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The evaluation of an intelligent closed loop dynamic sitting system to promote good posture, pressure relief and tissue perfusion

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ABSTRACT

Aim: When sitting, buttocks and thighs are subjected to higher pressures, which if sustained can be a risk factor in pressure ulcer development. This study aimed at evaluating the biomechanical and physiological performance of a dynamic sitting system incorporating pressure sensitive air cells technology to provide pressure relief and maintaining skin health.

Materials and methods: Thirteen participants were recruited and asked to adopt five static postures in a random order, each held for 10 min. Measurements at the chair-participant interface included interface pressure, internal pressure of the chair air cells, transcutaneous tissue gas tensions at the ischial tuberosities, and accelerometer data collected from the sternum. Area under the Receiver Operating Characteristic curve was used to evaluate sensitivity and specificity of all parameters in detecting postural change events, examining the 1st spatial derivative.

Results: Data revealed a high inter-subject variability, with interface pressure e.g. peak pressure gradient and contact area data showing statistically significant difference between postures. This was reflected in the physiological response with some individuals exhibiting low O_2 levels and associated high CO_2 (>25 % from baseline). Area under the curve values revealed interface pressure parameters and actimetry data accurate in detecting postural changes events (≥0.6).

Conclusion: The dynamic seating support depended on posture, although there remained some significant differences in interface pressure values and local tissue physiology. Further research is required to assess the impact of these sitting conditions in vulnerable individuals.

1. Introduction

In the seated position, approximately 75 % the body weight is supported by the buttocks and upper thighs. These subjected to high mechanical loads exerted over a relatively small contact area, which represents ~10 % of the body area. When these loads are sustained for prolonged periods, they can lead to the development of mechanically induced skin and soft tissue damage, in the form of seating acquired Pressure Ulcers (PU). PU typically occur in vulnerable individuals who have an impaired ability to move and impaired tissue health (insensate or history of wounds) [1]. They have a major implication on an individual's quality of life and represent a financial burden on health services [2]. Indeed, PU treatment costs the National Health Service ~ £4B per annum [3], with individuals in wheelchairs particularly at risk, with lifetime prevalence of 48 % [4].

Prevalence studies have demonstrated that many at-risk patients do not receive specialist chair equipment and do not adhere with the pressure relieving frequency and/or magnitude of movements currently recommended [5,6]. Amongst the seating systems available, the majority offers a static support, with generic cushion designs and crude material interfaces e.g., foam, gel, or air. Although effective in providing some pressure redistribution, these systems are unable to adapt to the user's position and posture, limiting the possibility for the individuals to actively self-managing their pressure ulcer risk. Thus, they contribute to increase the time spent in the same position without moving.

Over the last decades, interface pressure measurements have been employed to assess the performance of support surfaces and promote optimal postures. Literature reveals a significant number of studies examining the effect of different cushions and sitting postures in vulnerable individuals e.g. Spinal Cord Injured [7–11]. This is typically

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performed during short periods of monitoring and pressure features such as peak and average pressures. This approach does not represent the time dependent nature of prolonged sitting which is associated with the development of pressure ulcers. In the recent years, it has been demonstrated that the long-term used of interface pressure monitoring can act as surrogate for movement [12], with specific pressure parameters e.g. centre of pressure (COP) and contact area both sensitive and specific to postural changes. In addition, Artificial Intelligence (AI) algorithms were used to automatically detect posture and mobility events [13], combined to create new objective risk monitoring tools [14].

Technical challenges remain for the integration of AI with sitting systems to automatically provide postural correction, pressure relief, and corresponding PU prevention. There is therefore a compelling need for innovation. A new dynamic seating system which automatically reacts to shifts in position ensuring optimal posture has been proposed (Aergo Health Ltd) to facilitate active movements and self-management of PU risk. The present study aims to evaluate the performance of a closed loop dynamic sitting system (Aergo PS, Aergo Health) to provide automated postural management and pressure relief, whilst maintaining skin health.

