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A sensitivity analysis to evaluate the performance of temporal pressure - related parameters in detecting changes in supine postures

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ABSTRACT

Pressure mapping systems have been traditionally used to assess load distributions in individuals at risk of pressure ulcers. Recently, the technology has been adapted to monitor pressures over prolonged periods. The present study aims to investigate the predictive ability of selected biomechanical parameters estimated from pressure distributions for detecting postural changes in lying.

Healthy participants ($n = 11$) were recruited and positioned in different lying postures, by utilizing the head of bed (HOB) angle and an automated tilting system to achieve evoked movements in the sagittal and transverse planes, respectively. Measurements included continuous monitoring of interface pressures and accelerations from the trunk and waist. Selected interface pressure parameters included; centre of pressure, contact area and pressure gradient. A threshold range for all parameters was established and Receiver Operating Characteristic (ROC) curves presented to determine the sensitivity and specificity for detecting postural changes.

Temporal trends in the data revealed significant variance in the signal perturbations during each evoked postural change. Indeed, sensitivity and specificity were influenced by the specific threshold values and the relative position of the individual. As an example, sensitivity of some parameters exhibited a compromised trend at higher HOB angles, with low corresponding area under the ROC curve. By contrast, contact area provided the highest values, with 7/12 signals achieve AUC >0.5. This corresponded with actimetry signals, which provided high discrimination between postures.

Parameters estimated from a commercial pressure monitoring can have the potential to detect postural changes. Further research is required to convert the data into meaningful clinical information, to inform patient repositioning strategies.

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1. Introduction

There are many situations where skin and underlying soft tissues are compromised by prolonged mechanical loading, particularly in individuals with restricted mobility. This can result in the breakdown of skin and soft tissues, typically over bony prominences, commonly termed pressure ulcers (PUs). Individuals with PUs have reduced quality of life [1] and their treatment costs represent a significant burden on healthcare providers [2]. The prevention of PUs therefore represents a high priority in all healthcare institutions. However, despite increased awareness and interventions to improve the efficiency of preventative strategies, the incidence in both the acute and community settings has remained unacceptably high, contributing an estimated wound care cost of £4 billion per annum in the UK [3].

In order to reduce the risk of developing PUs, international and national guidelines recommend frequent repositioning (2–4 h) [4]. This generally involves periodic redistribution of loads between the individual and a support surface (bed or chair) through postural changes. The associated movements are designed to provide periodic pressure relief to previously loaded areas. This is typically achieved through self-evoked movements, or where mobility is limited, by clinicians and carers who manually adjust the individual's posture. However, this manual strategy can be time consuming and labour intensive, with estimated costs between €200 and €250 per patient over a four week period [5]. Accordingly, in many healthcare settings where resources are limited, the frequency and magnitude of movements recommended for PU prevention are not regularly followed [6]. In addition, a recent study demonstrated that even experienced practitioners perform repositioning manoeuvres inconsistently, and, in some cases, critical sites such as the sacrum the pressure relief is inadequate for tissues to recover [7]. Furthermore, although regular repositioning

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is considered to represent an effective preventative strategy, it is inconsistently performed in practice. Moreover, there is limited evidence supporting the relationship between frequency of movements and reduction in PU incidence, which may be highly dependent on the individual susceptibility [8].

A number of biomechanical measurements have been used to assess postural movements. In particular, pressure measurements at the interface between the individual and support surface have been extensively used in both research and clinical settings [9]. Research has revealed that postural changes can have a significant effect on interface pressure both in terms of magnitude and distribution [10]. In the clinical setting, pressure mapping systems are typically used as a visual feedback to optimise individual repositioning and prescribe cushions and mattresses for pressure redistribution [11]. However, these assessments are typically performed either at a single time point or averaged over relatively short time periods, providing a "snap shot" of the interface conditions. Accordingly, the interpretation of this pressure signature can at best provide a limited overview of the long-term effects of different postures and it is not indicative of the magnitude and frequency of the postural changes, either through natural or evoked movements [12].

The literature reveals a significant number of studies using wearable sensors to assess both the frequency and the magnitude of individuals' postural movements. The measures of the tilt angles at a specific body sites, estimated from actimetry signals, were reported to accurately discriminate between postural changes in different anatomical planes [13–15]. Therefore, the use of actimetry systems have become popular in both research and clinical settings, to evaluate the effectiveness of relief strategies in individuals at risk of developing PUs [16,17]. As an example, in recent randomised control trials utilising actimetry, authors reported that the provision of optimal turning was enhanced with a wearable patient sensor [18,19]. In addition, individuals in intensive care settings were more likely to comply with repositioning over longer time periods and this was associated with a reduced incidence of in PUs [18].

A few studies have combined interface pressure measurements with actimetry to assess the efficacy of the postural changes in offloading vulnerable soft tissue areas [13,17,20]. However, the magnitude of movements were typically not achieved with traditional repositioning strategies [6] and there was only a weak correlation between interface pressures at the buttock region and segmental changes in body postures [16]. Therefore, although actimetry systems provide a reference for position and movement detection, they cannot characterise the mechanical conditions at the patient – support interface.

There is clearly a requirement to provide a robust objective measure of the effectiveness of pressure relieving strategies, involving both the position of body segments and the conditions at the body-support interface. Recently, pressure mapping systems have been adapted to record pressure distributions over periods of up to 72 h [21]. This provides the opportunity to estimate different temporal biomechanical parameters at the patient interface, which have the potential to evaluate postural changes, either natural or evoked. However, these systems have not been examined as to whether they can identify whether these temporal signals are sensitive and specific to particular postural movements. Accordingly, the current study aims to interrogate different biomechanical parameters estimated from a commercial pressure monitor to distinguish specific postural changes during a range of defined supine positions. The sensitivity and specificity of these temporal pressure values to detect posture changes will be compared with the performance of the signals estimated from an actimetry system.

2. Materials and methods

2.1. Participants

Eleven healthy participants (6 male and 5 female) were recruited from the local University community. Exclusion criteria included participants with a history of skin conditions, neurological or vascular pathologies which could affect tissue health or those who were unable to lie in a supine position for a period of 2 h. University of Southampton Ethics was granted for the study (Ref: 26379) and informed consent was obtained from each participant prior to testing. Participants were aged between 25 and 37 years (mean = 32 years) with an average height and weight of 1.72 ± 0.51 m and 71.2 ± 25.2 kg, respectively. The corresponding BMIs ranged between 20.4 to 30.1 kg/m^2.

2.2. Test equipment

Interface pressure measurements were recorded using a full body pressure monitoring system (ForeSite PT, XSENSOR Technology Corporation, Canada), in the form of a fitted mattress cover. It incorporates 5664 pressure measuring sensor cells, with a spatial resolution of 15.9 mm, covering a sensing area of 762 mm x 1880 mm. Each sensor operates within a range of 5–200 mmHg (0.7–26.6 kPa), with an accuracy $\pm$ 2 mmHg and an acquisition rate of 1 Hz. Four wearable sensors (Shimmer Platform, Realtime Technologies Ltd, Dublin, Ireland) measured trunk and waist movements, attached to the sternum and the left and right anterior iliac crests with a Velcro strap (Fig. 1). Each device represents a small wireless sensor (53 mm x 32 mm x 25 mm), integrating a triaxial accelerometer and gyroscope, that recorded real-time calibrated Euler angles data at 51 Hz (range $\pm$ 2 g).

