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Machine learning methods to evaluate fluctuation in oxygenation and peripheral tissue temperature, in sacral and trochanteric area under pressure in healthy subjects and institutionalized patients. A prospective non-randomized trial

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ABSTRACT

Aim: To evaluate the longitudinal changes observed over a period of 120 min in patterns of tissue perfusion, peripheral oxygenation and local temperature of sacral and trochanteric areas exposed to pressure, comparing a healthy population with one at risk of impaired skin integrity.

Methods: The study protocol is registered in ClinicalTrials.gov (NCT02736838). Non-randomised experimental study in two phases. Volunteers were recruited at the University and nursing homes from Nov 2017 to June 2020. The parameters were measured in the sacral and trochanteric areas under pressure using a laser Doppler monitor and near-infrared spectroscopy over 2 h. Body positions varied by area: supine for the sacral region and lateral supine for the trochanteric region.

Results: Comparative analysis between both groups of the sacral area showed significant fluctuations in perfusion ($p = .035$) and local temperature ($p = .013$). In the trochanteric area, the comparative analysis showed significant fluctuations in perfusion ($p = .044$), local temperature ($p > .001$), and oxygenation ($p = .049$). Nonlinear patterns were identified in the variables examined in both anatomical areas. This prompted the adoption of an algorithm based on the Random Forest Regressor technique to predict the parameters associated with the development of pressure injuries.

Conclusions: Individuals at risk of developing pressure injuries show a more limited compensatory physiological response compared to healthy individuals in terms of blood flow, oxygenation, and tissue temperature in pressure areas. Notably, at the 90-min, a turning point is observed, marking a critical threshold from which these parameters begin to decline.

1. Introduction

A pressure injury (PI) is usually of ischaemic origin, resulting from pressure or the combination of pressure with shear, which can provoke necrosis in the epidermis, dermis, subcutaneous tissue, muscles, joints and bones [1]. PIs are normally caused by the compression of soft tissues between two planes, such as a bony prominence of the body and an external surface [2].

Systematic reviews have revealed large variations in the prevalence of PIs among hospitalised patients, reporting values such as 8.4% worldwide [3], 9.3% in the USA [4], 6.2% in Australia [5], 12.7% in Turkey [6], 2.7-16.8% in Asia [5] and 18.1% in Europe [6]. In Spain, PIs are experienced by 7.87% of adult hospitalised patients, by 13.41% of

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Abbreviations

PI	Pressure Injury
NICE	National Institute for Health and Care Excellence
SaO_2	Oxygen Saturation
BMI	Body Mass Index
FFM	Fat-Free Mass
FM	Fat Mass
SBP	Systolic Blood Pressure
DBP	Dyastolic Blood Pressure
AU	Arbitrary Unit

those treated in nursing homes and by 8.51% of those included in home care programmes [6]. PIs affect the trochanters and sacrum in 9.9% and 32.7% of cases, respectively [6].

PIs can have severe negative consequences, both for patients and for the health system overall, heightening the risk of nosocomial diseases, provoking pain and/or disability [7,8], requiring extended hospital stays and increasing morbidity and mortality [9].

This challenging situation is best addressed in terms of prevention. In this respect, the presence or otherwise of PIs is taken as an indicator of the quality of health care [10], in the view that most such injuries can be prevented, with appropriate measures [11].

1.1. Background

Certain factors increase the risk of a PI developing. The conceptual framework employed in this study considers two groups of risk factors: on the one hand, those which are especially relevant to the appearance of PIs, such as individual susceptibility and tolerance (skin condition, poor perfusion, diabetes, moisture and low albumin); and on the other hand, those referring to the limits of mechanical conditioning (immobility and poor sensory perception/response) [12].

Preventing the development of PIs should be a primary consideration in clinical practice. In this respect, the European Pressure Ulcer Advisory (EPUAP), National Pressure Injury Advisory Panel (NPIAP) and Pan Pacific Pressure Injury Alliance (PPPIA) published a clinical practice guideline detailing appropriate interventions to prevent the appearance of PIs. These include assessing the risk of PIs developing, evaluating skin condition, repositioning the patient, avoiding skin massage, maintaining good nutritional/hydration status and making good use of support surfaces and barrier creams [13]. Of all these preventive actions, repositioning probably generates most controversy. For example, studies have observed no significant differences in outcomes whether patients are repositioned every 2 or 3 h versus every 4 h [14–17].

Much current research is being dedicated to the question of how existing preventive actions should be remodelled to prevent or decrease the development of PIs. In this respect, one of the most promising study paths focuses on understanding the pathophysiological mechanisms underlying the initial appearance of PIs [12,18,19].

To achieve this understanding, it is vitally important to characterise patterns of tissue response in the areas most liable to the appearance of PIs, such as the sacrum and the trochanters so that repositioning to prevent PIs can be performed in the most effective way. Studies have been conducted of residents (in nursing homes and critical care units) to evaluate the role of pressure, capillary blood flow and skin temperature of the sacrum and trochanters [20–22]. Other studies have focused on healthy subjects, measuring the perfusion and oxygen saturation (SaO_2) of the skin of the sacrum and trochanters [23–25], and have concluded that the risk of PIs due to prolonged ischaemia could be mitigated by the use of alternating pressure relief mattresses. The researchers also reported that persons with a low body mass index and those with morbid obesity were at greater risk of developing PIs.

However, to our knowledge no previous studies have been conducted to measure, both simultaneously and continuously, changes in capillary blood flow, SaO_2 and local temperature of the sacrum and trochanters of residents, resting for extended periods on a standard mattress at known levels of constant direct pressure, and to compare these values with those obtained for healthy subjects under the same conditions. This multifocal approach is adopted in the present study to enhance our understanding of tissue changes at a level of detail not previously possible, either because the parameters were measured at discrete intervals or over too short a period of time, or because only some of these parameters were measured separately.

In a preclinical phase of the present study, this method was used to examine healthy subjects, who acted as their own controls [26]. The analysis revealed significant changes in perfusion, SaO_2 and local skin temperature in the sacrum and trochanters when the skin was subjected to direct pressure over a 2-h period. Furthermore, differences were observed when these parameters were compared with control areas in which there was no pressure or where it was only minimal. Specifically, the temperature increased significantly (by 1.38 °C) in the areas under pressure. However, the increases in capillary blood flow and in oxygenation were not statistically significant. These findings provided important information about physiological responses to pressure, which could inform strategies to reduce or prevent the occurrence of PIs.

Having determined these threshold values for healthy subjects, the next step was to compare them with persons presenting a risk profile for the development of PIs, as is the case of aged care residents.

