Received: 28 October 2022 | Revised: 30 March 2023 | Accepted: 31 March 2023

DOI: 10.1111/iwj.14194

ORIGINAL ARTICLE

IWJ WILEY

Spatial and temporal changes in biophysical skin parameters over a category I pressure ulcer

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Funding information
H2020 Marie Skłodowska-Curie Actions, Grant/Award Number: 811965; European Union's Horizon 2020

Abstract

In acute care facilities, the detection of pressure ulcers (PUs) relies on visual and manual examination of the patient's skin, which has been reported to be inconsistent and may lead to misdiagnosis. In skin and wound research, various biophysical parameters have been extensively employed to monitor changes in skin health. Nonetheless, the transition of these measures into care settings as part of a routine clinical assessment has been limited. This study was designed to examine the spatial and temporal changes in skin biophysical parameters over the site of a category I PU, in a cohort of hospitalised patients. Thirty patients, each presenting with a category I PU, were enrolled in the study. Skin integrity was assessed at the PU-compromised site and two adjacent areas (5 and 10 cm away). Data was collected over three sessions to examine both temporal differences and longitudinal changes. Skin integrity was assessed using two biophysical parameters, namely, transepidermal water loss (TEWL) and stratum corneum (SC) hydration. In addition, the influence of intrinsic factors, namely, incontinence and mobility status, on the parameters was evaluated. TEWL values at the sites compromised by PU were statistically significantly greater ($P < .001$) than corresponding values at the adjacent control sites at 5 and 10 cm, which were consistent with a normative range (<20 g/h/m^2). By contrast, SC hydration values did not reveal clear distinctions between the three sites, with high inter-patient variation detected at the sites. Nevertheless, individual profiles were consistent across the three sessions, and the PU site was observed to be either abnormally dry or overhydrated in different individuals. No consistent temporal trend in either parameter was evident. However, intrinsic factors were shown to influence the parameters, with females, bedridden and incontinent patients presenting significantly higher TEWL and SC hydration values ($P < .05$). TEWL was able to identify differences in skin responses at skin sites compromised with a category I PU when compared to healthy adjacent skin sites. Accordingly, this parameter could be included in the clinical assessment for the identification of PU risk. Further

studies are required to elucidate the role of hydration and skin barrier function in the development of PUs and their ability to monitor temporal changes in skin integrity.

KEYWORDS

acute care setting, biophysical parameters, pressure ulcer (PU), skin assessment, skin health

Key Messages

- there were spatial and temporal changes in the skin biophysical parameters of patients presenting with a category I pressure ulcer
- transepidermal water loss was able to differentiate between early signs of damage and healthy skin
- category I pressure ulcers were objectively shown as localised damage to the skin
- the outputs of skin parameters were influenced by intrinsic factors associated with pressure ulcer risk

1 | INTRODUCTION

To reduce the burden of pressure ulcers (PUs) on the health care systems and ensure a better quality of life for affected patients, it is of critical importance to detect this skin condition at an early stage prior to a loss of skin integrity. Indeed, chronic wounds, such as PUs create a considerable burden for the individual as well as concern for the caregivers.[1] Indeed, when patients are admitted to acute care settings and considered at high risk of developing PUs, skin assessments are performed to identify early signs of damage.[2] This includes a thorough visual examination of at-risk body sites to identify the presence of erythema at the skin surface, followed by a manual test for non-blanching erythema, termed a skin tolerance test.[3] In addition to skin assessments, a PU risk assessment is also performed, using established tools, such as the Braden, Waterlow and Norton scales.[4] However, these tools have been shown to have poor sensitivity and limited value above that of the experience and judgement of the nurse and/or clinician.[5]

Depending on the severity of the skin damage, international guidelines have categorised PUs into four categories, namely I, II, III and IV, based on the magnitude of skin and subdermal damage.[6] Category I PU, characterised by non-blanchable erythema over intact skin, is the most common state and represents the first indication that skin integrity has been compromised.[7] The detection of PUs at this stage is of critical importance for the implementation of optimal preventive strategies, which could enable the restoration of skin health. However, even experienced clinicians face a significant challenge as a result of inconsistent and subjective diagnoses of skin damage using visual observations, medical histories and/or basic physical examination.[8,9] One such limitation is the reliance on skin redness, which can be misdiagnosed as incontinence-associated dermatitis or moisture lesions.[10] In addition, this local redness is impossible to identify in dark skin, resulting in a higher incidence of enhanced skin damage in some care settings.[11]

In the last few decades, various non-invasive in vivo measurement techniques have been introduced within research settings to monitor biophysical skin parameters associated with the structure and function of the skin.[12] Of these, the measurement of both transepidermal water loss (TEWL) and stratum corneum (SC) hydration has been regularly adopted in studies assessing individuals in long-term care facilities[13] and specific comorbidities, for example, chronic venous insufficiency (CVI), that can exacerbate the risk of skin damage.[14] TEWL is defined as a passive process through which water molecules diffuse from the dermal and epidermal layers of the skin to the environment, and it differentiates from sweat, which by contrast is an active process.[15] Although TEWL values are strongly influenced by different factors, including gender, age and anatomical sites, however, higher values of TEWL are generally associated with loss of skin integrity.[16,17] Similarly, a high SC hydration value is reflective of over-hydrated skin, which increases the coefficient of friction and exacerbates the risk of damage.[18] Conversely, dry skin at the feet may be considered a risk factor for heel PU development.[19] Changes in TEWL and SC hydration were also evident in the skin surrounding venous leg ulcers[20] and have been examined in a range of different dermatological studies.[21,22]

Lab-based studies with prescribed insults to the skin have demonstrated that different biophysical skin parameters could accurately monitor changes in skin health.