2. Materials and methods

The present study adopted a randomised cross-over design in a cohort of healthy participants.

2.1. Description of the closed loop dynamic sitting system

The Aergo PS sitting system is a dynamic device (Fig. 1), which incorporates a closed loop of six independent pressure air cells positioned across the seat and back support, to provide thigh raise, left and right pelvic tilt, lumbar and thoracic support, aiming at creating an immersive environment with corrective air bellows to support more neutral sitting postures. In its responsive mode, the technology automatically adjusts the internal pressure of the air cells to movements, creating patterns of inflation and deflation, adjusting depending on the user position. Specifically, the system employs a PID controller to dynamically manage the air pressure within the six cells. The maximum pressure value is set at 2.0 psi and the threshold for inflation and deflation is pre-configured at ± 0.2 psi. The AI framework is built on unsupervised learning algorithms that cluster air pressure data from the cells to identify postural patterns. The threshold values are dynamically updated within the feedback loop based on pressure deviations, ensuring user-specific adjustments and optimised postural support. The system samples pressure data at 1 Hz to accurately capture rapid postural changes, and a low-pass filter is applied to smooth the pressure signals and remove high-frequency noise, ensuring reliable data for control adjustments. In addition, the system ensures synchronisation across all cells to maintain balance and uniform support during postural transitions.

Fig. 1. Overview of the Aergo PS sitting system, which comprises of six air cells positioned across the seat and back support, offering upper trunk, lumbar and thigh support.

2.2. Test equipment

Any array of measurements was taken to characterize posture, interface pressure and local tissue physiology [15]. Interface pressure measurements were recorded using a pressure sensing array (SR Soft Vision, Sumitomo Riko, Japan) which incorporates 256 pressure sensors, with a spatial resolution of 2.2 cm^2. Each sensor was set to operate within the range of 1–266 hPa (0.75–199.5 mmHg) with an acquisition rate of 5 Hz.

An actimetry sensor (Shimmer Platform, Realtime Technologies Ltd, Dublin, Ireland), attached to the sternum with a Velcro strap, was used to measure trunk movements. The device represents a small wireless sensor (53 mm × 32 mm x 25 mm), integrating a tri-axial accelerometer and gyroscope, that recorded real-time calibrated Euler angles data at 51 Hz (range ± 2 g).

Physiological measures of transcutaneous oxygen and carbon dioxide tensions (T_cPO_2, T_cPCO_2, measured in mmHg) were monitored at the right and left ischial tuberosities using a transcutaneous gas electrodes heated to 43.5°C to ensure maximum vasodilation [16]. Each electrode was attached to a separate monitor (TCM4 and TCM5, Radiometer, Denmark), recording at a frequency of 0.3 Hz and 1Hz respectively. Transcutaneous monitoring has been used to assess local tissue perfusion, providing a surrogate measure for pressure induced local ischemia [17,18].

2.3. Participants

Participants were recruited from the local community at the University of Southampton. Exclusion criteria involved history of skin-related conditions, neurological or vascular pathologies which could affect tissue health and were able to sit for a period of 50 min. Institutional ethics was granted for the study (ERGO 26379.A1) and informed consent was obtained from each participant prior to testing. This work has been carried out in accordance with The Code of Ethics of the World Medical Association (Declaration of Helsinki).

2.4. Test protocol

Test protocol, which is depicted in Fig. 2, was performed in the Biomechanics Testing Laboratory in the Clinical Academic Facility in Southampton General Hospital, where room temperature was maintained at 24° ± 2 °C. Participants were requested to wear loose fitting clothing and initially asked to lie on their side on a standard hospital bed frame with their hips flexed to 90° to attach the transcutaneous electrodes on the skin over the ischial tuberosities. An equilibrium period of 15 min was used to establish baseline unloaded T_cPO_2 and T_cPCO_2 values. Transcutaneous tissue gas electrodes were applied to the skin at both sites with a fixation ring containing an electrolyte at the electrode skin interface. A silicon ring to surround the electrodes was applied to minimise pressure gradients caused by the electrodes.