In short, our study aim was to evaluate the longitudinal changes observed over a period of 120 min in patterns of tissue perfusion, peripheral oxygenation and local temperature of sacral and trochanteric areas exposed to pressure, comparing a healthy population with one at risk of impaired skin integrity (nursing home residents). As a secondary aim, we wished to determine whether there was a turning point at which these three parameters became statistically and clinically significant.

2. Method

2.1. Design

In this experimental, non-randomised study, the participants were recruited in two phases: preclinical, with healthy volunteers, and clinical, with aged care participants who were at risk of deteriorating skin integrity due to their mobility-impaired condition [27].

2.2. Inclusion and exclusion criteria

In the preclinical phase of the study, students at the Faculty of Health Sciences of the University of Málaga were invited to participate in an online recruitment survey. This questionnaire was designed as a screening tool to assess eligibility based on the established inclusion and exclusion criteria. Following this initial selection, eligible candidates were contacted for a physical assessment of tissue integrity prior to definitive inclusion. In the clinical phase, volunteers were recruited at three nursing homes for the residents in the province of Málaga.

The following inclusion and exclusion criteria were applied to the healthy subjects: age 18-65 years, non-smoker, non-drinker and non-user of drugs of any type. In addition, they should have a normal body mass index (BMI) (18.5-24.9 kg/m^2) and not suffer from any disease or functional limitation. Finally, they should have observable tissue integrity and no tattoos in the measurement area [26].

The following criteria were applied to the aged care participants: age at least 65 years, and at risk of developing PI, defined as <16 points on the Braden scale for persons aged under 75 years and <18 points otherwise. Patients who were being treated with heparin, anticoagulant medications, alpha/beta blockers, agonists, calcium antagonists, nitrites, angiotensin II receptor blockers, renin inhibitors, or diuretics were eligible for inclusion provided these medications were administered orally. Those with respiratory failure were also considered for inclusion, although the analyses were adjusted to take this factor into account when measuring tissue oxygenation.

Any persons already presenting with a PI were excluded, as were those who at the time of the study required the use of vasoactive drugs, of any type, in infusion. Also excluded were any patients fitted with a pacemaker or defibrillator; those who presented with a fever, anaemia with haemoglobin <10 g/dl or who had been transfused in the last 4 weeks; those with hypotension (systolic blood pressure <80 mmHg); those being treated with erythropoietin or blood products; those with tattoos in the measurement area; and those who had suffered the amputation of a lower limb. The above criteria were applied in order to obtain a homogeneous study sample and to ensure that the values measured for tissue perfusion and peripheral oxygenation were not affected by these factors.

Finally, prior to inclusion, all participants gave their signed informed consent to take part in the study.

2.3. Data collection

Study data were obtained at the tissue integrity laboratory of the School of Health Sciences between November 2017 and May 2018 (for the healthy volunteer group) and at the participating nursing homes between September 2019 and June 2020 (for the resident group).

Among the explanatory variables considered were age, sex, height (cm) and weight (kg). Height and weight were determined using a medical scale with a stadiometer (Laboratorios ASIMED, Spain), while the participants were barefoot and wearing light clothing.

Data for BMI (kg/m^2), fat-free mass (FFM) (kg) and fat mass (FM) (kg) were obtained using a BodyComp MF Hexa-AKERN impedance meter (Akern, Italy). Bioimpedance was determined with the participant in a resting state, making no contact with any conductive surface and lying in a supine position with the arms and legs slightly separated from the body (with a minimum separation of 25 cm). Prior to obtaining this measurement, the participants were asked to remove shoes, socks and any metal objects that might alter the conductivity value obtained. All measurements were taken in multifrequency mode (400 μARMS, 5–250 kHz) with the electrodes in a tetrapolar arrangement: the emitting electrode was placed on the midline of the flexure of the right wrist, the receiving electrode on the mid-intermalleolar line of the right foot and the detector electrodes at least 5 cm from the other two (one on the metacarpophalangeal midline and the other on the metatarsophalangeal midline).

Systolic (SBP) and diastolic blood pressure (DBP) (mmHg) were measured with a digital blood pressure monitor (OMRON M6 AC, HEM-7322-E; Omron Healthcare, Japan), with the participant in the same supine position described above.

In addition, data for the following outcome variables were obtained, using a MoorVMS-LDF2 laser Doppler blood flow monitor: perfusion (in arbitrary units, AU: a relative unit of measurement that describes the proportion of perfusion to a predetermined reference measurement value for the device used); and temperature (°C) of the skin of the anatomical areas to be measured (sacral and trochanteric areas under pressure). In this non-invasive measurement method, the laser light is transmitted by optical fibre to the tissue (to a depth of 1 mm) and the light scattered by the tissue is received by a photodetector. Tissue oxygenation data (SaO_2 in %) were obtained by spectroscopy using a MoorVMS-NIRS near infrared spectroscopy monitor (Moor Instruments, UK). The information on these three parameters was integrated into the MoorVMS-PC V4.0 software package and compiled into 15-min averaged intervals, over a total period of 2 h of uninterrupted measurement. However, the first 15-min measurement interval, while the participants adjusted to the process, was excluded from the analysis.

To ensure optimum control of the study conditions, a measurement protocol was applied by an experienced professional trained specifically to handle the devices used in this study. For both study groups (healthy volunteers and nursing home residents), identical conditions were maintained. Healthy volunteers were measured at the tissue integrity laboratory of the School of Health Sciences, while for the residents, the equipment was transported to the nursing homes to perform the measurements in their own rooms. In all cases, the rooms were maintained at a constant temperature of 26 °C, which was chosen to ensure a stable thermal environment and prevent peripheral vasoconstriction that could alter microvascular measurements [28].

The laser Doppler and infrared sensors were then placed in the sacral and trochanteric areas under pressure. These anatomical areas were measured on different days in order to avoid physiological alterations of the measurements.

The support surface was standardized for all participants, both healthy subjects and residents remained in an articulated bed with a standard foam mattress (non-alternating pressure). For the sacral region, the instruments were positioned in the corresponding area, while the participants adopted a supine position on a standard mattress supported by an articulated bed base with an elevation of 0° during the 2 h of measurement. To measure the trochanteric area, the instruments were placed in the trochanteric region after locating the bony prominence, and the participants were positioned with an elevation of 30°, determined with a manual goniometer.