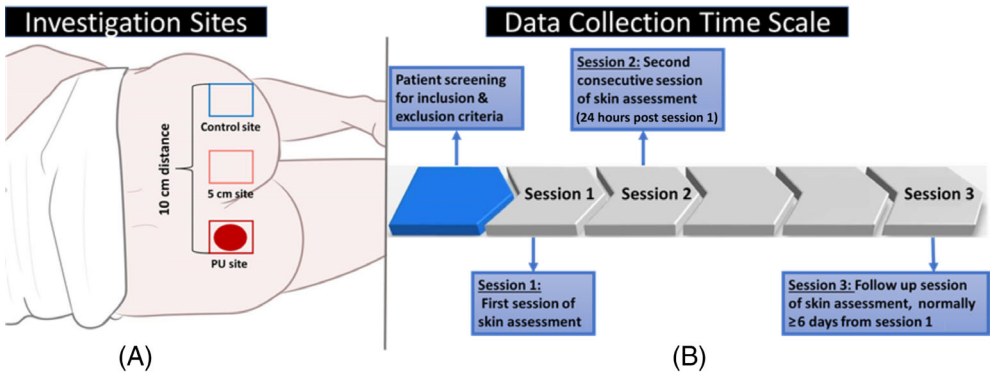

FIGURE 1
(A) Investigation sites associated with the location of the category I pressure ulcer and at distances of 5 and 10 cm from this location, the latter representing a control site. (B) Study protocol involving three test sessions.

In addition, the combination of these parameters may serve as a more powerful tool to differentiate between healthy and compromised skin sites.[23] There have, however, been a limited number of studies assessing changes in skin parameters over the site of early-stage PUs. One such study involved estimating skin biophysical parameters in spinal cord injured (SCI) patients and comparing their baseline values to other controls on both SCI patients and able-bodied cohorts.[24] Nonetheless, category I PU remains a challenge to detect and classify,[6] despite the growing awareness of the pathogenesis of skin damage. The majority of PUs are initiated in the superficial skin layers, thus presenting an opportunity to monitor the changes in biophysical skin parameters to reflect the development of the damage. Therefore, this study was designed to assess the spatial and temporal changes in the biophysical skin parameters of hospitalised patients presenting with category I PU.

2 | MATERIALS AND METHODS

2.1 | Study protocol

An observational longitudinal cohort study was designed to assess the spatial and temporal differences between a category I PU site, defined by non-blanching erythema to a healthy control skin site in hospitalised patients. The anatomical locations of the investigation included the area of skin compromised by skin damage (PU site) and an adjacent healthy site 10 cm lateral to it (control site) (Figure 1A). During this evaluation of spatial differences in skin sites, each enrolled patient was assessed on two separate occasions, namely Session 1 (following screening for inclusion/exclusion criteria) and Session 2 (24 hours after Session 1) (Figure 1B). Furthermore, investigations were also conducted on a sub-cohort of patients at an intermediary site 5 cm between the control site and the PU site (Figure 1A). To examine the temporal response, a convenience sample of patients had a third assessment on a selected day, termed Session 3, which took place at least 6 days after the first assessment (Figure 1B), prior to hospital discharge.

2.2 | Study cohort

Participants were purposefully recruited from four geriatric departments at one large university hospital in the UK. The recruitment process, which lasted 4 months (March–July 2022), was conducted in close collaboration with the relevant clinicians, in particular ward nurses, who approached potential participants with no undue coercion. The study inclusion criteria consisted of: (a) patients above 18 years of age, (b) patients of all genders and ethnicities and (c) patients presenting with a category I PU. The exclusion criteria included (a) patients with broken skin and/or presenting with active skin conditions at the sites of interest, (b) patients approaching the end of life, (c) patients who cannot be repositioned because of medical reasons and/or situated in COVID-19 departments and (d) patients unable to provide informed consent and/or unable to understand the study protocol.

The study received ethical approval from the UK Research Ethics Committee (REC) and the Health Research Authority (HRA) (IRAS 301685). A signed and dated informed consent was received from each participant on the day of screening.

2.3 | Screening and data collection setting

Prior to being enrolled in the study, each patient, identified by a nurse as presenting with redness and erythema on the skin surface, was subjected to a further assessment to ensure that the erythema could be classified as a category I PU. The PU was verified by performing a test for non-blanching erythema, as established in a skin tolerance test.[3] To review briefly, a finger was pressed over

the area compromised by erythema for 15 seconds. If the skin remained red following the lifting of the finger, the patient was considered to present with a category I PU. This procedure was carried out during the initial assessment for each patient but not repeated during subsequent test sessions. Patient assessments were performed in the hospital bay in which patients were admitted, which was maintained at a temperature between 22°C and 25°C. The privacy and dignity of participants were maintained via hospital curtains, and patients could request a chaperone (member of the clinical staff or a relative) where needed.

2.4 | Skin measurements

Spatial and temporal responses were evaluated by using two skin parameters, namely TEWL and SC hydration. TEWL was measured using the open chamber Tewameter TM 300 (Courage + Khazaka, Germany), which was gently placed on the skin sites and collected values at 1 Hz for 1 minute with an output in gram per hour per square metres estimated from the mean of the last 10 readings when equilibrium was achieved. SC hydration was assessed using the Corneometer CM 825 (Courage + Khazaka, Germany), which was gently placed on the skin site, and its response was expressed in arbitrary units (A.U.) as the mean of five repetitive measurements.

In addition, demographic data, medical history and relevant patient notes pertaining to nursing descriptions of the skin damage and relevant information from the hospital PU risk assessment scale were recorded. These included gender, age, ethnicity, height, weight, body mass index (BMI), current medications, a routine skincare regimen and any prophylactic measures adopted to minimise the progression of skin damage. Risk factors for the development of PUs were identified based on an adapted risk assessment scale, and patients recruited were deemed to be at high risk of developing PUs.

2.5 | Data analysis

Data from the biophysical parameters were imported into Microsoft Excel (Microsoft Office 365, USA) and IBM SPSS Statistics V28 (IBM, Armonk, New York). Shapiro–Wilk and D'Agostino–Pearson's analyses revealed that the parameters were non-normally distributed, and hence non-parametric statistics were used. The Wilcoxon signed-rank test was used to compare differences between the PU and healthy control sites within patients. A Mann–Whitney *U* test analysis was performed to establish the independent effect of variables associated with demographics (ie, gender), as well as intrinsic factors (ie, mobility status, incontinence and comorbidities). A group-level analysis was carried out using a Friedman test to assess the independent effect of time on skin parameters across the three sessions. Furthermore, to establish individual time-dependent profiles, data were normalised to Session 1 values, and the ratio change over time for each patient was estimated, as previously described by the authors.[25] Spearman correlation was used to evaluate associations between TEWL and SC hydration parameters. Statistical significance is defined as $P < .05$.

