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Moisture-Responsive Thermal Conductivity Properties of Hydrofiber Versus Polyurethane Foam: Implications for Pressure Injury Prevention

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ABSTRACT

Effective thermal management at the skin-dressing interface is essential in pressure injury prevention by means of prophylactic dressings. This study quantified the thermal conductivity of AQUACEL Hydrofiber Technology (AHT, hydrofiber) and polyurethane foam dressing materials under normothermic (32°C) and febrile (40°C) conditions across increasing moisture levels. Using a validated custom heat-flow meter system, dry hydrofiber exhibited significantly greater thermal conductivity than the polyurethane foam (0.43 ± 0.01 vs. 0.20 ± 0.01 W/m K at 32°C; $p < 0.001$). Upon hydration at 32°C, thermal conductivity values increased nonlinearly for both materials but to a much greater extent for the hydrofiber. At 15% moisture, the hydrofiber reached 4.73 ± 0.12 W/m K compared to the polyurethane foam at 1.03 ± 0.02 W/m K. At 40°C, hydrofiber achieved 3.39 ± 0.19 W/m K with only 10% moisture, indicating a temperature-responsive biphasic transformation. Overall, hydrofiber demonstrated a fivefold greater thermal conductivity response to moisture than the polyurethane foam. These findings highlight critical, material-dependent differences in heat dissipation under clinically relevant conditions. The superior moisture-responsive thermal conductivity of hydrofiber highlights its potential to improve heat dissipation at the skin-dressing interface under clinically relevant conditions and thereby mitigate local heat accumulation, contributing to skin protection. Thermal conductivity and thermal adaptability studies should be integrated into dressing efficacy research and be used for selection criteria for pressure injury prevention programs alongside mechanical and absorptive performance.

1 | Introduction

Pressure injuries (PIs) remain a substantial burden in both acute and long-term healthcare settings, affecting millions of patients worldwide. The development of PIs is a multifactorial process driven by sustained mechanical loading of cells in soft tissues over bony surfaces, inflammation, potentially impaired perfusion, and critically, the quality of the skin-support microenvironment [1–3]. Among these contributing factors, the skin microclimate, comprising local temperature, humidity, and moisture, has emerged as a key determinant of tissue integrity under load [4–9]. Elevated skin temperature is associated with increased metabolic demand of 6%–13% per degree Celsius, and a rise of 1°C in the skin temperature therefore contributes as much to ischemia as 5 mmHg of added pressure or more [10]. Hence, when the microclimate is not adequately

Abbreviations: HFM, heat-flow meter; PI, pressure injury; PIP, pressure injury prevention; PU, polyurethane; SD, standard deviation; TC, thermal conductivity.

Summary

- The hydrofiber thermal conductivity always exceeds that of polyurethane foam.
- Moisture boosts the hydrofiber thermal conductivity, but foam adapts slightly.
- Hydrofiber adapts thermally at both 32°C and 40°C interface temperatures.
- The superior heat release supports hydrofiber in pressure injury prevention.
- Thermal testing is key for evaluating the performance of prophylactic dressing.

managed, skin overhydration (maceration) combined with ischemic tissue conditions and frictional forces at the skin-support interface can accelerate the onset and progression of tissue damage, even in the absence of excessive mechanical stresses [5, 11, 12]. There is numerous clinical evidence that the skin microclimate, and particularly an elevated skin temperature, is associated with the PI risk during critical illness [13].

Increased skin temperature, whether due to febrile states or trapped metabolic heat under occlusive materials, elevates tissue metabolic demand and reduces ischemic tolerance [4–6, 14]. Simultaneously, perspiration and trans-epidermal water loss may lead to excess moisture accumulation beneath dressings, softening the stratum corneum and impairing its barrier function [6]. This combination of thermal and moisture stress weakens dermal collagen, increases the coefficient of friction between skin and support surfaces, and contributes to shear deformation, an established mechanism of deep tissue injury [11, 12, 15]. Hence, thermal management of the skin-dressing interface must play a vital role in pressure injury prevention (PIP) strategies.