2.4. Ethical considerations

Both the Malaga Research Ethics Committee and the Ethical Experimentation Committee of the University (98-2015-H) reviewed and approved the study. The ethical standards of the Declaration of Helsinki were observed at all times and all study data were obtained in accordance with the principles established in current legislation on the protection of personal data. The databases were stored on computers dedicated exclusively to this project. The participants all provided signed informed consent, either in person or via their legal guardians, after receiving a complete explanation of the study.

2.5. Data analysis

The data analysis initially proposed is described in the study protocol [27]. For bivariate analysis, the Student's *t*-test and ANOVA (if there were more than two groups) were performed if the variables followed a normal distribution, and the Mann-Whitney and Wilcoxon U tests (when applicable) otherwise. A correlation analysis was performed to determine the relevance of the anthropometric characteristics, together with the health parameters involved in the incidence of PIs.

Our analysis of the main study variables was based on two approaches: first, we considered a general linear model of repeated measures. We then searched for non-linear patterns in the variables examined, for both of the anatomical areas of interest. This method enabled us to implement a prediction algorithm based on a Random Forest Regressor (RFR) for one-step-ahead time series forecasting in which previous time steps (lagged values) of the study variables were used as predictors. This approach is particularly suitable for short physiological time series, as it allows temporal dependence to be explicitly incorporated through lagged variables without imposing assumptions of linearity or stationarity.

This supervised machine learning technique is particularly well suited to short physiological time series, as it deals effectively with complex and non-linear relationships, including temporal dependencies between input variables [29], providing strong predictive performance while overcoming the assumptions of linearity and stationarity inherent in traditional linear models [30]. By aggregating the predictions of multiple decision trees, providing an automated understanding that both facilitates the identification and prediction of crucial dependent variables and supports clinical decision making [19]. This approach enables the identification of emerging dynamic patterns in microvascular response that may not be adequately captured by linear models, especially during prolonged loading conditions.

All analyses were carried out using Jamovi v2.3.21 software [31] and assuming a 95% confidence interval. The scikit-learn library in Python was used to develop the RFR model, with fixed hyperparameters: number of estimators = 100, minimum number of samples per leaf = 1, and minimum number of samples required to split an internal node = 2, to ensure consistent training and predictions across intervals.

3. Results

30 adults (18 healthy and 12 aged care participants) were included in the study. The data for each anatomical area (sacrum and trochanters) were measured for 2160 min in the healthy subjects and for 1440 min in the residents. The flowchart of study participation is shown in Fig. 1.

Among the 30 persons in the total sample, 70% were women and 30% were men. The mean age of the healthy participants was 23.6 years (SD: 5.27); for the aged care participants, it was 90.2 years (SD: 6.49). Table 1 shows the mean values of the anthropometric parameters considered and the mean blood pressures obtained for each group. The resident group had a mean BMI of 5.96 kg/m^2 and, on average, 12.41 kg more FM than the healthy participants. Moreover, their mean SBP was 18.67 mmHg higher. These differences in the means were statistically significant (Mann-Whitney *U* test; $p < .001$, $p = .003$ and $p < .001$, respectively).

Table 2 summarises the data obtained for capillary flow, tissue oxygenation and local temperature, by measurement time, anatomical area exposed to pressure (sacrum and trochanter) and type of subject (healthy vs. residents). With respect to the values measured on the skin of the sacrum, the values obtained for the final measurement section (minutes 105-120), were higher (indicating a better compensatory response) in the healthy subjects than in those who were residents. Specifically, the differences in the means between these groups were 15.3 AU for capillary flow, 8.8% for SaO_2 and 0.3 °C for local temperature, respectively. In the first two of these cases, the differences were statistically significant ($p = .004$ and $p < .001$, respectively). However, for the skin of the trochanters, although the differences found in the 105-120 min section were statistically significant for SaO_2 (8.5%, $p = .004$) and local temperature (2.1 °C, $p = .026$), this was not the case for tissue perfusion (19.9 AU, $p = .102$). Moreover, in the latter case, the values were higher (better) for the healthy subjects.

The correlation analysis revealed a notable inverse association between DBP and local tissue temperature of the tissues studied; the coefficient of correlation was close to −0.58. However, a positive relationship was identified between SaO_2 and local temperature, with correlation coefficients between 0.55 and 0.68, depending on the measurement interval considered. These results were used for decision making by the prediction algorithm described below.