3 | RESULTS

A cohort of 30 inpatients (15 male and 15 female) presenting with category I PUs were recruited into the study as detailed in Table 1. Participants were from a White ethnic background, with ages ranging from 71 to 95 years old (mean ± SD = 85.9 ± 6.6 years). The mean height and weight were 1.66 ± 0.09 m and 65.7 ± 21.3 kg, respectively, with a corresponding mean BMI of 24.3 ± 7.6 kg/m^2. Of the cohort, 67% (n = 20) presented with PU located at the sacrum, 63% (n = 19) were incontinent, 53% (n = 16) were bedridden and had good nutritional intake, while only 17% (n = 5) had a previous history of PUs. Patients presented with good sensory perception and were managed with 2 hours of 30° repositioning, according to international recommendations.[26] Despite these interventions, 10 individuals developed a category II PU or greater during their hospital stay. Three patients opted out of the study before Session 2 and, as such, their data were used for Session 1 comparisons only.

3.1 | Spatial differences in skin parameters

3.1.1 | TEWL differences between PU site and control site

Data revealed that the TEWL values at the control site for all patients were at normative levels,[27] ranging between 3.2 and 16.8 g/h/m^2 and between 3.1 and 19.0 g/h/m^2 on Sessions 1 and 2, respectively (Figure 2A,B). By contrast, the corresponding TEWL values at the PU sites ranged from 21.4 to 118 g/h/m^2 and 18.4 to 157.5 g/h/m^2. The differences in values between the two sites were statistically significant ($P < .001$), with a median difference between sites of 39.9 and 62.3 g/h/m^2 on Sessions 1 and 2, respectively.

There was considerable variation at the PU sites, although the differences between Sessions 1 and 2 were

TABLE 1 Anthropometric and demographic data of study participants with details of the locations compromised by pressure ulcer (PU) and associated clinical conditions.

Participant ID	Gender	Age (y)	Body mass index (kg/m^2)	Body surface area (m^2)	Location of PU	History of PU	Mobility status	Incontinent	Diabetic	Number of medications
#1	Female	79	34.6	1.77	Buttock	No	Reliant mobility	No	Yes	12
#2	Male	78	19.1	1.65	Sacrum	No	Reliant mobility	Yes	No	5
#3	Male	88	24.0	1.74	Sacrum	No	Reliant mobility	Yes	No	8
#4	Male	84	23.2	1.71	Sacrum	Yes	Reliant mobility	Yes	Yes	9
#5	Male[a]	94	23.1	1.79	Sacrum	No	Bedridden	Yes	No	11
#6	Male	80	16.3	1.60	Sacrum	No	Reliant mobility	No	No	9
#7	Male	93	20.6	1.69	Sacrum	No	Bedridden	No	No	6
#8	Male[a]	88	32.4	2.29	Buttock	No	Reliant mobility	No	No	n/a
#9	Female	83	14.8	1.31	Sacrum	No	Bedridden	Yes	Yes	5
#10	Male[a]	75	27.7	1.92	Sacrum	Yes	Bedridden	Yes	Yes	11
#11	Male	77	22.1	1.79	Sacrum	No	Reliant mobility	No	Yes	12
#12	Male[a]	93	17.4	1.62	Sacrum	Yes	Bedridden	Yes	No	9
#13	Female	95	30.0	n/a	Buttock	No	Bedridden	Yes	No	8
#14	Male	94	18.3	1.52	Sacrum	No	Bedridden	Yes	No	12
#15	Male	84	27.8	2.01	Sacrum	No	Reliant mobility	No	No	12
#16	Male	95	21.3	1.74	Buttock	Yes	Reliant mobility	No	No	9
#17	Male	89	21.4	1.95	Sacrum	No	Reliant mobility	Yes	No	7
#18	Female	71	26.8	1.50	Sacrum	No	Bedridden	No	Yes	14
#19	Female[a]	93	19.5	1.46	Sacrum	No	Bedridden	No	No	16
#20	Female	82	n/a	n/a	Buttock	No	Bedridden	yes	yes	18
#21	Female[a]	83	26.7	1.72	Buttock	No	Reliant mobility	No	Yes	14
#22	Female[a]	92	45.9	2.33	Sacrum	No	Bedridden	Yes	No	15
#23	Female[a]	91	30.3	1.67	Sacrum	No	Reliant mobility	Yes	No	6
#24	Female[a]	85	35.4	1.84	Buttock	No	Reliant mobility	Yes	No	11
#25	Female[a]	82	16.6	1.54	Buttock	No	Bedridden	Yes	Yes	15
#26	Female	86	17.0	1.37	Buttock	No	Reliant mobility	Yes	Yes	7
#27	Female	89	16.4	1.45	Sacrum	No	Bedridden	No	No	4
#28	Female	90	19.4	1.46	Buttock	Yes	Bedridden	Yes	No	12
#29	Female	88	39.4	2.02	Sacrum	No	Bedridden	Yes	No	12
#30	Male	75	17.6	1.61	Sacrum	No	Bedridden	Yes	No	n/a

Abbreviation: n/a, data not available.

[a]Patients who developed category II PU or greater.

