone, and clinical status (applicable to SCI participants only) will be considered in all analyses to interpret the proportion of variance unexplained by the main effects (i.e. temperature, time, and group) and their interactions.

Results

Recruitment began in January 2024. As of February 2025, 43 participants have been enrolled on to the study. Data collection and analysis are ongoing, published findings are expected to be available in early 2026.

Discussion

Prolonged mechanical loading from pressure, or pressure in combination with shear over a bony prominence such as the heel, can lead to skin damage and the formation of PUs [1]. Research that addresses the physiological tolerance of human skin to repeated mechanical shearing, is important for improving scientific knowledge and meeting societal demands. As such, this study protocol aims to investigate how cooling may influence the skin's pathophysiological responses to repeated shear loading at the heel, and how these responses may be modulated by aging and the presence of a SCI. This study will provide a comprehensive understanding of the physiological processes and the

potential benefits of cooling strategies to minimise the pressure ulcer risk at the posterior heel, whilst generating novel insights on temperature-modulated skin tolerance in vivo. This information will be relevant to skin physiologists, bioengineers, medical device manufacturers, and clinicians.

The study benefits from using a repeated measures design to purposefully sample clinically relevant groups of individuals and targeting relevant physiological and perceptual mechanisms. The heel is an anatomical location that contains minimal subcutaneous tissue, making it a vulnerable site for the development of pressure ulcers by impacting the integrity of the superficial layers of the skin [49]. The heel is particularly susceptible to injury in patients who are required to maintain semi-recumbent positions, for example in bed, where individuals may repeatedly engage in repositioning (e.g., from sliding down in bed) or transferring between support surfaces. Movement is often initiated by loading through the heels, creating both pressure and shear forces at the skin interface. Recent studies have shown how repeated pressure exposure, and pressure in combination with shear has elicited a biophysical and biomarker response from the skin [11, 44, 50, 51], indicative of early signs of damage.

Previous animal data has shown that reducing skin temperature during applied mechanical loading could lower the metabolic demands of the underlying tissues, protecting metabolic and myogenic components of skin blood flow [23]. There is further evidence to indicate that lowering skin surface temperature can reduce the kinetic coefficient of friction [13]. In addition, the effects of both heat and moisture in decreasing the resilience of the epidermis in load bearing regions of the body is well documented [52, 53]. However, whether these findings from other anatomical sites translate to the skin of the heel, and how these mechanical interactions may lead to the risk of tissue of damage, are unknown [10].

The study has been robustly designed but is not without limitation. Shear forces will be delivered via a dry aluminium interface, which may limit generalizability to clinical scenarios where the heel interacts with beddings with varying moisture saturations. The authors recognise the importance of

evaluating the effect of temperature modulation of friction using patient centred materials (e.g., textiles used in the fabrication of chairs and beds), and the subsequent translation of clinically relevant findings. This research is currently being undertaken in our laboratory. Given the lack of data on localised cooling at the heel, identifying how the effects of skin cooling vary both physiologically and perceptually will therefore be important for developing bespoke patient centred solutions to maintain skin integrity under shear stress, that are both effective and comfortable.

Funding

The project is being supported by a Medical Council Research grant (MR/X019144/1) and has a lifespan of 42 months from March 2023.

Availability of data and materials.

Data management will adhere to the University of Southampton's policy on data quality, which forms part of the University's Information Governance Framework, complying with the requirements of the Data Protection Act 2018 and the University of Southampton's Ethics Committee (ERGO) policies. This project involves human participants and will be conducted in line with the University's Policy on the Ethical Conduct of Research and Studies involving Human Participants, and the Medical Research Council's policies on ethics and data sharing. Data will be fully anonymised at the earliest opportunity and before being made available open access in the University's data repository. All data that supports publications will be deposited and will be citable using a persistent identifier (DOI). Research findings will be published in high quality peer reviewed academic journals.

Conflict of interest

The authors declare that they have no conflicts of interests.