Fig. 2 shows the results of the comparative analysis between the

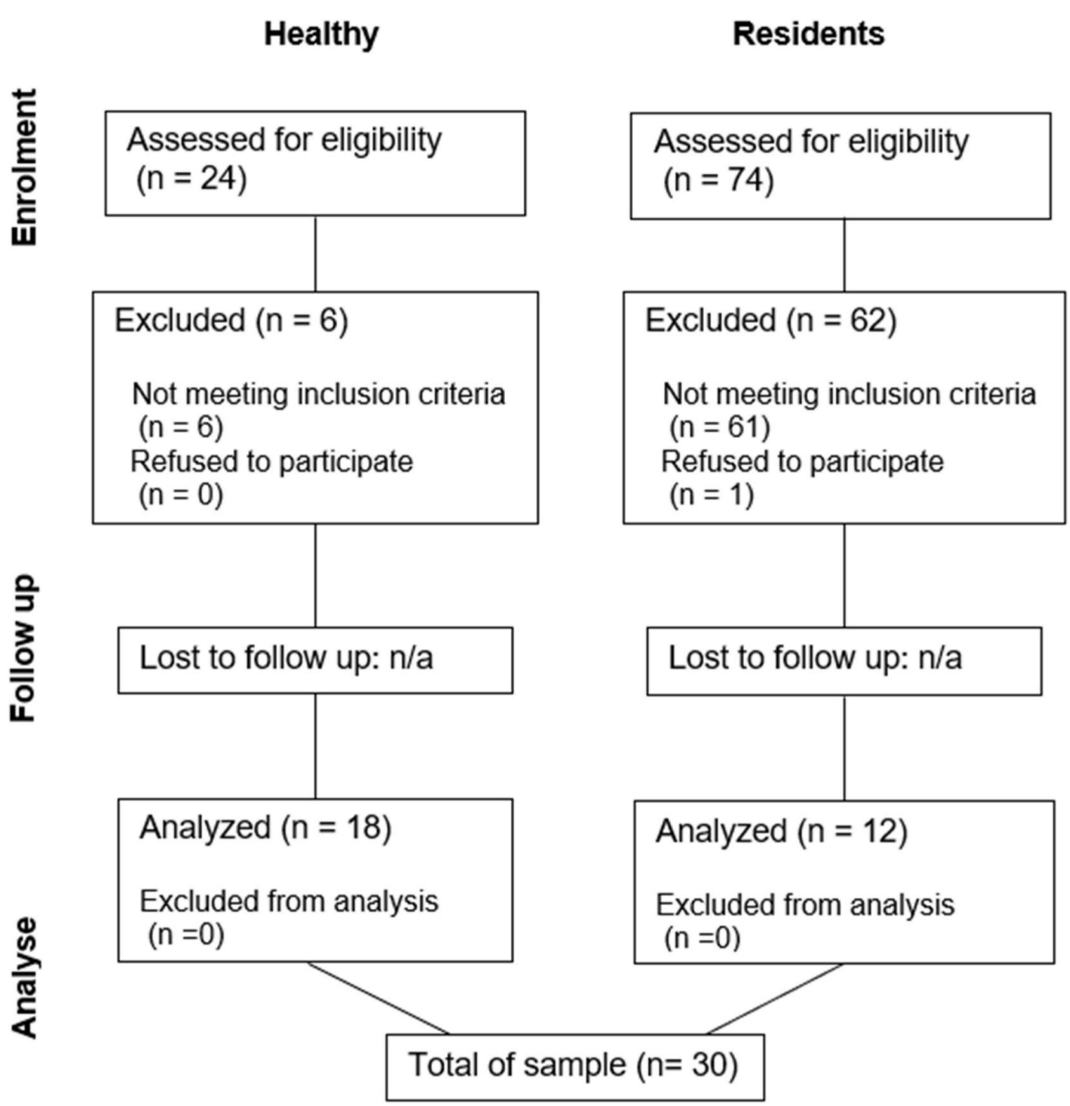

Fig. 1. Flow diagram.

Table 1
Differences in the means: anthropometric variables and blood pressure.

	Mean (SD)		Mean difference	p	Std. error	95% CI	
	Healthy	Residents				Lower	Upper
BMI (kg/m^2)	22.2 (1.59)	28.2 (6.2)	−5.96	<0.001	1.52	−9.07	−2.84
FFM (kg)	47.8 (9.43)	43.1 (7.56)	4.62	0.168	3.26	−2.06	11.29
FM (kg)	15.4 (4.45)	27.8 (15.33)	−12.41	0.003	3.81	−20.21	−4.61
SBP (mm/Hg)	104.7 (11.17)	123.3 (8.88)	−18.67	<0.001	3.85	−26.55	−10.78
DBP (mm/Hg)	63.3 (7.53)	60 (6.03)	3.33	0.211	2.60	−1.99	8.66

SD: standard deviation; Std. error: standard error; BMI: body mass index; FFM: fat-free mass; FM: fat mass; SBP: systolic blood pressure; DBP: diastolic blood pressure.

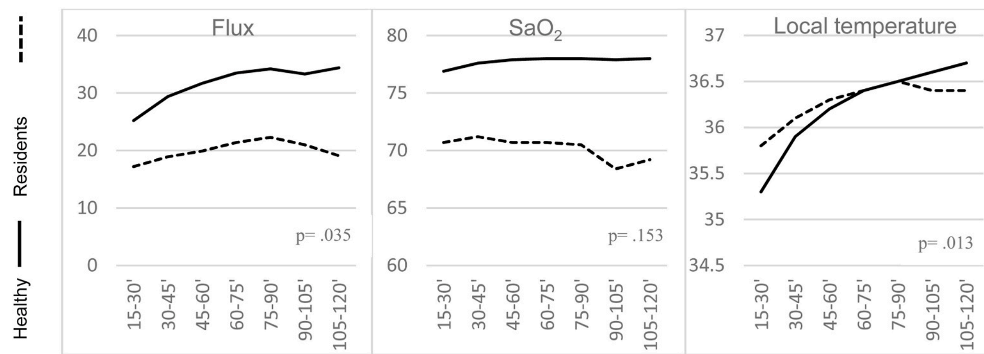

Fig. 2. Fluctuations in tissue perfusion, SaO_2 and local temperature in the skin of the sacrum, among healthy and residents.

study groups, by time intervals, for the three parameters evaluated in the skin of the sacrum. The fluctuations in capillary blood flow (F [2.81; 85.2] = 3.08; p = .035) and in tissue temperature (F [1.34; 2.03] = 5.86; p = .013) were statistically significant. However, there were no statistically significant differences in the fluctuations in tissue oxygenation of the sacral skin (F [1.59; 40.4] = 2.02; p = .153). An inflection point was apparent in the 75-90-min time interval in all three parameters evaluated (this outcome can be seen numerically in Table 2). Specifically, while healthy subjects showed a continuous and stable increase in perfusion, oxygenation, and temperature throughout the 120 min, residents reached a physiological peak during the 75-90-min interval, followed by a steady and significant decline in all values until the end of the measurement period.

Finally, Fig. 3 describes the comparative analysis made of the two groups, by time intervals, for each of the three outcome variables, for the skin of the trochanters. In this case, the analysis revealed statistically significant differences in the three parameters that were measured: tissue perfusion (F [1.54; 1353] = 3.69; p = .044), SaO_2 (F [1.59; 160.5] = 3.5; p = .049) and local temperature (F [2.08; 7.23] = 8.34; p > .001). The values of these three parameters were always higher among the healthy subjects vs. those who were residents. Furthermore, among the members of the latter group the changes in the risk of skin integrity were

Table 2
Differences in the means of the outcome variables by time interval and anatomical area, among healthy and aged care residents.