2.3. Test protocols

All test procedures were performed in the Biomechanics Testing Laboratory in the Clinical Academic Facility in Southampton General Hospital, where room temperature was maintained at $24° \pm 2°$. Participants were requested to wear loose fitting clothing and adopt a series of postures on a standard hospital bed frame (AvantGuard^{TM,} Hill-Rom, US) and mattress with castellated foam surface (Solace Foam Mattress, Invacare UK). Prescribed sagittal movements started in the supine posture followed by raising the head of bed (HOB) by 10° increments to a maximum of 60°, representing a high cardiac posture (Fig. 1A-D). The HOB was then lowered in 10° increments until the supine posture was re-established. Each posture was evoked by the researcher using the bed frame control and held for a period of 10 min. The subsequent movements involved 20–25° tilting the mattress in the transverse plane on an automated 10 min cycle time (Fig. 1E-F) using a continuous lateral rotational system (CLRS) (Vikta Komfitilt®), placed underneath the mattress. Interface pressure distributions and accelerometers data were continuously recorded throughout the two hour test period. Participants were instructed to remain as still as possible on the mattress, so that the movements were evoked either through the bed frame or the CLRS device.

2.4. Outcome parameters

Pressure distributions and accelerometer signals were processed and analysed using custom software developed in Matlab (Mathworks, US). The temporal profile of the tilt angles in the sagittal and transverse planes were estimated from the accelerometer data and re-sampled at 1 Hz. The corresponding profiles of the three

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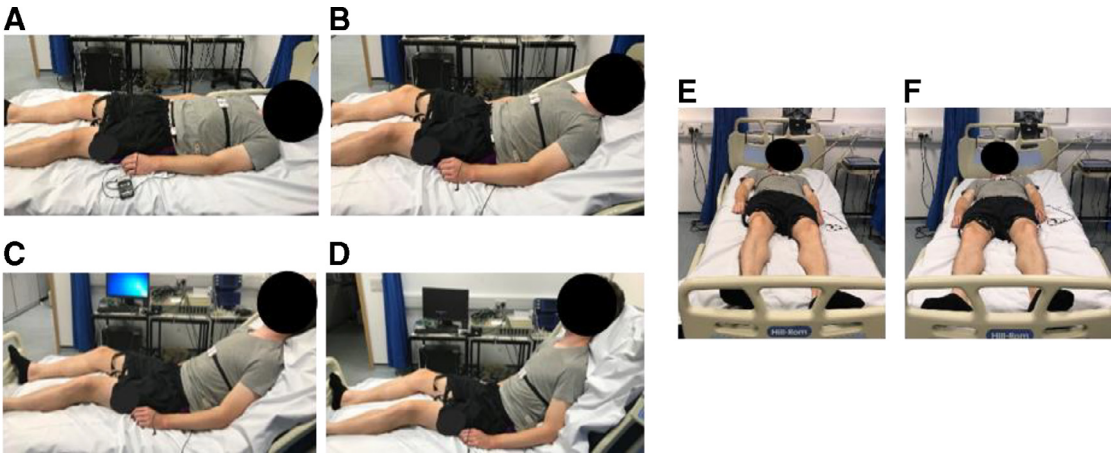

Fig. 1. Images of the sagittal and lateral postures: Supine (A), 20° increment of the HOB (B), 40° increment of the HOB (C), 60° increment of the HOB (D), 20° increment of the HOB (B), left and right lateral turning (E, F).

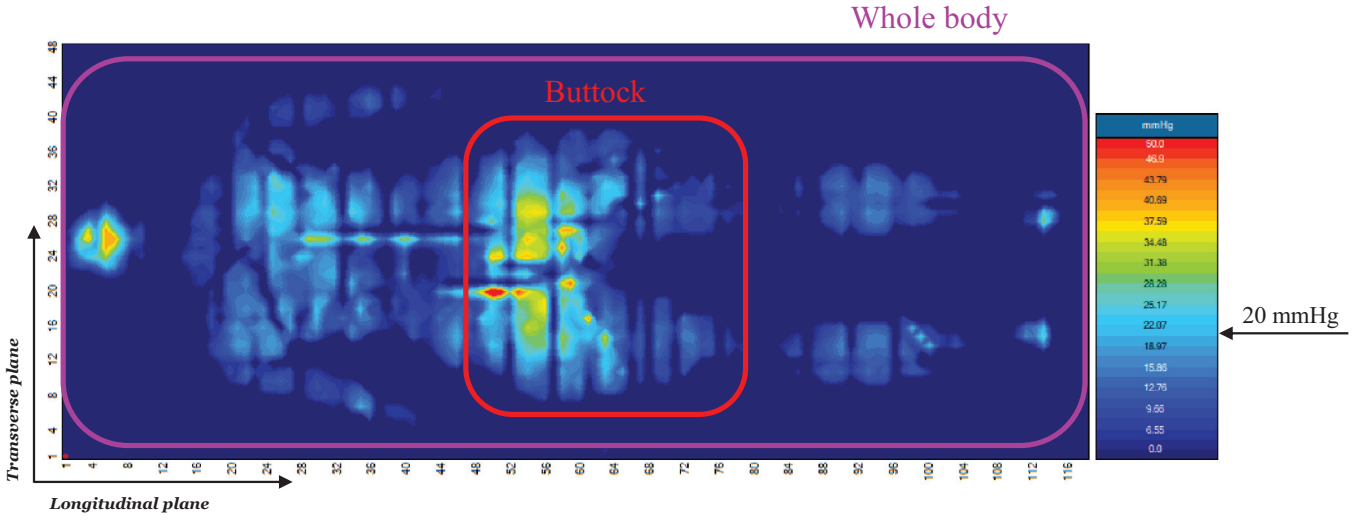

Fig. 2. ROIs selection from the distributions of the pressure. The colour gradient of the pressure distribution is associated with a scale bar (scale on the right), which represents the pressure range between 0 and 50 mmHg. The pressure values below 20 mmHg, approximated by most shades of blue, were not included in the analysis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

biomechanical signals calculated from the pressure distributions were:

- centre of pressure (COP), defined as the centroid of the distribution;
- contact area (CA) between the mattress and the individuals in which sensors record a pressure of or above a minimum threshold of 20 mmHg;
- peak pressure gradient (PG) in a direction perpendicular to the long axis of the mat, which describes the maximum change in pressure between adjacent sensing cells.

Each parameter was estimated from two distinct regions of interest (ROIs), namely, the whole body and buttock area (Fig. 2). Upper and lower body ROIs were not included in the analysis as they were affected by signal deviations for natural movements in the legs, arms and head. Lower pressure values were subjected to increase noise in the signal due to small postural shifts, naturally performed by participants. Accordingly, for the estimation of contact area pressure readings above a 20 mmHg (2.7 kPa) threshold were included, as they were most indicative of evoked postural movements. The pressure gradient was evaluated only in the direction perpendicular to the long axis of the mat, as it was observed that with sagittal movements there was a higher deviation in values across the width of the mat.

2.5. Post – processing and analysis of data

A series of distinct processes were performed to optimise the data for analysis. Briefly, all signals were filtered using a moving average filter with a window length of 15 samples to remove the high frequency noise. Subsequently, these signals were manually labelled denoting each posture. Both the amplitude of the signal changes between the postures and the deviations during each posture were estimated for all outcome parameters. The descriptive pressure data were expressed as median ± interquartile (IQ) values for all the participants. By contrast, the descriptive tilt angles data were expressed as mean ± standard deviation (SD). Appropriate threshold ranges, detailed in Table 1, were selected for each of the parameters.