Author contributions

Authors contributions are defined according to the CRediT taxonomy:

Conceptualization (DF, PW)

Data curation (DF, PW, RG)

Formal analysis (DF, PW, RG, CS)
 Funding acquisition (DF, PW)
 Investigation (RG, CS)
 Methodology (DF, PW, RG, CS)
 Project administration (DF, PW, RG, CS)
 Writing – original draft (RG)
 Writing – review & editing (DF, PW, RG, CS)

List of abbreviations

CoF	Kinetic coefficient of friction
IFN γ	Interferon gamma
IL-1RA	Interleukin-1receptor agonist
IL-1 α	Interleukin-1 alpha
IL-1 β	Interleukin-1 beta
IL-6	Interleukin-6
IL-8	Interleukin-8
LDF	Laser doppler flowmetry
N	Newtons
OCT	Optical coherence tomography
PU	Pressure ulcer
SCI	Spinal cord injury
TNF α	Tumour necrosis factor alpha
UK	United Kingdom

References

1. Kottner, J., et al., *Prevention and treatment of pressure ulcers/injuries: The protocol for the second update of the international Clinical Practice Guideline 2019*. J Tissue Viability, 2019. **28**(2): p. 51-58.
2. Guest, J.F., et al., *Health economic burden that wounds impose on the National Health Service in the UK*. BMJ Open, 2015. **5**(12): p. e009283.
3. Gorecki, C., et al., *Impact of Pressure Ulcers on Quality of Life in Older Patients: A Systematic Review*. Journal of the American Geriatrics Society, 2009. **57**(7): p. 1175-1183.
4. Fryer, S., et al., *Continuous pressure monitoring of inpatient spinal cord injured patients: implications for pressure ulcer development*. Spinal Cord, 2023. **61**(2): p. 111-118.
5. Worsley, P.R., et al., *An evaluation of dermal microcirculatory occlusion under repeated mechanical loads: Implication of lymphatic impairment in pressure ulcers*. Microcirculation, 2020. **27**(7): p. e12645.
6. Bouten, C.V., et al., *The etiology of pressure ulcers: skin deep or muscle bound?* Arch Phys Med Rehabil, 2003. **84**(4): p. 616-9.
7. Thorpe, L., *Assessing, preventing and managing heel pressure ulcers*. Wounds UK, 2017. **13**(2): p. 67-70.
8. Wong, V.K. and N.A. Stotts, *Physiology and prevention of heel ulcers: The state of science*. J Wound Ostomy Continence Nurs, 2003. **30**(4): p. 191-8.
9. Cichowitz, A., W.R. Pan, and M. Ashton, *The heel: anatomy, blood supply, and the pathophysiology of pressure ulcers*. Ann Plast Surg, 2009. **62**(4): p. 423-9.
10. Greenwood, C., *Heel pressure ulcers: understanding why they develop and how to prevent*