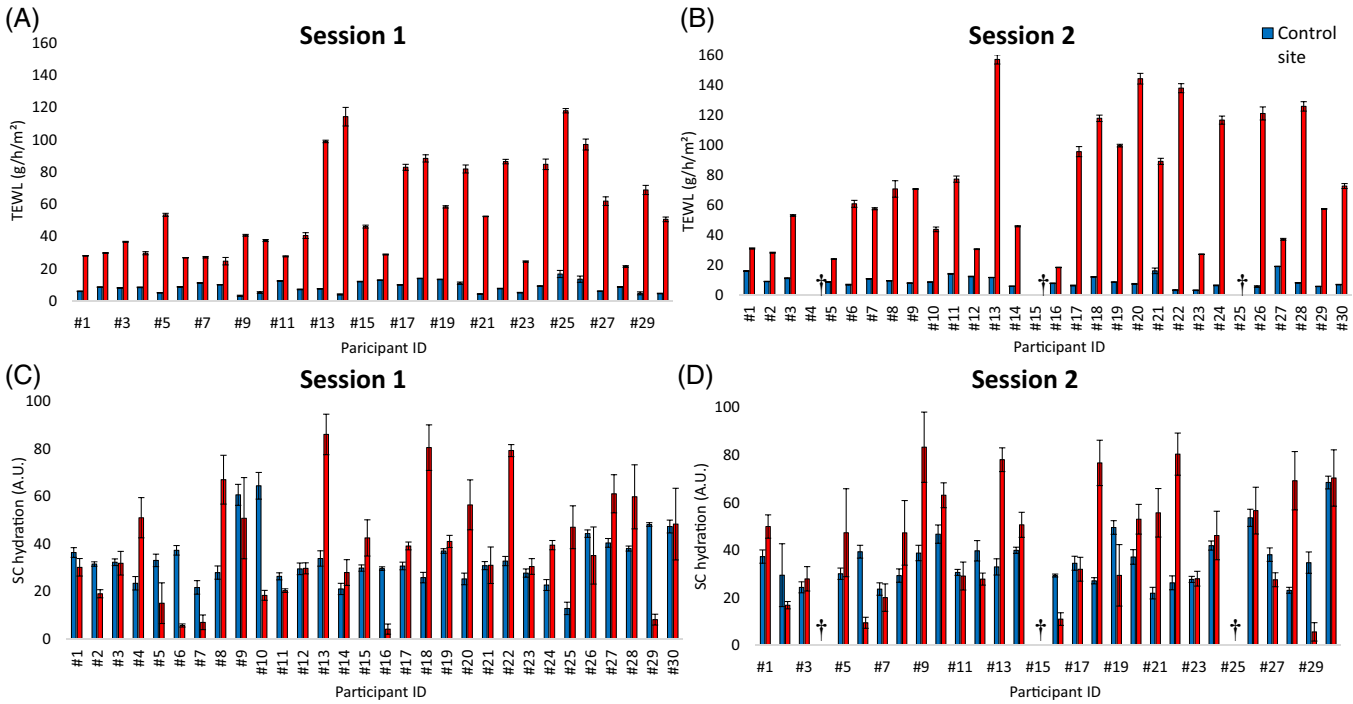

FIGURE 2 Absolute changes in transepidermal water loss (A, B) and stratum corneum hydration (C, D) values at the pressure ulcer compromised and adjacent 10 cm healthy control sites for each participant. †Missing data.

not statistically significant ($P = .07$). Indeed, while some patients exhibited a progressive increase in TEWL values in Session 2, with values exceeding twice that of Session 1 (#6, #7, #8, #11 and #28), this trend was not evident with other patients who showed similar TEWL values between sessions (#1, #2, #5 and #14).

3.1.2 | SC hydration differences between PU site and control site

Spatial changes in skin status as measured by SC hydration revealed a high degree of inter-patient and site variation (Figure 2C,D). Indeed, there were no clear trends in differences between control and PU sites. Indeed, the values at the control site were generally consistent between sessions, with ranges between 13.0–64.5 and 22.0–68.5 A.U. at Sessions 1 and 2, respectively. The corresponding ranges at the PU sites were 4.3–86.1 and 5.7–83.4 A.U., which indicated considerable variation in response between patients.

A closer examination of the data revealed that a subgroup of patients (#8, #13, #18, #22 and #28) presented with elevated skin hydration values at the PU site at both test sessions. By contrast, several patients presented with very dry skin at the PU site (#6, #16 and #29). It was also noted that at the PU site, a number of patients (#1, #5, #6, #7, #9, #10, #14, #16, #21 and #26) revealed SC hydration values greater than a 1.5 fold change from Sessions 1 to 2, with a maximum fold change of 3.4 (#10).

3.2 | Local variations in TEWL values at a distance from the PU site

Further analyses were performed on a sub-cohort of 19 patients to assess changes in skin TEWL response at a distance of 5 cm from the PU site. The data for both sessions are detailed in Table 2. Similar to the values at the 10 cm control site, TEWL responses at the 5 cm site were generally at the normative level, with values ranging from 2.7 to 18.7 g/h/m^2 and 1.7 to 20.0 g/h/m^2 on Sessions 1 and 2, respectively. It was noted, however, that 6/19 patients (#13, #14, #20, #21, #25 and #27) exhibited TEWL values >20.0 g/h/m^2 at the 5 cm site in one or both of the test sessions.

3.3 | Temporal differences in skin parameters

Ten patients who had an extended hospital stay were included in a follow-up assessment (Session 3) to

TABLE 2 Transepidermal water loss absolute value at the three investigation sites for the two consecutive test sessions.

	Session 1			Session 2		
Participant ID	Control site	5 cm site	PU site	Control site	5 cm site	PU site
#11	12.5	18.7	27.7	14.1	20.0	77.5
#12	7.2	9.4	40.6	12.3	14.0	30.6
#13	7.6	10.1	99.0	11.6	41.1	157.5
#14	4.1	62.6	114.3	5.8	23.3	45.9
#15	12.1	15.2	46.2	n/a	n/a	n/a
#16	12.9	11.3	28.9	7.8	11.6	18.4
#17	10.0	10.4	82.9	6.3	10.4	95.8
#18	14.0	13.8	88.4	12.0	13.2	118.1
#19	13.4	16.2	58.4	8.5	9.3	99.8
#20	11.0	10.7	81.9	7.3	29.8	144.7
#21	4.3	7.2	52.5	16.1	35.6	89.3
#22	7.6	8.0	86.5	3.2	7.2	138.3
#23	5.2	7.1	24.5	3.1	1.7	27.2
#24	9.3	9.5	84.8	6.4	8.0	116.9
#25	16.8	53.1	118.0	n/a	n/a	n/a
#26	13.5	12.2	97.1	5.6	14.4	121.4
#27	6.1	2.7	61.9	19.0	24.0	37.2
#28	8.7	7.4	21.4	8.1	8.1	126.1
#30	4.7	5.4	50.6	6.9	6.3	72.8