Recent advances in wound care have brought attention to the thermal conductivity (TC) of dressing materials as a key factor in maintaining favourable skin conditions under sustained loading [14, 16, 17]. The TC describes the ability of a material to transfer heat. Higher TC properties indicate that the material allows faster dissipation of metabolic heat from the skin to the environment. This is particularly important in patients who are confined to a bed or wheelchair, where inefficient heat clearance from the skin under prophylactic dressings may lead to localised thermal build up and exacerbate tissue vulnerability [4, 8, 9, 14]. However, despite its clinical relevance in PIP, TC remains under-reported in efficacy research and performance standards for dressings, with most evaluations centered on the mechanical performance of preventative dressings [18].

The thermal behaviour of a dressing is never static, including in PIP applications. The thermal characteristics of a preventative dressing are profoundly influenced by the hydration state (i.e., the contained moisture levels) of the materials in the dressing construct, which in a PIP context, typically translates to the absorbency of perspiration into the dressing and its retention in the dressing. For example, some hydrophilic materials used in advanced dressings absorb and retain fluid, undergoing a phase transformation into a hydrated gel-like structure with markedly different thermal properties from their dry state. In contrast, polyurethane (PU) foams, while commonly used as dressing materials for their absorbency and cushioning properties, have a high air content that inherently limits their TC, especially when dry [14, 19, 20]. The presence of water (or sweat) that has a much higher TC than air, can elevate the overall TC of a moist dressing, which in turn contributes to improved skin microclimate conditions. Clinical evidence from the related field of wheelchair cushions supports this mode of action, e.g., study participants sitting on foam-fluid hybrid cushions showed significantly lower pelvic skin temperatures than those sitting on air-filled and foam cushions [21]. However, the impact of this important biophysical phenomenon may vary significantly across material types used in dressings, depending on their specific microstructure, fluid uptake capacity, and its distribution pattern [8, 17].

To date, there is a paucity of quantitative data describing how different dressing materials respond thermally to clinically relevant levels of moisture and interface temperatures. Understanding these dynamics is crucial for selecting or designing dressings that actively support thermoregulation in the skin-dressing-environment continuum for effective PIP. Assessing how the TC of dressing materials evolves as a function of skin moisture and heat is also essential for guiding use of preventative dressings in patients with elevated skin temperatures due to systemic illness or localized inflammation [14, 16].

The aim of the present study was therefore to characterise and compare the TC of two widely used dressing materials, namely, AQUACEL Hydrofiber Technology (AHT, hydrofiber)[1] versus a medical-grade PU foam used in commercial dressings,[2] under both normothermic (32°C) and febrile (40°C) simulated conditions and across incremental material moisture levels. A custom-designed, axial heat-flow meter (HFM) system was developed and validated for this purpose, simulating the mechanical and thermal boundary conditions typical of the skin-dressing interface in PIP applications [8, 17]. Through methodological laboratory testing, this study provides new empirical evidence demonstrating, for the first time in the literature, how the dressing material, moisture level and interface temperature interact to determine the thermal performance. The reported findings have important implications for improving dressing selection criteria and for guiding clinical practice in PIP.

2 | Methods

2.1 | Heat-Flow Meter System Design

A custom axial HFM was developed to quantify the TC properties of dressing material specimens under conditions that simulate the skin-dressing-environment interface, particularly during PIP scenarios. The system configuration was adapted from the design reported by Gefen and colleagues [8, 17] and is illustrated in Figure 1. It consists of two parallel metal blocks,