Sensitivity and specificity to detect postural changes for each threshold value were then estimated for all biomechanical signals and presented as a percentage of the cohort ($n = 11$). Sensitivity was calculated by assessing the number of cases in which a biomechanical signal, with respect to each threshold level, correctly classified a specific postural change, i.e. a true positive, as depicted in

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Table 1
Summary of the threshold levels for each of the biomechanical parameters.

Biomechanical parameters	Threshold levels				
COP [mm]	5	10	20	30	
PG [mmHg/mm]	0.1	0.2	0.3	0.4	0.5
CA [% variation]	5	10	15	20	25
Tilt angles [degree]	2	4	6	8	10

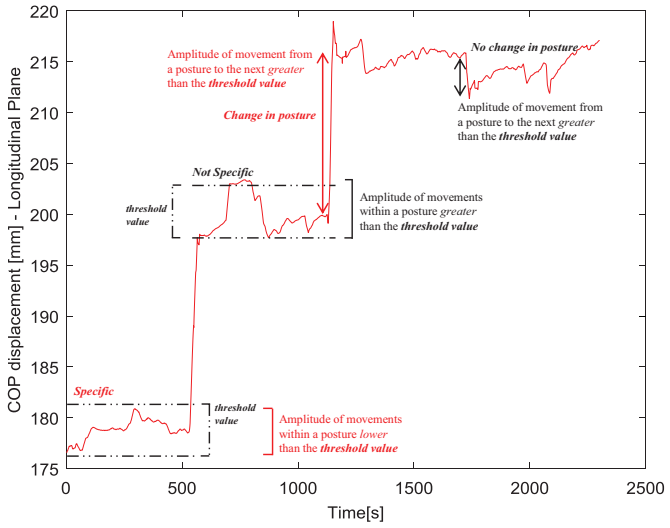

Fig. 3. Characteristic features of four postures related to the COP displacements at the buttock. A pre – determined threshold value, represented by the dotted lines, has been selected to denote the sensitivity and specificity analyses. A specific change in posture (true positive) was identified where the amplitude of the movement in the change in posture was greater than the selected threshold value. A true negative was identified where the amplitude of the movements within a posture did not exceed the threshold value.

Figure 3. Specificity was calculated for each posture as the proportion of cases where the biomechanical signals did not exceed the selected threshold level during the 10 min static posture i.e. a true negative (Fig. 3). Specificity during the lateral tilting was not evaluated, as the turning system did not produce significant spatial changes in any of the parameters during the static lateral postures.

Receiver Operating Characteristic (ROC) analysis, performed within Matlab (MathWorks, US), was used to determine the optimal range of parameters, which discriminate between the presence and absence of postural changes. Each of the biomechanical signals and the possible thresholds were examined to identify the combination with the optimal sensitivity and specificity for all evoked movements. The area under the ROC curve (AUC), which plots sensitivity versus (100 – specificity) [22], was calculated to assess the overall accuracy in discriminating postural changes for each signal. AUC quantifies the probability that the test correctly discriminates the presences or absences of a postural movement, ranging from 0 to 1. An AUC of 0.5 suggests no discrimination between true positive and true negative condition, while a value of 1 indicates a perfect discrimination. The lowest threshold value is the point closest to the top left corner of the ROC curve.

3. Results

As illustrated in Figure 4, the temporal trends of both interface pressure parameters and tilt angles are characterized by incremental steps coinciding with the evoked movements in the HOB angles (Fig. 4A and B) and the CLRS system (Fig. 4C and D). It is evident that the changes in HOB angles are clearly reflected in the tilt angles in the sagittal plane with similar increments between each posture (Fig. 4B). However, the increments in the COP displacements at the buttock ROI revealed differences in the magnitude during the test protocol, with only small increments observed when the HOB exceeded 40°. In addition, when the HOB was lowered, some hysteresis was evident in the COP values (Fig. 4A).

3.1. Sagittal postural changes

Table 2 summarises the interface pressure parameters at both ROIs and the tilt angles at the trunk and waist, associated with the sagittal movements. It is evident that for whole body and buttock ROIs from supine to 10° HOB there is limited change in the median COP value (<5 mm). Subsequent magnitudes in signal change at the whole body ROI were larger and approximately equivalent up to maximum HOB angles. When the HOB was lowered, the displacements were relatively small, until lower angles (HOB < 30°) where they increased again. By contrast, signal changes at the buttock ROI were smaller for HOB angles >30°. However, at lower HOB angles the displacements were larger and approximately equivalent, while the final transition from 10° HOB to supine yielded a median COP in the buttock of >24 mm. With respect to the contact area for both ROIs, the percentage changes were relatively small with median values less than 6% and 18% for whole body and buttock, respectively when the HOB angle was raised up to 30°. The values increased for high HOB angles reaching the maximum percentage variation at 60°, and subsequently decreased when the HOB was lowered. The percentage changes were ~ 2–4 fold greater at the higher HOB angles. Pressure gradient signals revealed considerable variability and few trends with respect to HOB angles. Sagittal tilt angles at the trunk and waist revealed similar changes for each incremental HOB angle (Table 2). However, in the final postural change from 10° HOB to supine these changes were considerably smaller at both body sites.

3.2. Lateral postural changes

Results showed changes in specific parameters during lateral turning (Table 3). Changes in median COP displacements in excess of 11 mm were observed in both whole body and buttock ROIs during the turning stages. However, the data revealed almost a two fold increase in the median values when turning to the right compared to the left. This was associated with a corresponding decrease in the contact area, with percentage reductions of <20% and >30% for whole body and buttock, respectively. As with the sagittal plane movements (HOB), pressure gradients revealed only small magnitude changes with large variability in both ROIs. The tilt angles measured at the trunk and pelvis indicated only moderate lateral turns were achieved (<10°), with higher angles measured at the trunk than at the waist.

3.3. Sensitivity and specificity analyses

Sensitivity and specificity to detect evoked postural changes for each of the parameters were assessed at each of the defined threshold levels (Table 1).

3.3.1. Postural changes in the sagittal plane

The relative inclination of the bed angle had a significant effect on sensitivity of both ROIs. As an example, the sensitivity of the COP estimated from the buttock ROI for each threshold is presented in Figure 5A. It was evident that at low HOB angles (<40°) the smallest threshold (5 mm) was sensitive to detect postural changes (55–92%). By contrast, when the HOB exceeded 40° the corresponding sensitivity reduced (10–40%). The sensitivity of the whole body COP revealed a similar trend with values decreasing from supine to 10° HOB (approximately 35%) and from 60° to