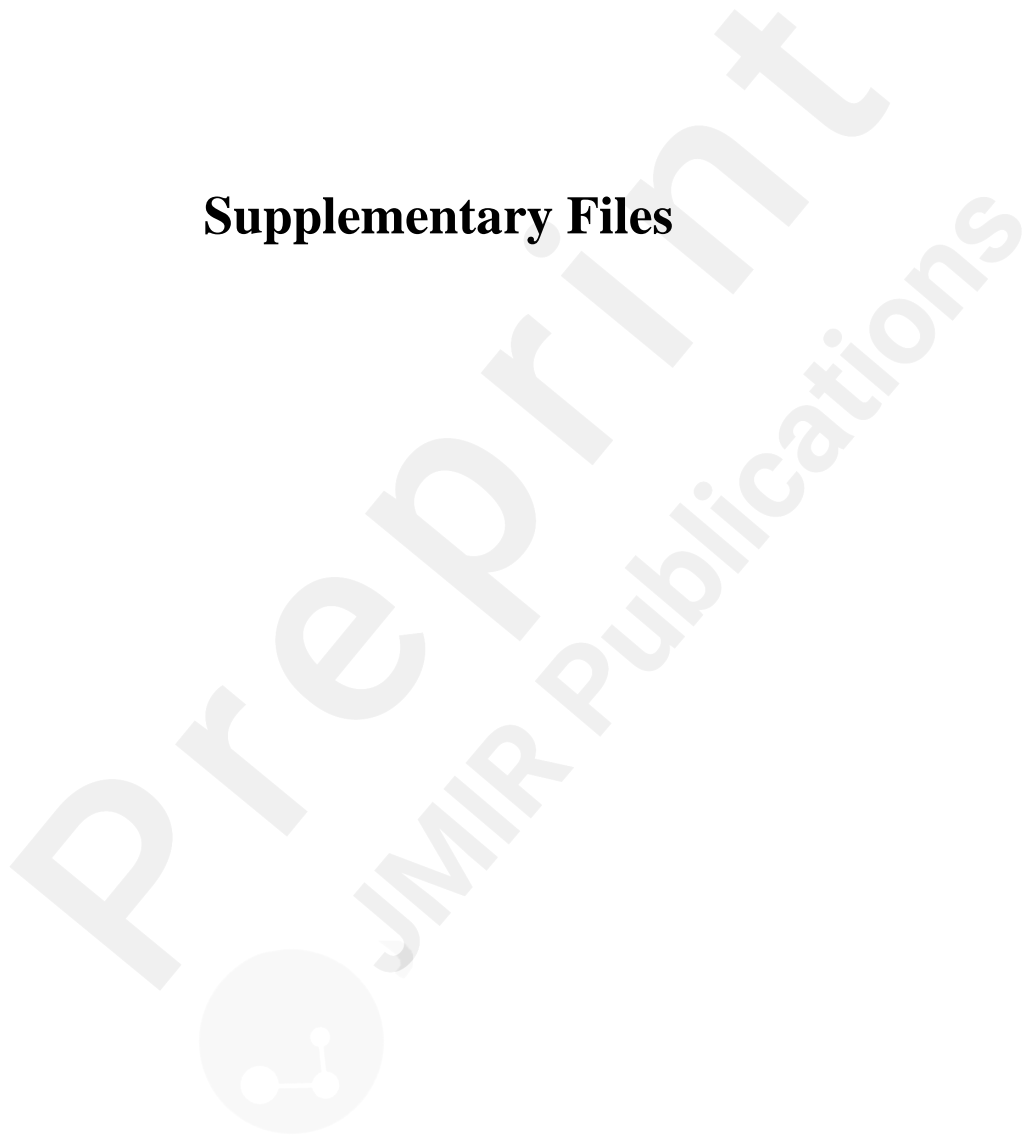
- them. *Nurs Stand*, 2022. **37**(2): p. 60-66.
11. Bostan, L.E., et al., *The influence of incontinence pads moisture at the loaded skin interface*. *J Tissue Viability*, 2019. **28**(3): p. 125-132.
 12. Kottner, J., et al., *Microclimate: A critical review in the context of pressure ulcer prevention*. *Clin Biomech (Bristol, Avon)*, 2018. **59**: p. 62-70.
 13. Valenza, A., et al., *Thermal modulation of skin friction at the finger pad*. *J Mech Behav Biomed Mater*, 2023. **146**: p. 106072.
 14. Bader, D.L. and P.R. Worsley, *Technologies to monitor the health of loaded skin tissues*. *Biomed Eng Online*, 2018. **17**(1): p. 40.
 15. Abinand Anbazhagan Manorama and Seungik Baek and Joseph Vorro and Alla Sikorskii and Tamara Reid, B., *Blood perfusion and transcutaneous oxygen level characterizations in human skin with changes in normal and shear loads — Implications for pressure ulcer formation*. *Clinical Biomechanics*, 2010. **25**(8): p. 823-828.
 16. Clark, M., *Microclimate: Rediscovering an Old Concept in the Aetiology of Pressure Ulcers*, in *Science and Practice of Pressure Ulcer Management*, M. Romanelli, et al., Editors. 2018, Springer London: London. p. 103-110.
 17. Iaizzo, P.a.K.G.L.a.K.J.Y.a.L.K.J.a.H.G.a.S.E., *Prevention of pressure ulcers by focal cooling: Histological assessment in a porcine model*. *Wounds*, 1995. **7**: p. 161-169.
 18. Kokate, J.Y., et al., *Temperature-modulated pressure ulcers: a porcine model*. *Arch Phys Med Rehabil*, 1995. **76**(7): p. 666-73.
 19. Bernard Lee and Siribhinya Benyajati and Jeffrey, A.W.a.Y.-K.J., *Effect of local cooling on pro-inflammatory cytokines and blood flow of the skin under surface pressure in rats: Feasibility study*. *Journal of Tissue Viability*, 2014. **23**(2): p. 69-77.
 20. Wang, W., et al., *Thymol activates TRPM8-mediated Ca(2+) influx for its antipruritic effects and alleviates inflammatory response in Imiquimod-induced mice*. *Toxicol Appl Pharmacol*, 2020. **407**: p. 115247.
 21. Lachenbruch, C., *Skin cooling surfaces: estimating the importance of limiting skin temperature*. *Ostomy Wound Manage*, 2005. **51**(2): p. 70-9.
 22. Bergstrand, S., et al., *Blood flow measurements at different depths using photoplethysmography and laser Doppler techniques*. *Skin Research and Technology*, 2009. **15**(2): p. 139-147.
 23. Jan, Y.K., et al., *Local cooling reduces skin ischemia under surface pressure in rats: an assessment by wavelet analysis of laser Doppler blood flow oscillations*. *Physiol Meas*, 2012. **33**(10): p. 1733-45.
 24. Tzen, Y.T., et al., *Effects of local cooling on sacral skin perfusion response to pressure: implications for pressure ulcer prevention*. *J Tissue Viability*, 2010. **19**(3): p. 86-97.
 25. Ledger, L., et al., *Patient involvement in pressure ulcer prevention and adherence to prevention strategies: An integrative review*. *Int J Nurs Stud*, 2020. **101**: p. 103449.
 26. Filingeri, D., et al., *Thermal and tactile interactions in the perception of local skin wetness at rest and during exercise in thermo-neutral and warm environments*. *Neuroscience*, 2014. **258**: p. 121-30.
 27. Worsley, P.R. and D.L. Bader, *A modified evaluation of spacer fabric and airflow technologies for controlling the microclimate at the loaded support interface*. *Textile Research Journal*, 2019. **89**(11): p. 2154-2162.
 28. van Leen, M., R. Halfens, and J. Schols, *Preventive Effect of a Microclimate-Regulating System on Pressure Ulcer Development: A Prospective, Randomized Controlled Trial in Dutch Nursing Homes*. *Adv Skin Wound Care*, 2018. **31**(1): p. 1-5.
 29. Denzinger, M., et al., *A quantitative study of transepidermal water loss (TEWL) on conventional and microclimate management capable mattresses and hospital beds*. *J Tissue Viability*, 2019. **28**(4): p. 194-199.