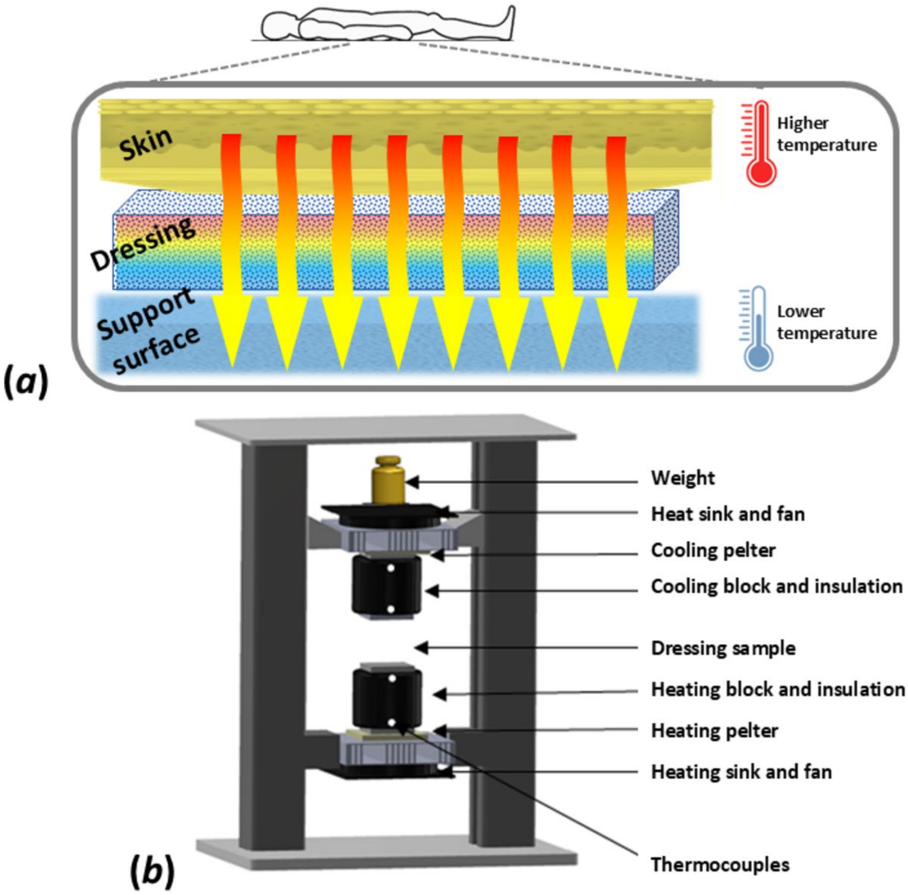

FIGURE 1 | Concept and measurement of the thermal conductivity (TC) of materials in prophylactic dressings for pressure injury prevention (PIP). (a) Biophysical model illustrating heat transfer pathways in skin covered by a dressing. Skin acts as a metabolic heat source. For prophylactic use, a dressing should support efficient heat dissipation from the skin to the environment by conduction through the dressing and subsequent convection and radiation. If the dressing has low TC, heat becomes trapped at the skin interface, elevating tissue metabolic demand, triggering perspiration, and increasing the risk of maceration and ischemic damage. This impaired microclimate may compromise the stratum corneum, dissolve collagen crosslinks, and increase the likelihood of skin failure. (b) Heat-flow meter system employed to quantify the TC of dry and moist specimens of hydrofiber and foam dressings. This method reflects a clinically relevant configuration by simulating the skin-contacting and environment-facing conditions under pressure and heat gradients.

aluminium (top) and steel (bottom), each 4×4×5 cm in size, designed to sandwich a dressing material specimen within a vertical slot. Four thermocouples were soldered symmetrically into each block (two above and two below the specimen) to record the axial temperature gradient across the dressing thickness. Thermocouple signals were captured using a Pico TC-08 data logger and analysed on a connected PC. Thermal gradients were imposed using two thermoelectric (Peltier) coolers (DollaTek, TEC1-12704, China), powered by independent AC–DC switching power supplies (ISO-Tech IPS 303D, IsoTek Power Systems Ltd., United Kingdom, and Lascar PSU 130, Lascar Electronics, United Kingdom) to independently heat the inferior block and cool the superior block. Both blocks were uniformly insulated using 13-mm nitrile thermal insulation sheets (RS Pro, RS Components, United Kingdom) with a known TC of 0.034 W/m K to suppress radial heat loss and promote unidirectional heat flow. A constant weight inducing a pressure of 20 mmHg was applied on the superior surface (Figure 1b) to ensure consistent contact pressure across the dressing interface, simulating typical mechanical loading from a patient lying on a high-end, for example, high-envelopment specialised air PIP support surfaces [22, 23].