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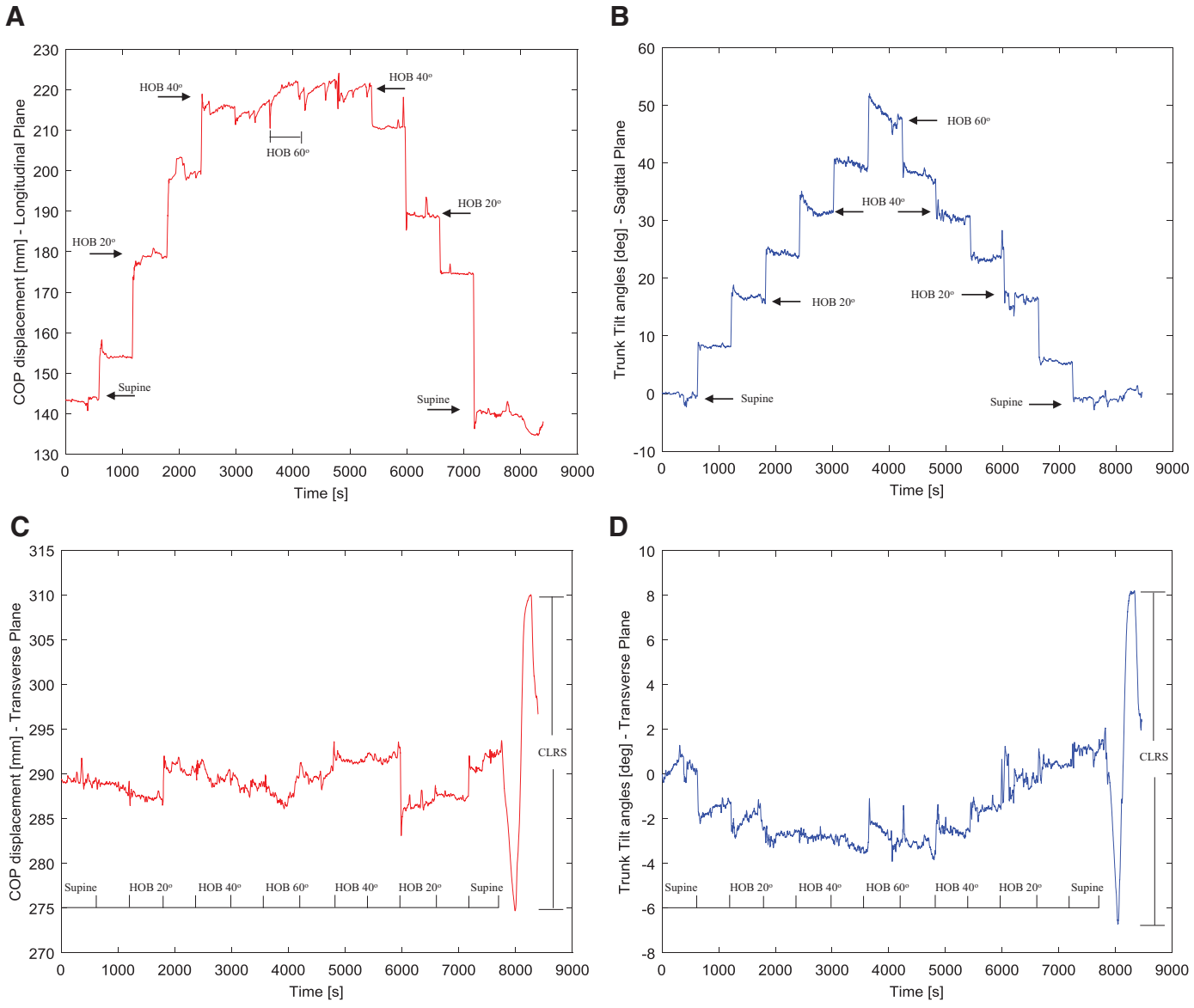

Fig. 4. Temporal trends of the displacement of the COP at the buttock area in the longitudinal plane (A) and transverse plane (C) and the tilt angles of the trunk in the sagittal plane (B) and transverse plane (D).

Table 2
Summary of the median (interquartile) values of the interface pressure parameters estimated at the whole body and buttock ROIs and the mean (standard deviation) of tilt angles estimated at the trunk and waist, during sagittal changes in posture.

	Sagittal postural changes							
	COP [mm]		CA [% variation]		PG [mmHg/mm]		Tilt angle [degree]	
	Whole Body	Buttock	Whole Body	Buttock	Whole Body	Buttock	Trunk	Waist
Supine – 10°	3.4 (0.5)	4.8 (0.6)	3.2 (6.1)	11.1 (9.4)	0.8 (9.4)	0.1 (3.5)	8.2 (1.5)	5.4 (3.6)
10°–20°	17.5 (0.6)	13.4 (0.8)	4.6 (6.8)	5.5 (15.3)	1.0 (8.2)	0.2 (1.8)	8.3 (1.1)	5.6 (3.5)
20°–30°	13.4 (0.5)	11.7 (0.5)	5.6 (9.8)	17.7 (16.7)	0.5 (8.0)	0.4 (3.9)	7.6 (4.3)	6.8 (3.3)
30°–40°	20.6 (2.1)	12.6 (0.5)	13.6 (9.9)	30.2 (21.9)	0.3 (6.3)	0.2 (1.6)	9.1 (2.5)	5.2 (1.7)
40°–50°	15.1 (1.4)	3.9 (0.8)	15.4 (20.6)	31.1 (12.4)	0.5 (14.3)	0.4 (8.5)	8.7 (3.8)	4.2 (2.6)
50°–60°	12.7 (1.8)	2.3 (0.3)	22.8 (21.8)	37.1 (14.6)	0.6 (7.9)	0.6 (8.1)	9.4 (3.7)	5.4 (2.6)
60°–50°	7.3 (0.2)	2.9 (0.4)	35.1 (21.0)	41.9 (21.0)	0.5 (9.0)	0.3 (7.7)	7.5 (2.4)	6.1 (3.5)
50°–40°	6.0 (1.4)	2.0 (0.3)	20.7 (9.7)	32.8 (8.7)	0.8 (5.3)	0.3 (3.8)	7.2 (2.7)	6.7 (3.5)
40°–30°	4.3 (0.4)	5.0 (0.4)	19.4 (15.2)	33.4 (11.6)	0.4 (9.1)	0.3 (6.7)	8.7 (1.9)	7.6 (2.7)
30°–20°	11.4 (1.3)	9.0 (0.7)	16.5 (6.3)	23.5 (8.0)	0.4 (15.2)	0.1 (2.5)	8.4 (2.7)	6.3 (2.3)
20°–10°	16.7 (1.4)	14.3 (0.4)	10.5 (10.6)	19.6 (9.8)	0.6 (7.1)	0.2 (4.1)	8.8 (2.4)	6.2 (3.0)
10°–Supine	19.2 (1.0)	24.4 (1.0)	6.6 (5.7)	9.3 (15.7)	0.2 (5.9)	0.3 (2.4)	5.7 (0.8)	2.2 (1.9)

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Table 3
Summary of the median (interquartile) values of the interface pressure parameters estimated at the whole body and buttock ROIs and the mean (standard deviation) of tilt angles estimated at the trunk and waist, during the postural changes in the transverse plane.