		Healthy		Residents		Mean differences			
	Time	Sacrum[a]	Trochanter[a]	Sacrum[a]	Trochanter[a]	Sacrum	p[b]	Trochanter	p[b]
Flux (AU)	15-30′	25.2 (13.61)	18.3 (15.71)	17.8 (8.03)	16.6 (7.35)	7.4	0.102	1.7	0.725
	30-45′	29.4 (15.89)	22.5 (22.22)	18.9 (9.07)	19.2 (7.98)	10.5	0.048*	3.3	0.631
	45-60′	31.7 (15.96)	27.3 (29.96)	19.9 (9.44)	20.2 (9.3)	11.8	0.030*	7.1	0.436
	60-75′	33.5 (15.66)	31.9 (35.6)	21.4 (10.04)	19.9 (9.69)	12.1	0.025*	12	0.268
	75-90′	34.2 (15.63)	35.2 (38.44)	22.3 (11.41)	21.4 (9.97)	11.9	0.031*	13.7	0.238
	90-105′	33.3 (15.46)	38.7 (42.31)	21 (11.34)	21.3 (10.11)	12.3	0.026*	17.4	0.174
	105-120′	34.4 (14.4)	39.5 (39.82)	19.1 (10.08)	19.6 (8.71)	15.3	0.004*	19.8	0.102
SaO_2 (%)	15-30′	76.9 (4.81)	72.1 (5.81)	70.7 (6.17)	67.8 (10.15)	6.2	0.005*	4.3	0.150
	30-45′	77.6 (4.47)	73.6 (5.09)	71.2 (6.19)	69.3 (8.71)	6.4	0.003*	4.2	0.104
	45-60′	77.9 (4.44)	74.8 (5.03)	70.7 (6.86)	69.3 (8.34)	7.2	0.002*	5.5	0.032*
	60-75′	78 (4.38)	75.8 (5.08)	70.7 (11.34)	67.6 (12.28)	7.3	0.002*	8.2	0.017*
	75-90′	78 (4.29)	76.5 (5.21)	70.5 (6.01)	65.9 (16.62)	7.5	<0.001*	10.6	0.017*
	90-105′	77.9 (4.42)	77.1 (5.29)	68.4 (9.11)	68.8 (11.18)	9.5	<0.001*	8.3	0.010*
	105-120′	78 (4.76)	77.7 (4.66)	69.2 (7.04)	69.2 (10.25)	8.8	<0.001*	8.5	0.004*
Temperature (°C)	15-30′	35.3 (1.06)	33.9 (1.45)	35.8 (0.44)	33.6 (2.87)	−0.5	0.208	0.3	0.721
	30-45′	35.9 (0.81)	34.8 (1.12)	36.1 (0.36)	33.9 (2.93)	−0.2	0.416	0.9	0.258
	45-60′	36.2 (0.66)	35.3 (0.85)	36.3 (0.33)	34.1 (2.94)	−0.1	0.723	1.2	0.118
	60-75′	36.4 (0.55)	35.7 (0.62)	36.4 (0.33	34.3 (2.88)	0	0.912	1.4	0.058
	75-90′	36.5 (0.46)	36 (0.48)	36.5 (0.32)	34.5 (2.78)	0	0.592	1.5	0.031*
	90-105′	36.6 (0.4)	36.2 (0.4)	36.4 (0.62)	34.5 (2.8)	0.4	0.163	1.7	0.019*
	105-120′	36.7 (0.35)	36.3 (0.34)	36.4 (0.54)	34.2 (2.73)	0.3	0.097	2.1	0.003*

*: p < .05.
[a] mean and standard deviation.
[b] Mann-Whitney *U* test; AU: arbitrary unit.

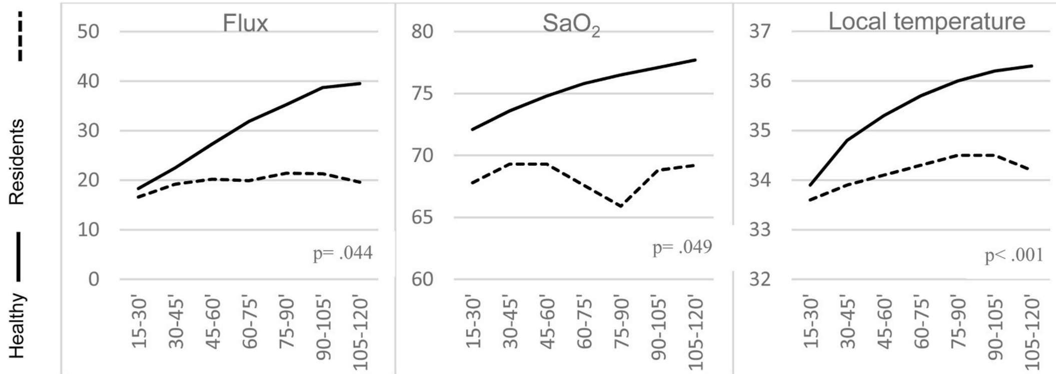

Fig. 3. Fluctuations in tissue perfusion, SaO_2 and local temperature in the skin of the trochanters, among healthy and residents.

non-linear, compared to the constant increase in values recorded for the healthy subjects.

Figs. 2 and 3 illustrate non-linear patterns identified in the variables considered, for both anatomical areas. In view of these findings, we then used an algorithm based on the RFR technique to predict the parameters associated with PI formation. Both anthropometric parameters and the perfusion, temperature and oxygenation data recorded at each time interval were included as predictors. Table 3 shows the coefficient of determination (R^2) for the forecasts in each time interval. Predictions were made starting from the 45–60 min period, as the RFR model relies on lagged values of the study variables and therefore requires a sufficient amount of prior temporal information (in this case, at least two lags). Earlier intervals exhibited higher physiological variability due to the initial loading phase, which limited their suitability for stable short-term forecasting and required the use of a minimum number of lagged values to provide the model with adequate temporal context.

The R^2 values for tissue perfusion (flux) were consistently lower than those obtained for SaO_2 and temperature, in both anatomical areas and in both groups of subjects, although they were higher in the healthy subjects than in the aged care participants, in most of the time intervals considered. For example, in the 45-60 min time interval for the sacrum, the R^2 values obtained for flux were 0.57 and 0.60 for healthy and residents, respectively. For SaO_2, these values were significantly higher, at 0.87 and 0.67; for temperature, the corresponding values were 0.83 and 0.74, respectively.

Table 3
Values of R^2 for tissue perfusion, SaO 2 and local temperature, for each time interval, by anatomical area and type of subject, used to evaluate the PI prediction algorithm.

		R^2 (Healthy)		R^2 (Residents)	
	Time	Sacrum[a]	Trochanter[a]	Sacrum[a]	Trochanter[a]
Flux (AU)	45-60′	0.57	0.27	0.60	0.77
	60-75′	0.41	0.33	0.49	0.71
	75-90′	0.68	0.36	0.26	0.56
	90-105′	0.69	0.30	0.30	0.37
	105-120′	0.56	0.32	0.30	0.13
SaO_2 (%)	45-60′	0.87	0.71	0.67	0.85
	60-75′	0.93	0.75	0.65	0.96
	75-90′	0.87	0.66	0.81	0.89
	90-105′	0.94	0.76	0.82	0.66
	105-120′	0.93	0.87	0.91	0.62
Temperature (°C)	45-60′	0.83	0.69	0.74	0.82
	60-75′	0.84	0.88	0.78	0.82
	75-90′	0.78	0.92	0.94	0.82
	90-105′	0.70	0.94	0.65	0.34
	105-120′	0.72	0.88	0.53	0.31

These differences suggest that the values obtained for flux are associated with greater variability or error than is the case of the other two parameters considered. Hence, for certain intervals, the R^2 values were below 0.3 for both anatomical areas, in both population groups. In contrast, the higher R^2 values obtained for SaO_2 and temperature are indicative of more reliable and consistent measurements than for flux, and consequently more accurate predictions.