Abbreviation: n/a, data not available.

evaluate temporal changes in the two skin parameters. For practical reasons, the day of data collection for Session 3 varied between patients, ranging from 6 to 18 days (7.9 ± 3 days) after Session 1. To assess time-dependent changes in skin response, the values of the two parameters at both control and PU sites from Sessions 2 and 3 were normalised to the corresponding TEWL and SC hydration values from Session 1. The absolute values for each session in conjunction with the fold changes are detailed in Table 3.

With reference to TEWL at the control site, there was generally a small increase, which was ≤1.7 fold in both sessions. However, three patients, that is, #21, #27 and #30, exceeded this threshold in at least one session. It is of note that the absolute TEWL values across all participants and sessions remained within the normative range, that is, <20.0 g/h/m^2.

At the PU site, fold changes were generally ≤1.8. However, three patients (#11, #21 and #26) exhibited increases in TEWL that were >2 fold on one or both sessions (Table 3). By contrast to the control site, the absolute values revealed that the PU-compromised site was >20.0 g/h/m^2 in all patients. Indeed, for each session, at least 70% (7/10) of the cohort had PU TEWL values >50.0 g/h/m^2.

With reference to skin hydration, 6/10 and 7/10 of the patients exhibited a decrease (<0.8) or no change at the control site during Sessions 2 and 3. By contrast, a small increase in fold change for SC hydration was evident at the PU site, although these values were generally less than 2 fold. The one exception to this trend was patient #10, who presented with a 3.4 and 3.5-fold increase on Sessions 2 and 3, respectively.

3.4 | Influence of intrinsic factors on TEWL and SC hydration

Analyses were performed to examine the influence of individual intrinsic factors, namely gender, mobility status, presence of incontinence, anatomical location of PU, nutrition status, presence of diabetes and previous history of PU, on both skin parameters.

TABLE 3 Fold changes in transepidermal water loss (TEWL) and stratum corneum (SC) hydration values at the 10 cm healthy control and pressure ulcer (PU) compromised site for test Sessions 2 and 3, with associated days of Session 3 assessment

	Session 1		Session 2		Session 3 (day of assessment)		Fold changes from Session 1							
							Session 2				Session 3			
Participant ID	Control site	PU site	Control site	PU site	Control site	PU site	Control site		PU site		Control site		PU site	
TEWL temporal profile														
#10	5.3	37.5	8.6	43.9	8.7	52.5 (18)	1.6	↑	1.2	nc	1.6	↑	1.4	↑
#11	12.5	27.7	14.1	77.5	14.5	163.8 (6)	1.1	nc	2.8	↑↑	1.2	nc	5.9	↑↑↑
#12	7.2	40.6	12.3	30.6	7.0	40.9 (7)	1.7	↑	0.8	nc	1.0	nc	1.0	nc
#20	11.0	81.9	7.3	144.7	14.0	74.1 (7)	0.7	↓	1.8	↑	1.3	↑	0.9	nc
#21	4.3	52.5	16.1	89.3	18.1	108.4 (6)	3.7	↑↑	1.7	↑	4.2	↑↑↑	2.1	↑
#22	7.8	86.5	3.2	138.3	3.1	71.6 (6)	0.4	↓	1.6	↑	0.4	↓	0.8	nc
#24	9.3	84.8	6.4	116.9	4.0	109.9 (8)	0.7	↓	1.4	↑	0.4	↓	1.3	↑
#26	13.5	97.1	5.6	121.4	4.7	78.2 (8)	0.4	↓	1.3	↑	0.3	↓	0.8	nc
#27	6.1	61.9	19.0	37.2	8.7	48.0 (7)	3.1	↑↑	0.6	↓	1.4	↑	0.8	nc
#30	4.7	50.6	6.9	72.8	9.5	134.2 (6)	1.5	↑	1.4	↑	2.0	↑	2.6	↑↑
SC hydration temporal profile														
#10	64.5	18.5	46.8	63.2	46.4	64.5 (18)	0.7	↓	3.4	↑↑	0.7	↓	3.5	↑↑
#11	26.4	20.4	30.7	29.2	25.9	32.6 (6)	1.2	nc	1.4	↑	1.0	nc	1.6	↑
#12	29.6	29.8	39.8	27.9	40.2	43.5 (7)	1.3	↑	0.9	nc	1.4	↑	1.5	↑
#20	25.4	56.5	37.2	53.1	26.5	57.4 (7)	1.5	↑	0.9	nc	1.0	nc	1.0	nc
#21	30.9	31.1	22.0	55.8	40.4	22.6 (6)	0.7	↓	1.8	↑	1.3	↑	0.7	↓
#22	32.9	79.3	26.3	80.5	29.6	78.3 (6)	0.8	nc	1.0	nc	0.9	nc	1.0	nc
#24	22.8	39.6	42.0	46.2	42.0	68.8 (8)	1.8	↑	1.2	nc	1.8	↑	1.7	↑
#26	44.4	35.2	53.7	56.7	45.4	68.5 (8)	1.2	nc	1.6	↑	1.0	nc	1.9	↑
#27	40.5	61.1	38.2	27.6	35.6	27.0 (7)	0.9	nc	0.5	↓	0.9	nc	0.4	↓
#30	47.4	48.4	68.5	70.4	54.3	84.1 (6)	1.4	↑	1.5	↑	1.1	nc	1.7	↑

Note: ↓ = <0.8-fold change; n.c. (no change) = 0.8–1.2; ↑ = >1.2-fold change; ↑↑ = ≥2.5-fold change; ↑↑↑ = ≥3.5-fold change.