2.2 | System Calibration and Specification Studies

System calibration and stability testing were conducted using materials with known TC values: a 1%-agar gel having a 2 cm thickness (TC: 0.5–0.6 W/m K) and a polymethyl methacrylate (PMMA, Perspex) calibration sheet with 1.5 cm thickness (TC: 0.19 W/m K) [24–27]. Measured values were 0.5341 and 0.1996 W/m K for the 1%-agar gel and Perspex, respectively, confirming the accuracy of the HFM within acceptable bounds. To validate the thermal stability of the HFM, it was considered to reach a quasi-steady state if thermocouple readings fluctuated by less than 1% over a 10-min period. The target interface temperature was 32°C ± 1°C, representing average skin temperature. The HFM system consistently met these criteria. All tests were initiated only after a 10-min stabilisation period. System sensitivity was further evaluated by measuring the TC of a PU foam dressing material incrementally moistened with deionised water with known TC of 0.598 W/m K at 20°C, at 5% increments. The HFM system detected clear, progressive increases in the TC of the moistened PU foam, up to 15% moisture, after which conductivity values plateaued, confirming a sufficient resolution to detect clinically relevant moisture changes.

2.3 | Thermal Conductivity Studies of the Dressing Materials

Two dressing material types were studied, hydrofiber versus a medical-grade PU foam commonly used in commercial, advanced wound dressings. Specimens were tested in both dry and moist states. Specifically, the hydrofiber and PU foam moisture levels were gradually increased at 5% increments[3] using a physiologically relevant solution, 'Solution A' containing 142 mmol sodium and 2.5 mmol calcium ions (prepared in-house as per EN 13726 [28]). Specimen moisture levels were prorated based on specimen size. The mean specimen dimensions were $4 \times 4 \times 0.16\,cm^3$ and $4 \times 4 \times 0.25\,cm^3$ for the hydrofiber and PU specimens, respectively, with a standard deviation (SD) of 0.01 cm per length dimension. The weight of specimens (mean ± SD) was 0.10 ± 0.01 and 0.50 ± 0.01 g for the hydrofiber and PU specimens, respectively. The TC measurements were conducted at two interface temperatures: 32°C (mimicking normothermic skin) and 40°C (simulating febrile conditions). For each dressing material specimen, after confirming a 10-min thermal stabilisation period, temperature data were collected for a minimum of 30 s and averaged to calculate the TC, based on Fourier's law and the temperature differential across the dressing thickness, as formulated in our published work [8, 17]. A minimum of five replicates were tested for each combination of material type, moisture level, and temperature condition. All tests were conducted only after steady-state conditions were achieved.

2.4 | Statistical Analysis

Descriptive statistics including means and SDs of the TC data per dressing material type and moisture level were calculated, and statistical analysis of the data was performed using Minitab version 19.2020.1 (Minitab LLC, Pennsylvania, United States of America). One-way analysis of variance (ANOVA) was applied to compare the TC values across increasing moisture levels within each dressing material type and for a given temperature (i.e., separately for the interface temperatures of 32°C and 40°C). Two-sample *t*-tests were used to compare the TC results of hydrofiber and PU foam at matched moisture levels and temperatures. A significance level of $p < 0.05$ was used to determine potential statistical differences within the same dressing material at different moisture levels or between the material types at a given moisture state.

3 | Results

The TC measurements in the dry state revealed that the hydrofiber dressing material exhibited consistently greater TC values compared to the PU foam at both tested interface temperatures (Figure 2). At 32°C, the TC was 0.43 ± 0.01 W/m K (mean ± SD) for hydrofiber and 0.20 ± 0.01 W/m K for the PU foam (Figure 2, left panel). At 40°C, the TC of the hydrofiber material showed a minor decrease to 0.38 ± 0.01 W/m K, while the TC of the PU foam increased slightly to 0.23 ± 0.00 W/m K (Figure 2, right panel). These results confirm that, when dry, hydrofiber has approximately double the TC of PU foam. Incremental moistening of the hydrofiber and PU foam with 'Solution A' led to marked, nonlinear increases in the TC for both dressing materials, however, the magnitude and rate of change were substantially greater for the hydrofiber compared to the PU foam (Figure 2). At an interface temperature of 32°C, the hydrofiber TC increased nearly fivefold at 5% moisture to 2.10 ± 0.05 W/m K, then continued to rise to 4.35 ± 0.12 W/m K at 10% moisture and began to