4. Discussion

Our study aim was to evaluate the changes produced in patterns of tissue perfusion, peripheral oxygenation and local temperature, for the sacral and trochanteric areas exposed to pressure, considering a healthy population versus one at risk of deterioration in skin integrity (residents in nursing homes), identifying and measuring the differences in these respects during a time interval of 120 min. In this analysis, it was taken into account that the baseline measurements for the two population groups were different.

The results obtained were significant in several ways. Firstly, with respect to the measurements made in the sacral area, for the healthy subjects, the values for all three parameters increased over time. This finding corroborates previous research [23,25,26,32,33], and probably reflects the compensatory mechanism activated in healthy subjects when the sacral skin is exposed to pressure. Among aged care residents at risk of PI, the values obtained for the same parameters for the sacral skin, during the 75-90-min interval, also increased, but less strongly. At greater time intervals, the values for the physiological parameters decreased significantly. This reduction suggests an exhaustion or failure of the compensatory physiological response, leading to a state of tissue hypoperfusion and hypoxia that marks the onset of potential ischemic damage. However, with respect to the sacral skin, previous studies have reported higher values for these parameters in persons with spinal cord injury [34], in patients admitted to the ICU [35] and among those who are residents [22]; in every case, the risk of PI was identified. In no case was there a decrease in the values for the parameters considered, but this may be due to the fact that the measurements were obtained with less than 60 min of follow-up.

In human skin, tissue oxygenation (up to 75%) [36] is the factor that most affects vasomotility (the intermittent contraction of meta-arterioles and precapillary sphincters) [37]. This explains why, when oxygen demand is increased by tissue pressure, a vasomotility activation response is triggered, increasing the duration of blood flow intermittency. In healthy individuals, the rate of tissue perfusion may vary in response to this situation. In the present study, the simultaneous evaluation of flux, oxygenation, temperature and pressure enabled us to conduct an in-depth analysis of the behaviour of the microvascular network, to determine whether losses of system flexibility might prevent microvascular networks from adapting effectively to a stressor such as pressure. The results obtained are in line with those reported by Kuliga et al. [36]. Specifically, our findings support their observation that tissue oxygenation is a primary driver of microvascular control. Furthermore, while Kuliga et al. [36] demonstrated that healthy individuals possess a high potential for 'flowmotion' adaptability, our study shows that in at-risk residents, this adaptability is compromised after 90 min of pressure, resulting in a declining spontaneous variation that signals a loss of system flexibility to physiological challenge.

Similar findings were obtained concerning the outcome when pressure is exerted on the trochanteric area, confirming our suggestion that this situation generates a compensatory process in the skin of healthy persons [26]. Our results also show that, at all times, the physiological values of the trochanteric skin exposed to pressure are lower for aged care residents than for persons in good health. Källman et al. [22] studied the impact of pressure on the trochanter skin of persons aged 65 years or more, residents in nursing homes, not currently presenting any PI but at risk of developing this condition. These authors reported significant increases in skin temperature and capillary blood flow. However, the study variables were measured under load for a period of just 60 min. Our results coincide with the latter findings up to the 60-min limit; however, there is an inflection point in these values during the 75-90-min interval. This inflection point represents a critical threshold where the resident's compensatory response (vasomotility and thermal regulation) is no longer able to counteract the sustained mechanical pressure. At this 90-min mark, the transition from a compensatory state to a state of progressive tissue failure begins, which could denote the initiation of irreversible histological changes and cellular necrosis. Consideration of this evolution will enhance our understanding of the initial pathophysiology of a PI.

To our knowledge, no previous studies have been conducted in which, after comparing a healthy population versus one at risk of PI, the findings are applied specifically to the trochanter area. Our analysis suggests that in persons at special risk of PI, not only is the compensatory response less effective than in a healthy population, but this response declines after 90 min, a threshold at which histological changes relevant to the onset of a PI might become apparent.

The algorithm devised to predict the parameters associated with the formation of these ulcerative lesions produced satisfactory results, with an R^2 greater than 0.8 for certain time intervals, both for SaO_2 and for temperature, in both anatomical areas and for both groups of study participants (with greater precision among the healthy population). Regarding tissue perfusion, however, the coefficients of determination were significantly lower. In view of this greater degree of uncertainty, the parameters in question should be interpreted cautiously.

Among the methods that can be used to evaluate peripheral tissue oxygenation and perfusion, the non-invasive approach used in the present study is among the most appropriate because it is not affected by variations in vascular calcification or anatomical structure [38]. On the other hand, it is difficult to determine optimal cutoff points. Our study findings advance our understanding of these questions, by determining flow, temperature and oxygenation thresholds in healthy subjects and confirming the existence of significant differences in this respect compared to patients at high risk of developing PI. Nevertheless, the reliability of flow measurement needs to be further improved.

Furthermore, clinical trials should be conducted to determine the extent to which the PI prevention measures available in routine clinical practice, such as support devices, repositioning and/or the application of hyperoxygenated fatty acids [7,39], could modify these parameters. In addition, consideration should be given to revising the current international recommendations [13] for addressing the risk factors for PIs [12]. Specifically, our results suggest that the standard 120-min repositioning interval may be excessive for high-risk residents, as their physiological compensatory response begins to decline significantly after 90 min. Therefore, for this vulnerable population, individualised repositioning schedules of 90 min or less should be considered to prevent the onset of ischemic tissue damage.

4.1. Limitations

This study is subject to certain limitations. Firstly, the research was conducted under highly experimental and controlled conditions to ensure the internal validity of the physiological measurements. While the preclinical phase took place in a university laboratory and the clinical phase in nursing homes, identical measurement protocols, equipment, and environmental controls (such as room temperature and support surfaces) were maintained in both settings to ensure comparability. However, this high level of control might restrict the external validity when applying these results to more complex clinical environments where such variables cannot be as strictly managed. Furthermore, although the clinical phase involved residents in their habitual environment, these participants did not present certain critical risk factors for PI, such as anaemia or severe hypotension.

Another significant limitation was the non-randomisation of the sample. However, the physiological response of the parameters evaluated is an objective measure. In this respect, selection bias is unlikely to have influenced the physiological results obtained. Furthermore, the strict inclusion and exclusion criteria applied in both phases ensured a homogeneous sample appropriate for our research purposes.