	Lateral postural changes							
	COP [mm]		CA [% variation]		PG [mmHg/mm]		Tilt angles [degree]	
	Whole Body	Buttock	Whole Body	Buttock	Whole Body	Buttock	Trunk	Waist
Left turning	11.4 (0.8)	11.4 (0.5)	9.6 (7.3)	11.5 (6.1)	0.7 (3.9)	0.4 (4.2)	8.2 (1.8)	5.3 (1.9)
Right turning	24.0 (1.0)	18.3 (0.7)	7.9 (6.6)	7.6 (5.1)	0.9 (2.5)	0.3 (0.1)	8.3 (2.5)	5.6 (3.5)

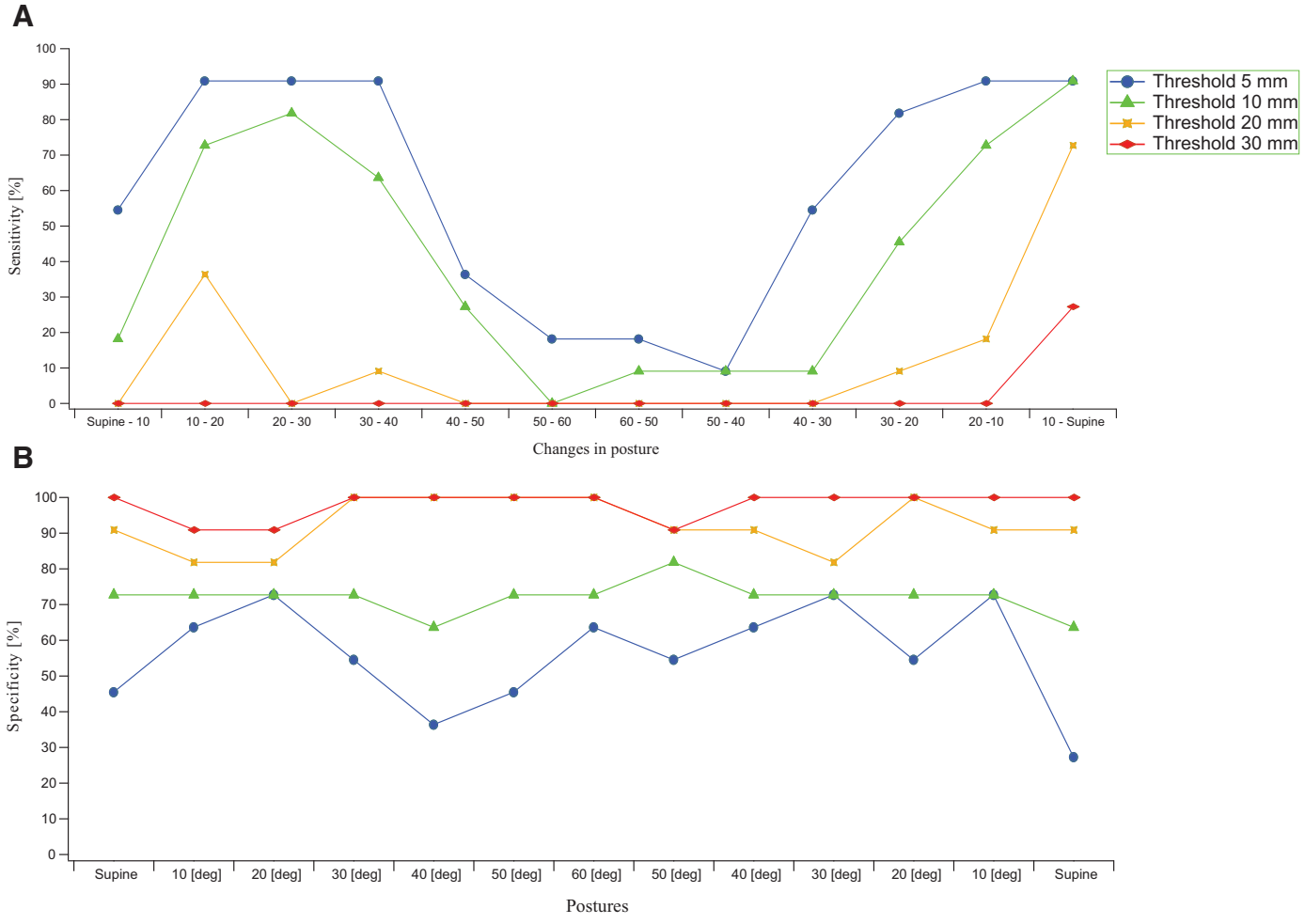

Fig. 5. (A) Sensitivity trend in evaluating spatial changes in buttock ROI for COP displacements. (B) Specificity trend in evaluating spatial changes during static in buttock area for COP displacements. Each curve represents the trend with respect a specific threshold value, ranging between 5 mm and 30 mm. Each data point represents the sensitivity (A) or the specificity (B) value [%], across all participants, for a specific threshold value.

40° HOB (35–45%) (data not shown). The sensitivity for contact areas at both ROIs yielded the highest percentage values at elevated HOB angles, even at the highest threshold (25%). Moreover, pressure gradients at the buttock ROI revealed high sensitivity values for high HOB angles, whereas no specific trends in sensitivity were identified at the whole body ROI. Tilt angles at the trunk and pelvis demonstrated a wide-range of sensitivity values across the threshold range, namely 2° to 10°. During the final transition from 10° HOB to supine, the sensitivity decreased to 0% for threshold value exceeding 6° and 4° for trunk and waist, respectively.

The specificity of the buttock COP for each threshold is presented in Figure 5B. It is evident that at the lowest threshold of 5 mm the specificity ranged from 27% to 70%, suggesting that the COP displacements were limited in predicting postural change. These can be compared to values of between 90 and 100% at the highest threshold of 30 mm. By contrast, the corresponding specificity often attained lower percentage values when considering the other pressure parameters at the buttock ROI (data not shown). No evident trends in the specificity values were evident for all parameters at the whole body ROI. In addition, tilt angles at the trunk and pelvis showed a wide-range of specificity values across the threshold range, with no evident trends.

3.3.2. Postural changes in the transverse plane

The sensitivity of movements in the transverse plane decreased for all parameters with increasing threshold values. This is exemplified in Figure 6 with the values estimated for the buttock COP. It reveals marked differences during the left and right lateral turning protocols, suggesting considerable asymmetry, which was also apparent with respect to the whole body COP and contact areas

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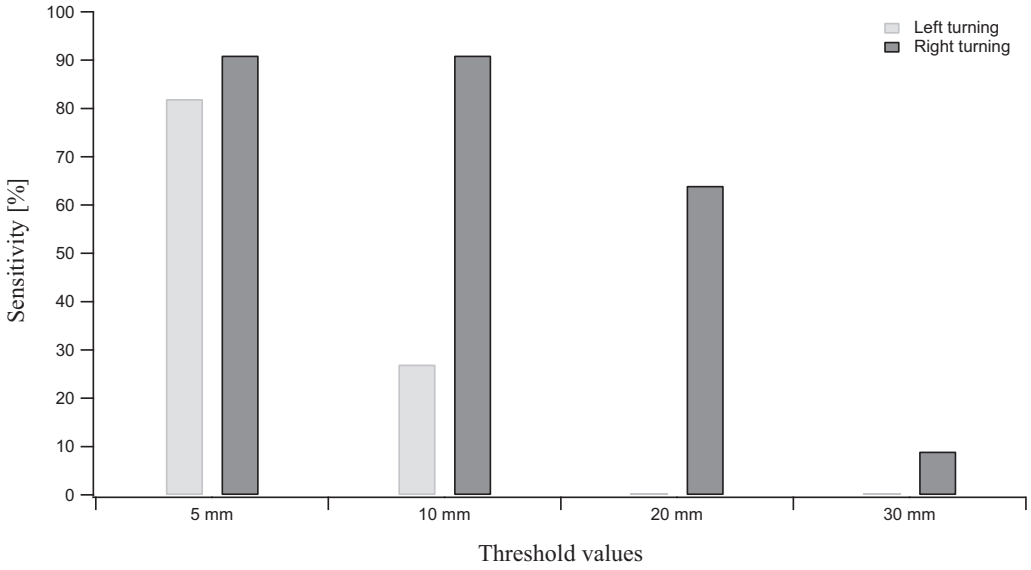

Fig. 6. Sensitivity values in detecting the changes in posture in the transverse plane during left and right turning for the buttock COP at four threshold values, ranging between 5 mm and 30 mm.