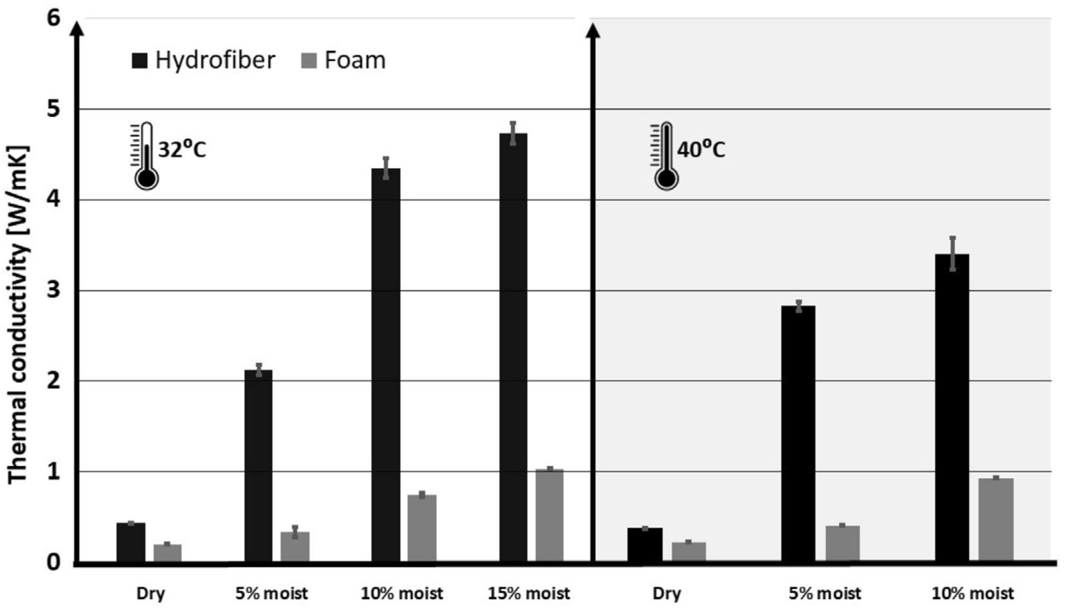

FIGURE 2 | Thermal conductivity (TC) of AQUACEL Hydrofiber Technology (AHT, hydrofiber) and foam dressings under clinically relevant thermal conditions: Measurements of dry and moist dressing specimens at target interface temperatures of 32°C (left panel; representing typical skin temperature) and 40°C (right panel; simulating fever). Values were recorded at the thermocouple closest to the dressing on the heating block side of the heat-flow meter setup (Figure 1b). Moisture in the dressing increases effective TC due to the high heat transfer capacity of water that is, the water retained in the hydrofiber contributes to increased TC, transforming this type of dressing material into a biphasic structure that more efficiently dissipates metabolic heat. This behaviour is critical in managing microclimate under dressings and aligns with the principle of reducing heat trapping and accumulation to mitigate the risk of pressure injuries.

stabilise at 4.73 ± 0.12 W/m K at 15%, plateauing thereafter at 4.85 ± 0.24 W/m K by 20% moisture level (Figure 2, left panel). In contrast, PU foam TC rose considerably more gradually, reaching 0.34 ± 0.06 W/m K at 5% moisture, then 0.75 ± 0.03 W/m K at 10%, and 1.03 ± 0.02 W/m K at a 15% moisture level, with no further increase beyond this point (Figure 2, left panel). The above results therefore demonstrate highly distinct TC values and TC impact by moisture between the hydrofiber and PU foam materials that is, their TCs are highly sensitive to their differing material structures, compositions and fluid absorption and retention capacities. Raising the interface temperature to 40°C to simulate febrile conditions had a modest amplifying effect on the TC for both dressing material types. The hydrofiber TC increased from 0.38 W/m K (dry) to 2.82 ± 0.06 W/m K at 5% moisture and further to 3.39 ± 0.19 W/m K at 10% moisture (Figure 2, right panel). The PU foam showed corresponding increases from 0.23 W/m K (dry) to 0.41 ± 0.01 W/m K and then to 0.93 ± 0.01 W/m K at 5% and 10% moisture, respectively (Figure 2, right panel). As with the simulated normothermic condition, the hydrofiber material demonstrated a substantially greater TC response to moisture than the PU foam, and its TC increased to a substantially greater extent, approximately five-times faster than that of the PU foam (for both interface temperatures of 32°C and 40°C, Figure 2).