Furthermore, the age difference between the healthy group (mean age 23.6) and the resident group (mean age 90.2) must be considered. Since aging naturally affects microvascular function and skin elasticity, some of the observed differences in perfusion and temperature may be partially attributed to the aging process itself rather than exclusively to pressure. However, this comparison allowed for the identification of extreme physiological patterns between a healthy baseline and a highly vulnerable clinical population.

5. Conclusions

When exposed to pressure on the skin, a person in good health will present a homeostatic compensatory reaction, with increases in capillary blood flow, tissue oxygenation, and local skin temperature in the affected areas. In contrast, individuals at prior risk of developing PIs will have a more limited compensatory physiological response. Among our study population of nursing home residents, an inflection point was observed after 90 min of sustained pressure. This is a critical threshold at which the values for tissue perfusion, peripheral oxygenation, and local temperature begin to decline significantly. This downturn could represent a physiological point of no return, potentially signaling the beginning of cellular necrosis.

These findings have several significant implications. Firstly, they provide the scientific community with a basis for further investigating the risk factors associated with the occurrence of PIs. In addition, they suggest new avenues of research to identify and evaluate preventive activities. Finally, individualised preventive measures might be adopted in response to differences in physiological responses, thus establishing a more personalised strategy.

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Conflict of interest

The authors declare they have no conflicts of interest regarding this study.