Table 4
AUC of the interface pressure parameters evaluated at the whole body and buttock area, and tilt angles evaluated at the trunk and waist, calculated from the ROC curves for all the changes in posture. * indicates AUC values which exceeded 0.5.

	AUC							
	COP		CA		PG		Tilt angles	
	Whole Body	Buttock	Whole Body	Buttock	Whole Body	Buttock	Trunk	Waist
Supine – 10°	0.06	0.12	0.16	0.31	0.01	0.27	0.53*	0.49
10°–20°	0.41	0.14	0.21	0.41	0.25	0.31	0.45	0.44
20°–30°	0.53*	0.04	0.25	0.36	0.40	0.47	0.49	0.47
30°–40°	0.61*	0.24	0.69*	0.53*	0.24	0.27	0.59*	0.45
40°–50°	0.36	0.14	0.59*	0.54*	0.22	0.41	0.64*	0.29
50°–60°	0.48	0.03	0.74*	0.61*	0.33	0.51*	0.80*	0.60*
60°–50°	0.31	0.03	0.71*	0.74*	0.26	0.48	0.81*	0.56*
50°–40°	0.21	0.03	0.71*	0.72*	0.30	0.34	0.55*	0.47
40°–30°	0.17	0.04	0.71*	0.71*	0.22	0.40	0.68*	0.68*
30°–20°	0.41	0.03	0.53*	0.55*	0.24	0.21	0.61*	0.50*
20°–10°	0.58*	0.27	0.31	0.43	0.30	0.22	0.59*	0.51*
10°–Supine	0.56*	0.19	0.23	0.19	0.14	0.40	0.27	0.09

(Table 3). By contrast, pressure gradients showed similar sensitivity values for each turning protocol.

3.4. ROC analyses

Examples of ROC curves for each of the postural changes for both the tilt angles at the trunk and the COP displacement of the buttock ROI are presented in Figure 7A and B, respectively. There are clear differences in the trends of these ROC curves. With respect to the tilt angles at the trunk, all the curves are above the dashed reference line, which denotes AUC = 0.5. By contrast, with respect to the COP displacements a number of curves, associated with higher HOB angles, are either below the line or do not incorporate the full range of sensitivity/specificity. This suggests a limited ability for these signals to detect these specific postural changes within the specified threshold ranges.

Table 4 summarises the AUC estimated for all the ROC curves associated all the biomechanical parameters. In all cases, the AUC values clearly vary with the relative posture of the individual. The initial movement from supine to 10° HOB had limited predictive capacity in the pressure – related parameters, yielding an AUC value < 0.31. In the majority of these pressure – related parameters, the AUC values did not exceed the 0.5 threshold. By contrast, the AUC values estimated from the contact area did exceed this threshold, indicating a good predictive capacity when HOB angles >20°. With respect to the accelerometer parameters, the majority of AUC values exceeded 0.5. The only exception to this finding was the relatively low AUC values (<0.27) associated with the trunk and waist when individuals changed posture from 10° HOB to supine.

4. Discussion

Examining the efficacy of repositioning strategies represents an important clinical challenge in pressure ulcer prevention. Several commercial sensing technologies are available to continuously measure how individual move in bed and chairs [23]. However, there is a lack of validated technologies, for example with respect to pressure mapping, where the effectiveness of relief strategies can be monitored in a robust objective manner.

The present study has evaluated biomechanical measures estimated at the body – support surface interface from a commercially available pressure monitoring system, to assess their capacity in detecting evoked postures in sagittal and transverse planes. In addition, segmental tilt angles estimated from an actimetry system positioned at the trunk and waist were used to provide a relative

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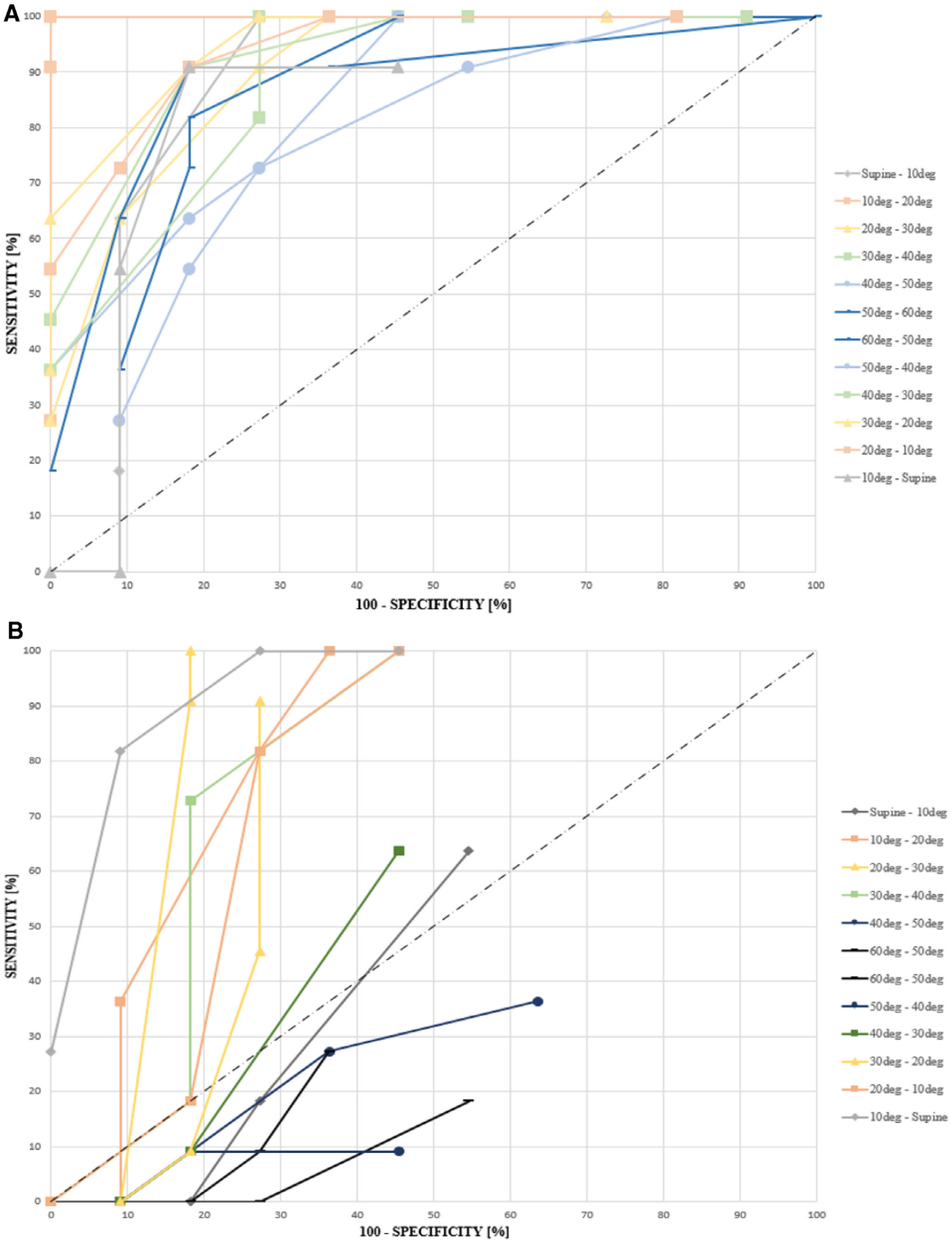

Fig. 7. ROC curves across all changes in posture for tilt angles evaluated at the trunk (A) and COP displacements at the buttock ROI (B). Each data point represents a sensitivity/specificity pair corresponding to a specific decision threshold. The threshold values increase from the right side to the left side of the curve.