In summary, both the dressing material type and moisture level substantially influenced the TC (Figure 2). Across all moisture levels and at both 32°C and 40°C, the hydrofiber material consistently exhibited significantly higher TC values than those of the PU foam ($p < 0.001$, Figure 2). Under both simulated normothermic and febrile conditions, the hydrofiber material exhibited TC values approximately two times greater in the dry state, and approximately four times greater at 10% moisture, being statistically significantly greater compared to those of the PU foam (Figure 2). The TC increased nonlinearly with the moisture level for both dressing material types, however, the hydrofiber showed an approximately fivefold greater rate of increase in its TC than the PU foam (Figure 2). A plateau in the TC was observed beyond 15% moisture at 32°C and beyond 10% moisture at 40°C, for both dressing types. Overall, these considerable TC differences between the hydrofiber and PU foam highlight the material-dependent nature of thermal performance under clinically relevant moisture and temperature conditions in a PIP context.

4 | Discussion

This study systematically quantified the TC of two commonly used dressing materials, hydrofiber and PU foam, under dry and hydrated conditions, and across clinically relevant skin interface temperatures. The experimental work demonstrated that the hydrofiber exhibits substantially higher and more responsive TC than the PU foam under both dry and hydrated conditions, particularly at clinically relevant temperatures (Figure 2). The empirical results further demonstrate a clear, nonlinear increase in TC with increasing moisture for both materials, with significantly greater TC rate of change in the hydrofiber material (Figure 2). These findings have notable implications for PIP, as they provide quantitative evidence that thermal properties of dressings which shape the microclimate conditions, and particularly the TC, are material- and moisture-dependent, and directly influence the skin temperature, moisture level and frictional properties, and thus, the injury risk [1–6, 9, 12, 14, 16]. The skin microclimate, defined by local temperature, humidity, and airflow, plays a critical role in cell and tissue viability, especially under conditions of sustained mechanical loading. Elevated skin temperature and moisture are known to compromise the integrity of the stratum corneum, while increasing the frictional forces applying on skin and the associated tissue shear deformations, thereby increasing the PI risk [5, 11]. High TC dressings promote more efficient heat dissipation from the skin, reducing local heat accumulation, perspiration, and subsequent maceration [8, 14, 16]. Our current results show that the hydrofiber material, especially when moistened, exhibits markedly greater TC values than PU foam, approximately a fourfold increase at 10% moisture, confirming the superior capacity of hydrofiber to evacuate metabolic heat under occlusive and weight-bearing conditions. In fact, the TC values of a slightly moist hydrofiber (with less than 5% contained moisture) are already similar to those of engineered, thermally conductive plastics specifically designed for use in the electronics industry to avoid overheating of electrical components, for example, polyamide filled with graphite which is used for producing heatsinks [29].

The observed differences in TC of hydrofiber versus PU foam reflect inherent variations in the material composition and microstructure. Polyurethane foams used in dressings are characterised by open-cell architectures with high air content, particularly in their dry state [19]. That contained air is inherently insulative (dry PU foam TC ≈0.05–0.11 W/m K [14]). While moisture absorption increases the TC, the effect is moderate and plateaus quickly due to the limited fluid retention and biphasic transformation capacity of foams [17, 20]. In contrast, hydrofiber materials, engineered to absorb and retain large quantities of exudate, quickly transition into a gel-like matrix with significantly higher water content and continuity of absorption than the capacity of PU foams, which considerably enhances the thermal conductivity of the hydrofiber. This biphasic transformation facilitates rapid and more efficient clearance of metabolic heat from the skin-dressing interface, thus potentially protecting against cell dysfunction under increased metabolic demand conditions. Importantly, under febrile conditions (40°C), which may occur in critically ill patients, both materials showed moderate TC increases (Figure 2; right panel), reinforcing the relevance of temperature-responsive materials in vulnerable populations. This behaviour suggests that dressing performance under elevated core body temperatures must be considered for at-risk patient groups, such as those with infections, systemic inflammation, or fever, where thermoregulation of the skin becomes even more critical, and where the contribution of hydrofiber to that regulation as the skin-interfacing material may be crucial.