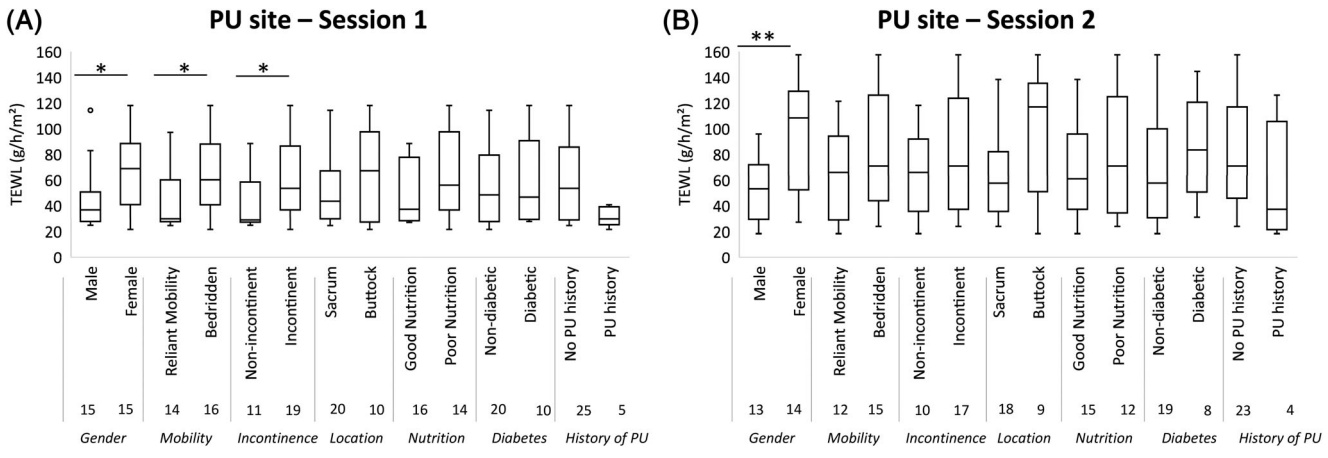

FIGURE 3 Impact of intrinsic factors on transepidermal water loss output values at the pressure ulcer site on Session 1 (A) and Session 2 (B). The data labels on the categories indicate the number of participants per group.

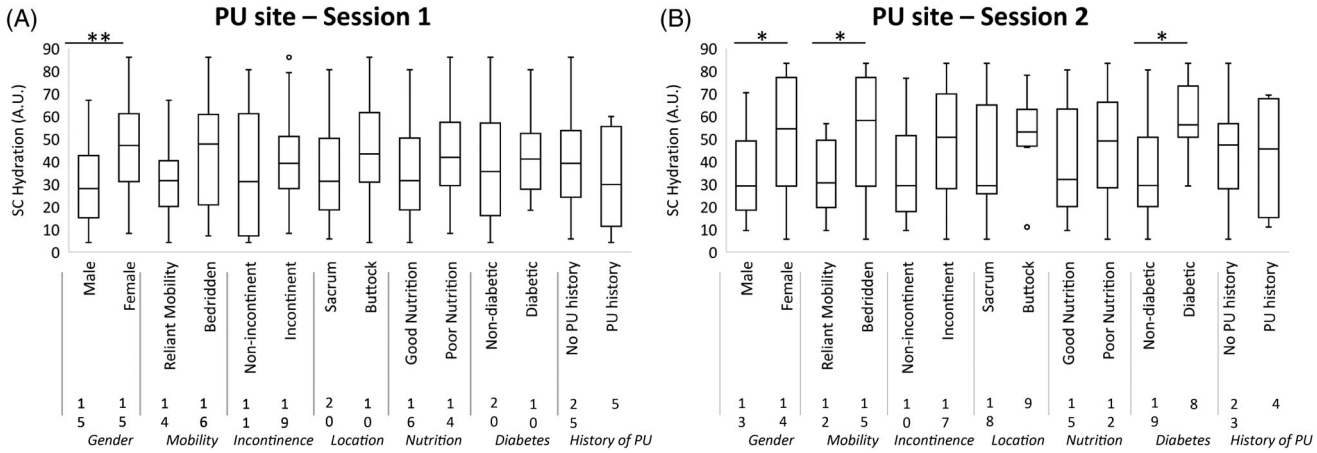

FIGURE 4 Impact of intrinsic factors on stratum corneum hydration output values at the pressure ulcer site on Session 1 (A) and Session 2 (B). The data labels on the categories indicate the number of participants per group.

3.4.1 | Transepidermal water loss

There was no significant influence on any of the seven intrinsic factors at the control site (data not shown). By contrast, some of these factors influenced the TEWL values at the PU site (Figure 3A,B). There were significant differences in TEWL values between genders, with female patients expressing significantly higher TEWL values compared with males in Session 1 ($P < .05$) and in Session 2 ($P < .01$). Similar significant trends were evident in Session 1 with mobility status and incontinence, with bedridden and incontinent patients presenting elevated TEWL values ($P < .05$), compared with those with reliant mobility (able to mobilise with assistance) and those who were independent with bladder and bowel function (Figure 3A). However, mobility and incontinence did not influence the Session 2 values, that is, $P > .05$. The impact of the other intrinsic factors revealed no statistically significant trends, although the anatomical locations presenting with PU, namely the sacrum and buttocks, differed, with TEWL values being higher at the buttocks on both sessions (Figure 3A,B).

3.4.2 | Stratum corneum hydration

There was no significant influence on any of the seven intrinsic factors at the control site (data not shown). In a similar manner to TEWL, gender was the main factor influencing skin hydration values at the PU site during Session 1 ($P < .01$) and 2 ($P < .05$) (Figure 4A,B). No other significant trends were evident in Session 1 in relation to the other factors. In Session 2, there were significant differences ($P < .05$) observed in mobility status and diabetes on SC hydration values. Although there were no significant SC hydration changes with incontinence ($P = .07$), it was noted that patients presenting with incontinence episodes tended to express higher values compared with those who had control of their bladder and bowels. The PU sites associated with the buttocks presented with higher skin hydration values compared with the sacrum on both sessions (Figure 4A,B).