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comparison of postural movement detection. The results revealed that there are limitations to the sensitivity and specificity of some of the interface pressure parameters to detect postural changes, depending on the angle of the HOB. As an example, the COP at the buttock ROI demonstrated low sensitivity at higher HOB angles i.e. >40° (Table 2 and Fig. 5A), and high specificity during each static postures, denoting limited COP displacements (Fig. 5B). This affected the capacity of this parameter to discriminate sagittal postural changes, as revealed by the ROC analysis (Fig. 7B) and the corresponding low AUC values (Table 4). Pressure gradient revealed a relatively poor predictive capacity in discriminating different postures. By contrast, the contact area estimated at both ROIs represented the best predictor of the interface pressure parameters, depicting the evoked postures when HOB angle exceeded 20°. Small changes in the interface pressure parameters during lateral turning indicated a limited redistribution of pressure, particularly evident in the buttock area. Our findings confirmed that the most robust signal to determine sagittal postural changes were derived from actimetry signals estimated at the trunk [24], which could accurately depict the majority of the evoked postures.

Previous research has examined the distribution of pressure to classify different postures [25–27], and evaluate the efficacy of individual postural changes by means of short periods of monitoring [8], providing an effective snap shot of the conditions at the body – support interface. This short – term monitoring approach clearly provides an inadequate representation of the temporal information and thus can not estimate the magnitude and the frequency of movements associated with repositioning and off – loading of vulnerable tissues. In some cases, a threshold value of 32 mmHg, which represents the closing pressure measured at the nail fold capillaries [28], is widely cited as a critical pressure for PU risk. However, this reference value is considered inappropriate as it does not accurately represent the internal stresses/strains within the tissues, which cause damage. Nevertheless, this pressure has been incorporated as a threshold into an algorithm of a current pressure monitoring system (e.g. ForeSite PT) to predict inadequate movements within an associated risk of tissue damage.

More advanced support surfaces including alternating pressure air mattresses and automated tilting systems, are designed to periodically relieve support pressures particularly for the immobile individuals. However, their benefits over the more economical foam mattress have not been fully demonstrated [29,30]. Despite the advances in support surface technology, involving a range of interface materials, the number of PUs remains unacceptably high. It is evident that there is a clear need for robust and reliable parameters that can objectively assess the efficacy of individual postural changes. This requires further research utilising combined biomechanical and physiological responses, to establish the relative effects of prolonged postures on the tissue response, relative to an individual tolerance [31–33].

The present study revealed that pressure monitoring had the potential to provide objective measures that can act as surrogate for postural movements. This new approach demonstrated that some of the interface pressure parameters at specific regions of interest (e.g. contact area) proved good predictors for detecting incremental changes in postures, depending on HOB angles. Furthermore, the capacity in detecting postural changes was also influenced by the corresponding specific threshold values. In some cases, the selected thresholds could not encompass the full range of sensitivities and specificities. This is reflected in the incomplete curves in Figure 7B and the corresponded low AUC values (Table 4).

It is inevitable that the use of a young able – bodied cohort in the present study precludes generalising the findings to all specific sub – populations deemed to be at risk of developing pressure ulcers i.e. elderly, the spinal cord injuries and those individuals in intensive care units. Further limitations of the study protocol involve a pre-determined order of small postural changes (10° increments) following a relative short period of 10 min in which each posture was maintained. Thus, future studies should examine fewer postures maintained for extended periods involving HOB increments changes of 20°. Future studies should examine also the movements performed at the upper body and lower body ROI and, in addition, estimate both the magnitude and frequency of movements.

In the light of our findings, a collection of signals estimated from both pressure mapping and actimetry system could accurately track postures and mobility during different relief strategies. They could also, whilst provide critical information with respect to interface conditions, which are indicative of pressure ulcer risk. In addition, they can inform both individuals and healthcare professionals of the status of mobility of an individual, providing the scope for efficient interventions. New analyses are required to provide a systematic means of combining and reducing data from pressure mapping and actimetry in order to provide meaningful information at minimal computational costs. The development of more sophisticated algorithms able to interrogate individual positioning and mobility and establish different tissue tolerance levels can contribute to a custom – based approach to predict early tissue damage. Accordingly, future studies should examine the application of machine learning approaches on the time – related biomechanical signals to accurately classify the range and frequency of movements [34,35]. Ultimately, the research approach has to be translated into a robust and simple-to-interpret data, from pressure monitoring and/or actimetry systems, in the clinical setting.

5. Conclusion

The present study revealed that a selected number of biomechanical parameters estimated from a commercial pressure monitoring system were capable of detecting a range of supine postures in the sagittal and transverse planes. Their sensitivity and specificity were affected by both threshold values of the parameters and the relative position of the individuals. Contact areas at both the whole body and buttock ROIs were identified as the most accurate of pressure – related parameters in depicting specific postural changes. A combination of pressure monitoring and actimetry systems can provide a means to accurately assess movements in supine postures.

Conflicts of interest

There were no conflicts of interest in this study.

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Ethical approval

University of Southampton Ethics was granted for the study (Ref: 26379).

References

[1] Spilsbury K, Nelson A, Cullum N, Iglesias C, Nixon J, Mason S. Pressure ulcers and their treatment and effects on quality of life: hospital inpatient perspectives. J Adv Nurs 2007;57:494–504. doi:10.1111/j.1365-2648.2006.04140.x.
[2] Guest JF, Ayoub N, McIlwraith T, Uchegbu I, Gerrish A, Weidlich D, et al. Health economic burden that different wound types impose on the UK's national health service. Int Wound J 2017;14:322–30. doi:10.1111/iwj.12603.
[3] Dealey C, Posnett J, Walker A. The cost of pressure ulcers in the United Kingdom. J Wound Care 2012;21:261–2 4, 6. doi:10.12968/jowc.2012.21.6.261.