30. Coleman, S., et al., *A new pressure ulcer conceptual framework*. J Adv Nurs, 2014. **70**(10): p. 2222-34.
31. Holbrook, K.A. and G.F. Odland, *Regional differences in the thickness (cell layers) of the human stratum corneum: an ultrastructural analysis*. J Invest Dermatol, 1974. **62**(4): p. 415-22.
32. Johnson, J.M., C.T. Minson, and D.L. Kellogg, Jr., *Cutaneous vasodilator and vasoconstrictor mechanisms in temperature regulation*. Compr Physiol, 2014. **4**(1): p. 33-89.
33. Forsyth, P., et al., *Independent Influence of Spinal Cord Injury Level on Thermoregulation during Exercise*. Med Sci Sports Exerc, 2019. **51**(8): p. 1710-1719.
34. Zeilig, G., et al., *The nature and course of sensory changes following spinal cord injury: predictive properties and implications on the mechanism of central pain*. Brain, 2012. **135**(Pt 2): p. 418-30.
35. Gordon, R., P.R. Worsley, and D. Filingeri, *An evaluation of the effects of localised skin cooling on microvascular, inflammatory, structural, and perceptual responses to sustained mechanical loading of the sacrum: A study protocol*. PLoS One, 2024. **19**(5): p. e0303342.
36. Fitzpatrick and Thomas, *Soleil et peau [Sun and skin]*. J Méd Esthétique, 1975. **2**: p. 33-34.
37. Urbaniak, G.C. and S. Plous. *Resaerch Randomizer (Version 4.0) [Computer software]*. 2013 [cited 2024; Available from: <http://www.randomizer.org>].
38. Jayabal, H., D.L. Bader, and P. Worsley, *Development of an Efficient Extraction Methodology to Analyse Potential Inflammatory Biomarkers from Sebum*. Skin Pharmacol Physiol, 2023. **36**(1): p. 38-50.
39. Amontons, G., *De la resistance causée dans les machines*. Mémoires de l'Académie Royale, 1706: p. 257-282.
40. Blau, P.J., *Amontons' Laws of Friction*, in *Encyclopedia of Tribology*, Q.J. Wang and Y.-W. Chung, Editors. 2013, Springer US: Boston, MA. p. 71-71.
41. Humeau, A., et al., *Laser Doppler perfusion monitoring and imaging: novel approaches*. Med Biol Eng Comput, 2007. **45**(5): p. 421-35.
42. Wright, C.I., C.I. Kroner, and R. Draijer, *Non-invasive methods and stimuli for evaluating the skin's microcirculation*. J Pharmacol Toxicol Methods, 2006. **54**(1): p. 1-25.
43. Lachenbruch, C., et al., *The relative contributions of interface pressure, shear stress, and temperature on tissue ischemia: a cross-sectional pilot study*. Ostomy Wound Manage, 2013. **59**(3): p. 25-34.
44. Soetens, J.F.J., et al., *Investigating the influence of intermittent and continuous mechanical loading on skin through non-invasive sampling of IL-1 α* . J Tissue Viability, 2019. **28**(1): p. 1-6.
45. Chaturvedi, P., et al., *An exploratory study of structural and microvascular changes in the skin following electrical shaving using optical coherence topography*. Skin Res Technol, 2024. **30**(7): p. e13830.
46. Adan, F., et al., *Optical coherence tomography versus punch biopsy for diagnosis of basal cell carcinoma: a multicentre, randomised, non-inferiority trial*. Lancet Oncol, 2022. **23**(8): p. 1087-1096.
47. Typolt, O. and D. Filingeri, *Evidence for the involvement of peripheral cold-sensitive TRPM8 channels in human cutaneous hygro-sensation*. Am J Physiol Regul Integr Comp Physiol, 2020. **318**(3): p. R579-r589.
48. Schweiker, M., et al., *Evaluating assumptions of scales for subjective assessment of thermal environments – Do laypersons perceive them the way, we researchers believe?* Energy and Buildings, 2020. **211**: p. 109761.
49. Hoogendoorn, I., et al., *The effect of pressure and shear on tissue viability of human skin in relation to the development of pressure ulcers: a systematic review*. J Tissue Viability, 2017. **26**(3): p. 157-171.