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References

[1] Pittman J, Black J, Padula W, DeJesus A. The standardized Pressure injury prevention protocol checklist 2.0: content validation. J Adv Nurs 2023. https://doi.org/10.1111/jan.15964.
[2] Lechner A, Kottner J, Coleman S, Muir D, Beeckman D, Chaboyer W, Cuddigan J, Moore Z, Rutherford C, Schmitt J, Nixon J, Balzer K. Outcomes for pressure ulcer trials (OUTPUTs) project: review and classification of outcomes reported in pressure ulcer prevention research. Br J Dermatol 2020. https://doi.org/10.1111/bjd.19304.
[3] Li Z, Lin F, Thalib L, Chaboyer W. Global prevalence and incidence of pressure injuries in hospitalised adult patients: a systematic review and meta-analysis. Int J Nurs Stud 2020;105:103546. https://doi.org/10.1016/j.ijnurstu.2020.103546.
[4] VanGilder C, Lachenbruch C, Algrim-Boyle C, Meyer S. The international pressure ulcer Prevalence^{TM} survey: 2006-2015: a 10-Year pressure injury prevalence and demographic trend analysis by care setting. J Wound, Ostomy Cont Nurs: Offi Publ Wound Ostomy Contin Nurs Soc 2017;44(1). https://doi.org/10.1097/WON.0000000000000292. Article 1.
[5] Jull A, McCall E, Chappell M, Tobin S. Measuring hospital-acquired pressure injuries: a surveillance programme for monitoring performance improvement and estimating annual prevalence. Int J Nurs Stud 2016;58:71–9. https://doi.org/10.1016/j.ijnurstu.2016.02.005.
[6] Pancorbo-Hidalgo PL, García-Fernández FP, Pérez-López C, Soldevilla Agreda JJ, Pancorbo-Hidalgo PL, García-Fernández FP, Pérez-López C, Soldevilla Agreda JJ. Prevalencia de lesiones por presión y otras lesiones cutáneas relacionadas con la dependencia en población adulta en hospitales españoles: resultados del 5º Estudio Nacional de 2017. Gerokomos 2019;30(2). Article 2.
[7] Coleman S, Gorecki C, Nelson EA, Closs SJ, Defloor T, Halfens R, Farrin A, Brown J, Schoonhoven L, Nixon J. Patient risk factors for pressure ulcer development: systematic review. Int J Nurs Stud 2013;50(7). https://doi.org/10.1016/j.ijnurstu.2012.11.019. Article 7.
[8] Ferris A, Price A, Harding K. Pressure ulcers in patients receiving palliative care: a systematic review. Palliat Med 2019;33(7):770–82. https://doi.org/10.1177/0269216319846023.
[9] Bail K, Draper B, Berry H, Karmel R, Goss J. Predicting excess cost for older inpatients with clinical complexity: a retrospective cohort study examining cognition, comorbidities and complications. PLoS One 2018;13(2):e0193319. https://doi.org/10.1371/journal.pone.0193319.
[10] Pittman J, Beeson T, Dillon J, Yang Z, Cuddigan J. Hospital-acquired pressure injuries in critical and progressive care: avoidable versus unavoidable. Am J Crit Care: Off Publ Am Assoc Critical Care Nurs 2019;28(5):338–50. https://doi.org/10.4037/ajcc2019264.
[11] Lovegrove J, Fulbrook P, Miles SJ, Steele M. Effectiveness of interventions to prevent pressure injury in adults admitted to acute hospital settings: a systematic review and meta-analysis of randomised controlled trials. Int J Nurs Stud 2021;122:104027. https://doi.org/10.1016/j.ijnurstu.2021.104027.
[12] Coleman S, Nixon J, Keen J, Wilson L, McGinnis E, Dealey C, Stubbs N, Farrin A, Dowding D, Schols JMGA, Cuddigan J, Berlowitz D, Jude E, Vowden P, Schoonhoven L, Bader DL, Gefen A, Oomens CWJ, Nelson EA. A new pressure ulcer conceptual framework. J Adv Nurs 2014;70(10):2222–34. https://doi.org/10.1111/jan.12405.
[13] European Pressure Ulcer Advisory Panel, National Pressure Injury Advisory Panel, Pan Pacific Pressure Injury Alliance. The international guideline. Prevention and Treament of Pressure Ulcers/Injuries: Clinical Practice Guideline; 2019.
[14] Defloor T, De Bacquer D, Grypdonck MHF. The effect of various combinations of turning and pressure reducing devices on the incidence of pressure ulcers. Int J Nurs Stud 2005;42(1). https://doi.org/10.1016/j.ijnurstu.2004.05.013. Article 1.
[15] Edsberg LE, Black JM, Goldberg M, McNichol L, Moore L, Sieggreen M. Revised national pressure ulcer advisory panel pressure injury staging system: revised pressure injury staging system. J Wound, Ostomy Cont Nurs: Offi Publ Wound Ostomy Contin Nurs Soc 2016;43(6). https://doi.org/10.1097/WON.0000000000000281. Article 6.
[16] Manzano F, Colmenero M, Pérez-Pérez AM, Roldán D, Jiménez-Quintana M del M, Mañas MR, Sánchez-Moya MA, Guerrero C, Moral-Marfil MÁ, Sánchez-Cantalejo E, Fernández-Mondéjar E. Comparison of two repositioning schedules for the prevention of pressure ulcers in patients on mechanical ventilation with alternating pressure air mattresses. Intensive Care Med 2014;40(11). https://doi.org/10.1007/s00134-014-3424-3. Article 11.
[17] Mervis JS, Phillips TJ. Pressure ulcers: prevention and management. J Am Acad Dermatol 2019;81(4). https://doi.org/10.1016/j.jaad.2018.12.068. Article 4.
[18] Loerakker S, Manders E, Strijkers GJ, Nicolay K, Baaijens FPT, Bader DL, Oomens CWJ. The effects of deformation, ischemia, and reperfusion on the development of muscle damage during prolonged loading. J Appl Physiol 2011;111(4):1168–77. https://doi.org/10.1152/japplphysiol.00389.2011.
[19] Wang Y, Pu L, Li Z, Hu X, Jiang L. Hypoxia-inducible factor-1α gene expression and apoptosis in ischemia-reperfusion injury: a rat model of early-stage pressure ulcer. Nurs Res 2016;65(1):35–46. https://doi.org/10.1097/NNR.0000000000000132.
[20] Coyer F, Clark M, Slattery P, Thomas P, McNamara G, Edwards C, Ingleman J, Stephenson J, Ousey K. Exploring pressures, tissue reperfusion and body positioning: a pilot evaluation. J Wound Care 2017;26(10):583–92. https://doi.org/10.12968/jowc.2017.26.10.583.
[21] Jan Y-K, Brienza DM, Boninger ML, Brenes G. Comparison of skin perfusion response with alternating and constant pressures in people with spinal cord injury. Spinal Cord 2011;49(1):136–41. https://doi.org/10.1038/sc.2010.58.
[22] Källman U, Engström M, Bergstrand S, Ek A-C, Fredrikson M, Lindberg L-G, Lindgren M. The effects of different lying positions on interface pressure, skin temperature, and tissue blood flow in nursing home residents. Biol Res Nurs 2015;17(2):142–51. https://doi.org/10.1177/1099800414540515.
[23] Karg P, Ranganathan VK, Churilla M, Brienza D. Sacral skin blood flow response to alternating pressure operating room overlay. J Tissue Viability 2019;28(2):75–80. https://doi.org/10.1016/j.jtv.2019.03.001.
[24] Rithalia SV. Evaluation of alternating pressure air mattresses: one laboratory-based strategy. J Tissue Viability 2004;14(2):51–8. https://doi.org/10.1016/s0965-206x(04)42002-6.
[25] Scheel-Sailer A, Frotzler A, Mueller G, Annaheim S, Rossi RM, Derler S. Challenges to measure hydration, redness, elasticity and perfusion in the unloaded sacral region of healthy persons after supine position. J Tissue Viability 2015;24(2):62–70. https://doi.org/10.1016/j.jtv.2015.03.002.
[26] Lupiáñez-Pérez I, Gómez-González AJ, Marfil-Gómez RM, Morales-Asencio JM, García-Mayor S, León-Campos Á, Kaknani-Uttumchandani S, Moya-Suárez AB, Aranda-Gallardo M, Morilla-Herrera JC. Tissue temperature, flux and oxygen of sacral and trochanteric area under pressure of healthy subjects: a quasi-experimental study. J Tissue Viability 2021. https://doi.org/10.1016/j.jtv.2021.01.006.
[27] García-Mayor S, Morilla-Herrera JC, Lupiáñez-Pérez I, Kaknani Uttumchandani S, León Campos Á, Aranda-Gallardo M, Moya-Suárez AB, Morales-Asencio JM. Peripheral perfusion and oxygenation in areas of risk of skin integrity impairment exposed to pressure patterns. A phase I trial (POTER study). J Adv Nurs 2018;74(2). https://doi.org/10.1111/jan.13414. Article 2.
[28] Kottner J, Black J, Call E, Gefen A, Santamaria N. Microclimate: a critical review in the context of pressure ulcer prevention. Clin BioMech 2018;59:62–70. https://doi.org/10.1016/j.clinbiomech.2018.09.010.
[29] Dai B, Gu C, Zhao E, Qin X. Statistical model optimized random forest regression model for concrete dam deformation monitoring. Struct Control Health Monit 2018;25(6):e2170. https://doi.org/10.1002/stc.2170.
[30] Shih S-Y, Sun F-K, Lee H-y. Temporal pattern attention for multivariate time series forecasting. Mach Learn 2019;108(8):1421–41. https://doi.org/10.1007/s10994-019-05815-0.
[31] Jamovi. (n.d.). [Software] (2.3.21).
[32] Kottner J, Dobos G, Andruck A, Trojahn C, Apelt J, Wehrmeyer H, Richter C, Blume-Peytavi U. Skin response to sustained loading: a clinical explorative study. J Tissue Viability 2015;24(3):114–22. https://doi.org/10.1016/j.jtv.2015.04.002. Embase.
[33] Völzer B, Kottner J. Associations between skin structural and functional changes after loading in healthy aged females at sacral and heel skin: a secondary data analysis. J Tissue Viability 2022;31(2):239–44. https://doi.org/10.1016/j.jtv.2022.01.010.
[34] Li Z-Y, Wang Y, Xin Q, Lu C-H, Li J-P, Zhang L-L. [assessment of the effects of pressure on sacrum tissue oxygenation using near infrared spectroscopy]. Guang Pu Xue Yu Guang Pu Fen Xi = Guang Pu 2011;31(6):1490–3.
[35] Ceylan B, Yapucu Gunes U, Uyar M. Examination of sacral tissue oxygen saturation among immobile patients. J Clin Nurs 2018;27(19-20):3641–51. https://doi.org/10.1111/jocn.14218.
[36] Kuliga KZ, Gush R, Clough GF, Chipperfield AJ. Time-dependent behavior of microvascular blood flow and oxygenation: a predictor of functional outcomes. IEEE Trans Biomed Eng 2018;65(5):1049–56. https://doi.org/10.1109/TBME.2017.2737328.
[37] Hall J. Guyton y hall. Tratado de fisiología médica. thirteenth ed. 2016.
[38] Pan X, Chen G, Wu P, Han C, Ho JK. Skin perfusion pressure as a predictor of ischemic wound healing potential. Biomed Rep 2018;8(4):330–4. https://doi.org/10.3892/br.2018.1064.
[39] Tzen Y-T, Brienza DM, Karg PE. Implementing local cooling to increase skin tolerance to ischemia during normal seating in people with spinal cord injury. J Tissue Viability 2019;28(4):173–8. https://doi.org/10.1016/j.jtv.2019.09.006.