[4] National Pressure Ulcer Advisory Panel, European Pressure Ulcer Advisory Panel and Pan Pacific Pressure Injury Alliance. Prevention and Treatment of Pressure Ulcers: Clinical Practice Guideline. Haesler E, editor. Perth, Australia: Cambridge Media; 2014.
[5] Moore Z, Cowman S, Posnett J. An economic analysis of repositioning for the prevention of pressure ulcers. J Clin Nurs 2013;22:2354–60. doi:10.1111/j.1365-2702.2012.04310.x.
[6] Defloor T, Bacquer DD, Grypdonck MHF. The effect of various combinations of turning and pressure reducing devices on the incidence of pressure ulcers. Int J Nurs Stud 2005;42:37–46. doi:10.1016/j.ijnurstu.2004.05.013.
[7] Woodhouse M. Are strategies, including mechanical and traditional repositioning, effective for pressure ulcer prevention? University of Southampton; 2016.
[8] Vanderwee K, Grypdonck MHF, Bacquer DD, Defloor T. Effectiveness of turning with unequal time intervals on the incidence of pressure ulcer lesions. J Adv Nurs 2007;57:59–68. doi:10.1111/j.1365-2648.2006.04060.x.
[9] Bucki M, Luboz V, Perrier A, Champion E, Diot B, Vuillerme N, et al. Clinical workflow for personalized foot pressure ulcer prevention. Med Eng Phys 2016;38:845–53. doi:10.1016/j.medengphy.2016.04.017.
[10] Defloor T. The effect of position and mattress on interface pressure. Appl Nurs Res 2000;13:2–11. doi:10.1016/S0897-1897(00)80013-0.
[11] Wong H, Kaufman J, Baylis B, Conly JM, Hogan DB, Stelfox HT, et al. Efficacy of a pressure-sensing mattress cover system for reducing interface pressure: study protocol for a randomized controlled trial. Trials 2015;16:434. doi:10.1186/s13063-015-0949-x.
[12] Bader DL, Worsley PR. Technologies to monitor the health of loaded skin tissues. BioMed Eng OnLine 2018:17. doi:10.1186/s12938-018-0470-z.
[13] Worsley PR, Rebolledo D, Webb S, Caggiari S, Bader DL. Monitoring the biomechanical and physiological effects of postural changes during leisure chair sitting. J Tissue Viability 2017;27:16–22. doi:10.1016/j.jtv.2017.10.001.
[14] Lyden K, John D, Dall P, Grant MH. Differentiating sitting and lying using a thigh-worn accelerometer. Med Sci Sports Exerc 2016;48:742–7. doi:10.1249/MSS.0000000000000804.
[15] Edwardson CL, Rowlands AV, Bunnewell S, Sanders J, Esliger DW, Gorely T, et al. Accuracy of posture allocation algorithms for thigh- and waist-worn accelerometers. Med Sci Sports Exerc 2016;48:1085–90. doi:10.1249/mss.0000000000000865.
[16] Stinson M, Schofield R, Gillan C, Morton J, Gardner E, Sprigle S, et al. Spinal cord injury and pressure ulcer prevention: using functional activity in pressure relief. Nurs Res Pract 2013;2013:8. doi:10.1155/2013/860396.
[17] Stinson M, Ferguson R, Porter-Armstrong A. Exploring repositioning movements in sitting with 'at risk' groups using accelerometry and interface pressure mapping technologies. J Tissue Viability 2018;27:10–15. doi:10.1016/j.jtv.2017.11.001.
[18] Pickham D, Berte N, Pihulic M, Valdez A, Mayer B, Desai M. Effect of a wearable patient sensor on care delivery for preventing pressure injuries in acutely Ill adults: a pragmatic randomized clinical trial (LS-HAPI Study). Int J Nurs Stud 2017. doi:10.1016/j.ijnurstu.2017.12.012.
[19] Ifedili IA, Kennerly SM, Sabol VK, Yap TL. Implementing a visual cueing technology intervention in a nursing home: nursing staff perceptions. Geriatr Nurs 2018;39:607–9. doi:10.1016/j.gerinurse.2018.09.005.
[20] Stinson M, Schofield R, Gillan C, Morton J, Gardner E, Sprigle S, et al. Spinal cord injury and pressure ulcer prevention: using functional activity in pressure relief. Nurs Res Pract 2013;2013 Article ID 860396, 8 pages.
[21] Walia GS, Wong AL, Lo AY, Mackert GA, Carl HM, Pedreira RA, et al. Efficacy of monitoring devices in support of prevention of pressure injuries: systematic review and meta-analysis. Adv Skin Wound Care 2016;29:567–74. doi:10.1097/01.ASW.0000504579.83707.f6.
[22] Alhassan S, Robinson TN. Defining accelerometer thresholds for physical activity in girls using ROC analysis. J Phys Activity Health 2010;7:45–53. doi:10.1123/jpah.7.1.45.
[23] Conti M, Orcioni S, Madrid NM, Gaiduk M, Seepold R. A review of health monitoring systems using sensors on bed or cushion. In: Rojas I, Ortuño F, editors. Bioinformatics and biomedical engineering. Cham: Springer International Publishing; 2018. p. 347–58.
[24] Smits EJ, Winkler EAH, Healy GN, Dall PM, Granat MH, Hodges PW. Comparison of single- and dual-monitor approaches to differentiate sitting from lying in free-living conditions. Scand J Med Sci Sports 2018;28:1888–96. doi:10.1111/sms.13203.
[25] Wai AP, Foo SF, Huang W, Biswas J, Hsia C-C, Liou K, et al. Lying posture classification for pressure ulcer prevention. J Healthcare Eng 2010;1:217–38. doi:10.1260/2040-2295.1.2.217.
[26] Yousefi R, Ostadabbas S, Faezipour M, Farshbaf M, Nourani M, Tamil L, et al. Bed posture classification for pressure ulcer prevention. In: Proceedings of the annual international conference of the IEEE engineering in medicine and biology society IEEE engineering in medicine and biology society annual conference; 2011. p. 7175–8.
[27] Rus S, Grosse-Puppendahl T, Kuijper A. Evaluating the recognition of bed postures using mutual capacitance sensing. J Ambient Intell Smart Environ 2017;9:113–27. doi:10.3233/AIS-160414.
[28] Landis E. Micro-injection studies of capillary blood pressure inhuman skin. Heart 1930;15:209–28.
[29] McInnes E, Jammali-Blasi A, Bell-Syer SEM, Dumville JC, Middleton V, Cullum N. Support surfaces for pressure ulcer prevention. Cochrane Database Syst Rev 2015. doi:10.1002/14651858.CD001735.pub5.
[30] Hui C-l, Feng Q, Wong MS, Ng S-f, Lin YYM. Study of main and cross-over effects on pressure relief among body mass index (BMI), body position and supporting material properties. Med Eng Phys 2018;51:72–8. doi:10.1016/j.medengphy.2017.10.012.
[31] Woodhouse M, Worsley PR, Voegeli D, Schoonhoven L, Bader DL. The physiological response of soft tissue to periodic repositioning as a strategy for pressure ulcer prevention. Clin Biomech (Bristol, Avon) 2015;30:166–74. doi:10.1016/j.clinbiomech.2014.12.004.
[32] Worsley PR, Parsons B, Bader DL. An evaluation of fluid immersion therapy for the prevention of pressure ulcers. Clin Biomech (Bristol, Avon) 2016;40:27–32. doi:10.1016/j.clinbiomech.2016.10.010.
[33] Chai CY, Sadou O, Worsley PR, Bader DL. Pressure signatures can influence tissue response for individuals supported on an alternating pressure mattress. J Tissue Viability 2017;26:180–8. doi:10.1016/j.jtv.2017.05.001.
[34] Manini A, Sabatini AM. Machine learning methods for classifying human physical activity from on-body accelerometers. Sensors 2010;10:1154–75. doi:10.3390/s100201154.
[35] Yousefi R, Ostadabbas S, Faezipour M, Nourani M, Ng V, Tamil L, et al. A smart bed platform for monitoring & ulcer prevention. In: Proceedings of the Fourth International Conference on Biomedical Engineering and Informatics (BMEI); 2011. p. 1362–6.

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