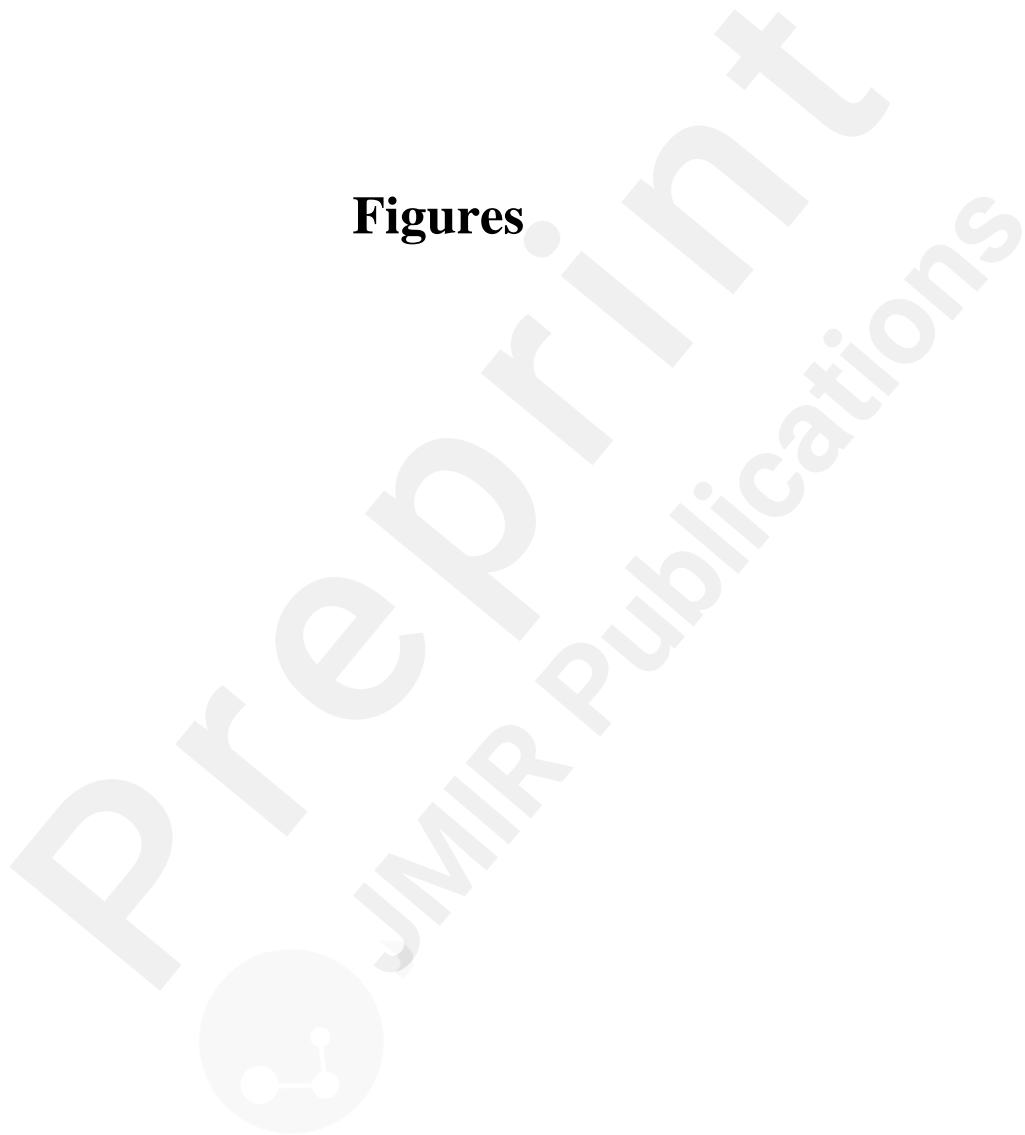
50. de Wert, L.A., et al., *A new method to evaluate the effects of shear on the skin*. Wound Repair Regen, 2015. **23**(6): p. 885-90.
51. Kottner, J., et al., *Skin response to sustained loading: A clinical explorative study*. J Tissue Viability, 2015. **24**(3): p. 114-22.
52. Sprigle, S., et al., *Clinical skin temperature measurement to predict incipient pressure ulcers*. Adv Skin Wound Care, 2001. **14**(3): p. 133-7.
53. Sae-Sia, W., D.D. Wipke-Tevis, and D.A. Williams, *Elevated sacral skin temperature (T(s)): a risk factor for pressure ulcer development in hospitalized neurologically impaired Thai patients*. Appl Nurs Res, 2005. **18**(1): p. 29-35.