3.5 | Correlation between skin parameters

The association between the TEWL and SC hydration parameters at the PU site revealed interesting trends, which are highlighted in Figure 5. A close examination of the data suggested that the individual TEWL values for Session 2 were often higher than the corresponding values for Session 1 for each category of SC hydration. In addition, it was observed that increasing skin hydration values corresponded to higher TEWL values. Although the parameters were not significantly correlated on Session 1 ($r = 0.3$, $P = .07$), a statistically significant positive association was evident for Session 2 ($r = 0.6$, $P < .001$).

Further analysis involved introducing SC hydration thresholds (Figure 5) to conveniently divide the skin into categories, namely, dehydrated (<35 A.U.), hydrated (36–69 A.U.) and overhydrated (>70 A.U.). In addition, a significant number of participants who demonstrated dehydrated skin values presented TEWL values for both sessions that were <30 g/h/m^2. By contrast, the few participants, that is, #13, #18 and #22 who demonstrated overhydrated skin values presented TEWL values for both sessions that were >80 g/h/m^2. The patients in the hydrated category ($35 \leq$ SC hydration ≤ 70 A.U.)

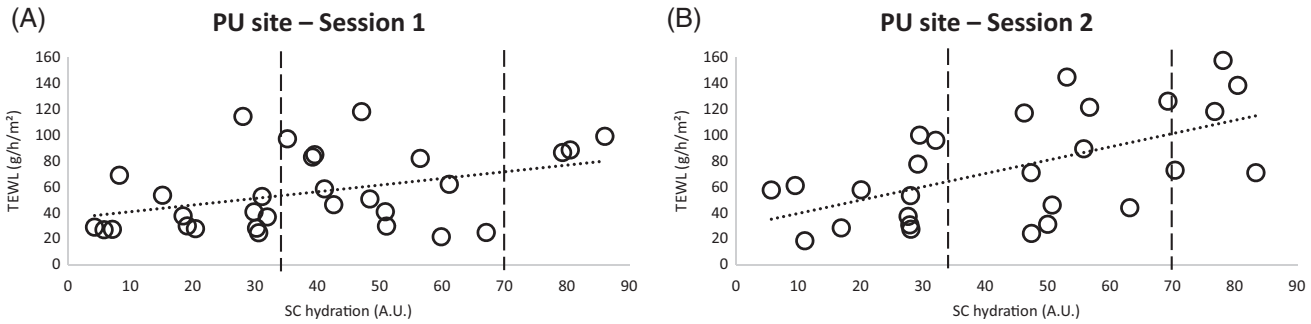

FIGURE 5 Correlations between stratum corneum hydration and transepidermal water loss values at the pressure ulcer site on (A) Session 1 ($r = 0.3$, $P = .07$) and (B) Session 2 ($r = 0.6$, $P < .001$).

revealed considerable variability in TEWL values, with a range of 21–145 g/h/m^2 for both sessions.

4 | DISCUSSION

The present study was designed to assess both spatial and temporal changes in skin parameters over the site of a category I PU. Two biophysical parameters reflecting skin integrity, derived from TEWL and SC hydration measurements, were monitored. The results revealed distinct local increases in TEWL values over the site of the PU, which for some patients varied over time and that were not evident at the control site. By contrast, a high degree of variability was observed in SC hydration values, with the PU site demonstrating both over-hydrated and dry skin properties. Intrinsic factors of gender, mobility and incontinence affected some of the biophysical values at the PU site during distinct sessions. The majority of the elderly cohort had mobility restrictions and required multiple pharmacological drugs (Table 1), indicative of multiple comorbidities and pathologies associated with ageing.

The site-specific differences in TEWL values were evaluated by comparing the responses of the PU-compromised anatomical location with those of control sites 5 and 10 cm away. In particular, significant increases in TEWL responses were detected at the PU site on both test sessions (Figure 2A,B). By contrast, the 5 and 10 cm values generally conformed to normative values,[17] suggesting that, for the majority of patients, the upregulation over the PU site was highly localised (Table 2). Similar TEWL upregulation has been reported for patients presenting with chronic venous leg ulcers,[20] although these authors used the forearm as the control site, which was at a significant distance from the open wound. Indeed, it is well established that TEWL outputs vary considerably depending on the anatomical sites of investigation within the individual.[28] To the best of our knowledge, no other study has investigated variations in the TEWL parameter fairly adjacent to a pressure-damaged skin location.

In contrast to TEWL, SC hydration did not yield clear differences, with similar values detected at the PU and control sites on both sessions for 67% (n = 20) of the patients (Figure 2C,D). These findings were consistent with previous studies where median skin hydration values were similar at a category I PU compared with control sites in a small cohort of SCI patients[24] and following the application of sustained mechanical loading on the heel and sacral skin of healthy participants.[29] Nonetheless, a recent systematic review reported an association between skin hydration and the development of PU,[18] although the authors highlighted both a high degree of variation in hydration values and a focus on its predictive capability. For example, a study in Indonesia reported inconsistent values attributed to ambient conditions that often reached 30°C,[30] whereas the present study was conducted at more moderate temperatures (22°C-25°C). In addition, variation in findings could also result from the presence of potential confounding variables, such as incontinence and impaired mobility, as presented by many of the patients (Table 1). It is worthy of note that the practice in each of the geriatric departments was to use absorbent pads for each patient during their inpatient stay, regardless of their incontinence state. This will have affected skin hydration values, as the use of incontinent pads can induce changes in the microclimate of an occluded area.[31]

The study also evaluated temporal changes in TEWL and SC hydration values after, at least, 6 days from the initial skin assessment. At the control sites, analyses revealed that the fold changes in both parameters did not exceed 1.7 for the majority of patients during the three sessions of data collection (Table 3). The corresponding fold changes at the PU sites only exceeded a 2.0 fold change in 3/10 of patients. Similar fold changes were also evident for SC hydration when values for sessions 2 and 3 were compared with Session 1 (Table 3). These small

temporal changes in skin barrier function over time could be attributed to reduced integrity in SC, although this suggestion could only be confirmed in an extended longitudinal analysis, which could assess the prognostic value of biophysical parameters to determine further skin damage or remodelling behaviour. It is important to further understand the relationship between TEWL and the structure and function of the SC. Indeed, cell-based studies have implicated the important role of SC corneocytes, which continually turnover within the SC following mechanical stimulation, which may explain the increased TEWL values.[32,33] However, further research is needed to elucidate this concept.