The role of dressings in PIP has traditionally emphasised tissue stress redistribution and attenuation of shear forces and stresses. However, the inclusion of thermal considerations, particularly in the context of microclimate control, is now also recognised as essential [30]. The results from this study align with emerging evidence that TC should be a standard parameter in the performance characterisation of prophylactic dressings [18]. Poor thermal conductivity leads to local heat accumulation, increasing metabolic tissue demands and exacerbating ischemic vulnerability. In contrast, high TC dressings, especially those whose properties improve under hydration, can help mitigate heat trapping and preserve cell and tissue viability under sustained loading [14, 16]. Furthermore, elevated skin temperatures under occlusive materials can trigger perspiration, which in turn promotes skin hydration beyond physiological levels [5]. This compromises barrier function, weakens dermal collagen, and increases the coefficient of friction at the skin-dressing interface, resulting in higher shear stresses and increased injury risk [5, 6, 11, 12, 15]. Therefore, selecting materials with high and adaptable TC characteristics, such as hydrofiber, for integration in PIP dressings, may represent a dual-mechanism strategy, mechanical and thermal, for PIP interventions. This is strongly supported by recent clinical evidence reported by Cavazana et al. [31]. These authors conducted a prospective case series study ($N=25$) evaluating the thermal performance of a hydrofiber-containing dressing during a seven-day period of thermographic sequencing. They observed effectiveness of the dressing under investigation at controlling the temperatures in the sacral region, with no statistical difference between measurements during the 7-day follow-up that is, there was no heating of the sacral skin during that time period [31].

This study has some limitations that should be considered when interpreting the current results. Specifically, while the axial HFM system and testing method developed for this study provided robust and reproducible TC measurements, they simplify certain aspects of real-world use of dressings (which is characteristic to laboratory testing equipment and techniques). Specifically, the moisture loading of the material specimens was controlled and set to be uniform, but the moisture distribution in dressings under clinical conditions is typically non-uniform. Patient-specific factors such as the body anatomy and habitus, the body surface curvature, alignment of the body region and dressing with respect to the gravity vector, the perspiration volume and rate depending on the medical conditions of the individual[4] and local perfusion may all affect the microclimate state and dynamics. Future relevant studies could hence benefit from simulating dynamic temperature fluctuations (e.g., the circadian rhythmicity of the body temperature), and further incorporate, for example, multiphysics finite element modelling to extend the empirical studies, as previously demonstrated [9, 32].

In conclusion, this study quantitatively confirms that the TC of dressing materials is not only material-dependent but also highly sensitive to the moisture content and temperature. Alongside mechanical and absorptive properties, the thermal performance of dressings plays a critical role in PIP. The hydrofiber material, through its microstructural transformation upon exposure to moisture, exhibited significantly superior TC properties compared to PU foams under the clinically relevant conditions simulated here. These findings highlight the importance of incorporating thermal performance into the design and selection of prophylactic dressings for PIP. When considered together with mechanical and absorptive properties, TC is a critical parameter in the development of preventative dressings, as well as in procurement decisions made in the context of PIP programs.

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Consent

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Endnotes

[1] AQUACEL Hydrofiber Technology (AHT) is a proprietary Convatec Ltd. technology of soft material made for direct contact with skin or wound tissues, composed of sodium carboxymethylcellulose (CMC) fibres. The CMC material gels upon exposure to moisture and is commonly used in gelling fibre dressings.

[2] The polyurethane (PU) foam tested in this study was a medical-grade, hydrophilic, open-cell, alveolar foam representative of materials commonly used as absorbent and cushioning components in commercial wound and prophylactic dressings. The foam was non-laminated, non-adhesive, and free of additional coatings or films, allowing assessment of the intrinsic thermal properties of the foam material itself.

[3] The specimen hydration steps were based on known absorbency values. Specifically, the hydrofiber material was moistened in increments based on is maximum absorbency of $0.15\,g/cm^2$. The polyurethane foam was moistened based on its free swell absorbency of 12 g/g, equating to 0.3 g steps.

[4] Extreme sweating (hyperhidrosis) scenarios are associated for example with endocrine disorders, some infection types, e.g., HIV and tuberculosis, emotional stress or neurological conditions.

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