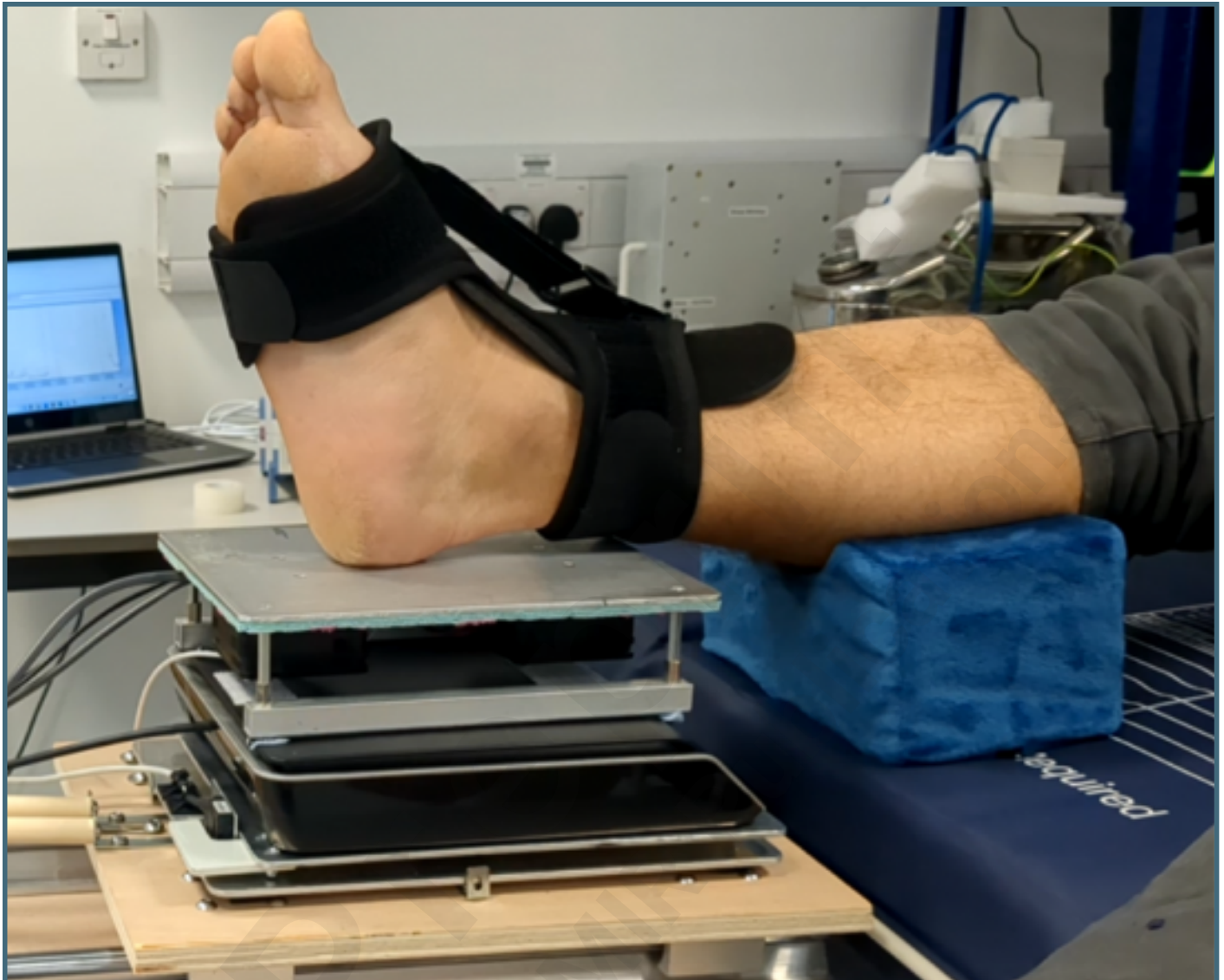
Supplementary Files



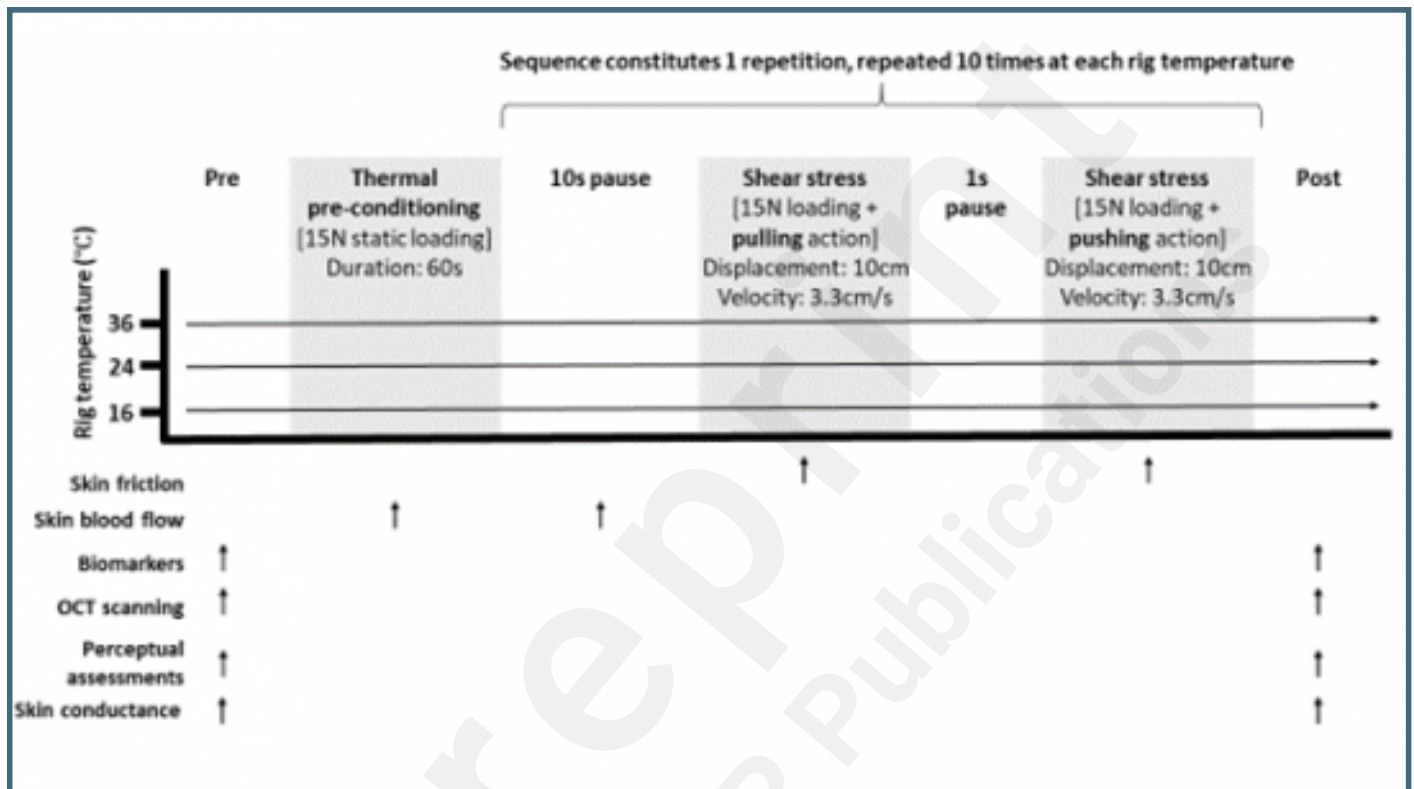
Figures



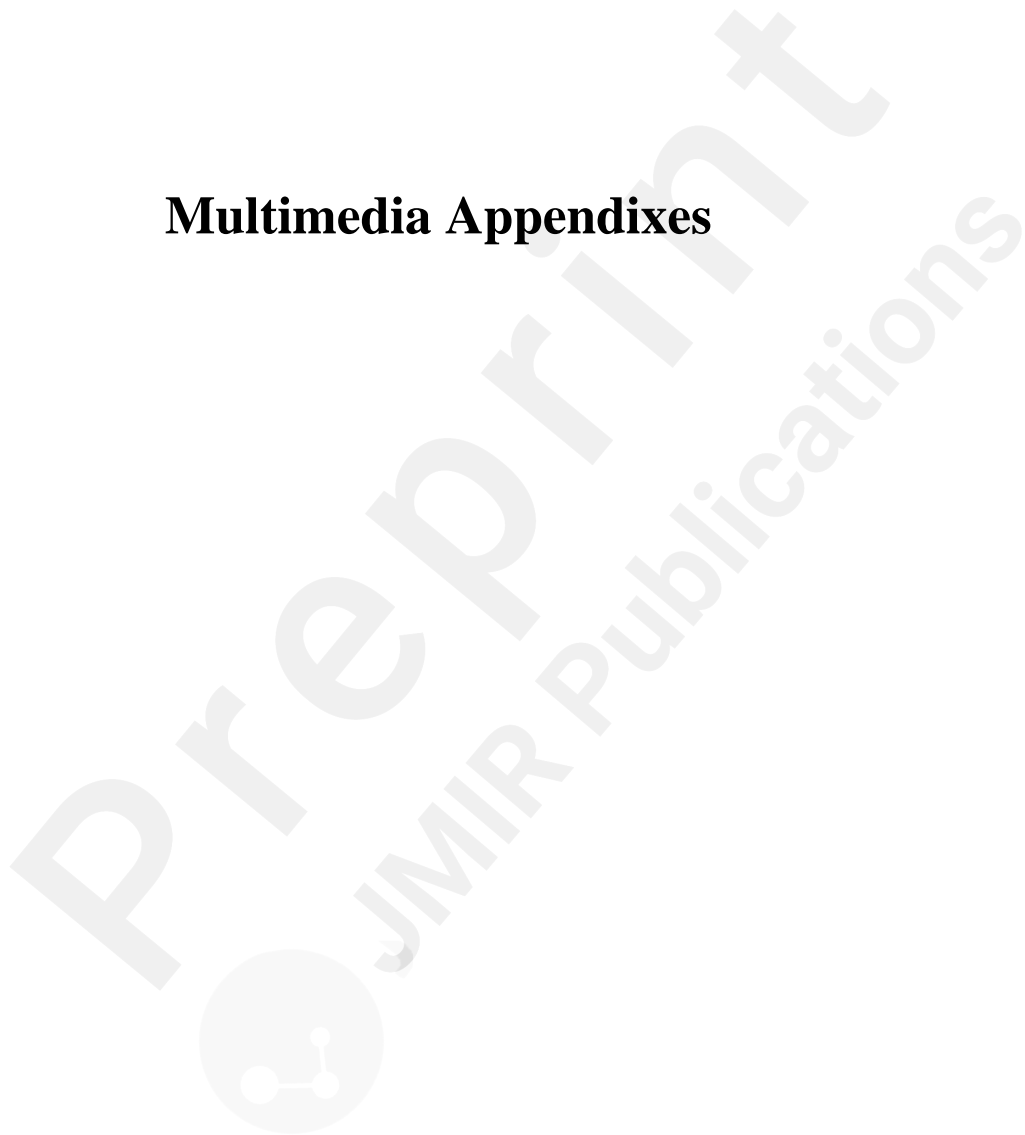
Experimental set up. The foot and ankle are supported by an orthotic brace and ankle support to standardise positioning whilst minimising movement during the shearing protocol.



Standardised repeated shear protocol delivered at the heel. The friction rig will be used to deliver a standardised protocol to evoke repeated shear stress under 3 thermal conditions, i.e. a control skin temperature evoking no cooling (i.e. 36 °C) and two cooling temperatures of 24 °C and 16 °C. During the protocol, a series of non-invasive measurements will be conducted [i.e. estimation of skin friction from the ratio of tangential and normal force, skin blood flow via LDF; inflammatory biomarker sampling from skin sebum; structural and functional imaging via Optical Coherence Tomography (OCT); perceptual assessment of subjective thermal sensation, comfort, and acceptance, and measurement of skin conductance to be used as an index of local skin hydration] at different time points (identified in the diagram by ?).



Multimedia Appendixes



Grant acceptance letter.

URL: <http://asset.jmir.pub/assets/aea639d4775233efb4ef42868b26f678.pdf>

Grant review 1.

URL: <http://asset.jmir.pub/assets/6f50252ae101c8076c0d985d00e03eff.pdf>

Grant review 2.

URL: <http://asset.jmir.pub/assets/421f849d7bc0f8e77370e9eecebe1ac76.pdf>

Grant review 3.

URL: <http://asset.jmir.pub/assets/55ecee00ec9f5f1e005a636d27a00f78.pdf>