The current study also examined the implications of intrinsic factors on biophysical outputs. Impaired mobility, poor nutrition and constant skin exposure to moisture have all been implicated as causal factors for PU development.[34] Results suggest that female patients and those who were either bedridden or incontinent generally expressed higher TEWL and SC hydration values at the PU sites during one or both sessions (Figures 3 and 4). The gender differences can be compared with a previous study at the skin sites of healthy volunteers aged >50 years, which reported higher female SC hydration values but similar TEWL values.[35] In addition, significantly higher TEWL and SC hydration values have been reported in bedridden and incontinent patients,[36] as well as in healthy individuals subjected to moisture in combination with mechanical loading.[25]

The present findings represent the first to present a correlation between two biophysical parameters, which was statistically significant for Session 2 (Figure 5), for patients presenting with skin sites demonstrating a category I PU. A similar correlation has been described previously in individuals affected by atopic dermatitis.[37] Nonetheless, the present trend was not apparent for all participants in the cohort, with some demonstrating impaired barrier function (TEWL >50 g/h/m^2) in dry skin (SC hydration <35 A.U.). The categorisation in terms of skin hydration levels represented an extension of that previously reported.[38] The added category incorporates overhydration values of >70 A.U. corresponds to those patients regularly exposed to moist interfaces, for example, an incontinence pad or excessive sweating. Impaired skin barrier function, namely an increase in TEWL, could be indicative of SC vulnerability and therefore the risk of further damage, that is, category II to IV PU, in which skin integrity has been lost, resulting in a wound. It is of note that 10 of the 30 patients developed progressive skin damage regardless of the preventative measures that had been prescribed (Table 1). Because of the limited number of participants, any associations with respect to either TEWL or SC hydration values could not be fully evaluated.

The study is limited by the relatively small sample size and a homogenous cohort of elderly Caucasian individuals, which limits the generalisability of the results to younger individuals and those with other ethnic backgrounds. Indeed, non-blanchable erythema has been reported to be difficult to detect in patients with dark skin, with a corresponding increase in the rate of PUs incurred in this sub-population.[39] Although skin measurements were standardised following internationally published guidelines,[40] the researcher adopted a pragmatic approach where the circumstances of hospital departments (ie, room temperature, humidity, etc) might have influenced the absolute value of the parameters. Indeed, assessments were performed at the same hours each day and the recruitment process was completed during warm periods of the year in order to avoid circadian rhythm and seasonal influences. Furthermore, skin parameters were assessed only at the sacrum and buttocks of the patients and not at other skin areas, for example, heels often vulnerable to PU damage. In addition, the individual diagnoses of the patients were not considered as it would have been difficult to interpret the impact of specific pathologies and comorbidities on skin parameters.

TEWL and SC hydration parameters have been widely used in dermatological skin research as markers of skin health. Nevertheless, their implementation in acute and/or long-term care clinical assessment routines as objective means of predicting physiological changes in skin status, has been limited. Of the two parameters utilised in the study, TEWL was highly sensitive to differentiate between healthy and damaged skin. Indeed, several studies have reported changes in TEWL values as clinically early markers of skin barrier disturbances prior to the presence of visible alterations.[23,41] Nevertheless, because of the complexity of the skin architecture, a single biophysical parameter may be insufficient to detail changes in skin health, particularly given the diverse nature of the pathoaetiological factors implicated in PU development. This has motivated recent research focusing on biochemical strategies to monitor changes in skin status. Among these, biomarkers have recently gained attention as an innovative approach to identifying early signs of skin compromise.[42] Indeed, there is growing evidence that cytokines such as IL-1alpha and IL-1RA play an important role in the early stages of skin damage.[43,44] Nonetheless, more studies are required to establish the clinical utility of these biomarkers and establish how complementary skin health parameters can be used to provide predictive or prognostic data. For example, the sub-epidermal moisture scanner (SEM, Bruin Biometrics, USA) has been reported to be sensitive to detect early signs of skin damage prior to clinical observation,[45] but has been shown to have a

limited positive predictive value (14%).[46] The combination of biophysical and biomarker parameters may provide an optimal solution to establish an objective means of predicting and monitoring PUs, supporting clinical practice and differentiating diagnosis.

5 | CONCLUSIONS

Two biophysical parameters reflecting skin integrity were evaluated to identify differences in responses on a category I PU when compared with healthy adjacent sites. The results based on a cohort of 30 patients showed spatial and temporal changes in TEWL, with gender, mobility and incontinence representing factors that can influence the outputs of the parameters. Objective biophysical parameters revealed that category I PUs represent localised damage in the form of compromised skin barrier function. The findings of this study demonstrate that increases in TEWL can be used as an objective parameter associated with the early development of PUs and could support clinicians in providing an improved assessment of skin compromise, thereby identifying patients who require effective preventive measures. Further research is required to determine if this approach would prove applicable to other patient groups at risk of developing PUs.

ACKNOWLEDGEMENTS

The authors wish to thank all the patients and the health care professionals who engaged with the study for their commitment. The primary author (Nkemjika S. Abiakam) received financial support as an Early Stage Researcher from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 811965 (Project STINTS—Skin Tissue Integrity under Shear). For the purpose of open access, the author has applied a CC BY public copyright licence to any Author Accepted Manuscript version arising from this submission.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

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

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How to cite this article: Abiakam NS, Jayabal H, Filingeri D, Bader DL, Worsley PR. Spatial and temporal changes in biophysical skin parameters over a category I pressure ulcer. *Int Wound J*. 2023; 1-13. doi:10.1111/iwj.14194