Each participant was then carefully positioned in an optimal sitting (hips positioned 90° relative to the trunk and knees positioned 90° relative to the feet), on the Aergo system. Participants were then asked to adopt four randomly allocated postures, namely slump (hips positioned 135° relative to trunk), right and left lean (trunk leaned over to the right and left at 15°) and forward lean (trunk leaned over at 25–30° from the hips with forearms placed on the thighs). Each posture was checked with a handheld goniometer, measuring at the trunk, hip, and knees by the researchers, and maintained for a period of 10 min.

Interface pressure, actimetry data and transcutaneous gas measurements were continuously monitored throughout the test period. Internal pressure of the six air cells was collated with a proprietary Python script.

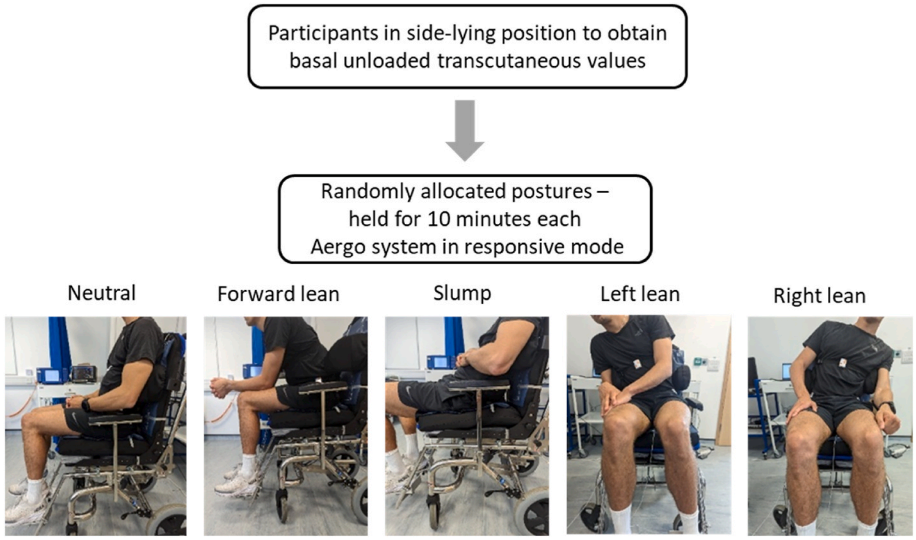

Fig. 2. Schematic of data collection, detailing the randomisation of postures.

2.5. Outcome measures

Interface pressure, internal pressure of the air cells, actimetry data and transcutaneous gas tension data were processed and analyzed using a Matlab custom-built code (MathWorks, US). Pressure parameters such as center of pressure (COP), contact area, peak pressure gradient (PPG), were estimated from the interface pressure and inclination angles with respect to the sagittal and lateral planes were exported from the actimetry data. These were subjected to filtering, according to previous studies from the authors [12,13]. The internal pressure of the air cell at the seat interface were subjected to the low pass filtering to remove noise. The transcutaneous gas data were normalized to baseline unloaded values, measured in the side lying position, and then categorized according to the following established characteristic responses [19].

1. Category 1: Perfused tissue, with normative $TcPO_2$ and $TcPCO_2$
2. Category 2: Partial ischemia, with reduced (>25 %) $TcPO_2$ and normal $TcPCO_2$
3. Category 3: Full ischemia, with reduced (>25 %) $TcPO_2$ and increased (>25 %) $TcPCO_2$

2.6. Statistical analysis

Statistical analysis of the data was performed using the Statistical Package for Social Sciences (IBM SPSS Statistics 28.0.1.0). All data were examined for normal distribution prior to analysis using the Shapiro-Wilk test. In the case of normal distribution, a one-factor repeated measures ANOVA was used to was used to compare the differences in all outcome measures between the seated postures. Wilcoxon signed rank-test was used if data was not normally distributed. Bonferroni post hoc correction was used to reduce the risk of Type I error associated with multiple comparisons. A level of 5 % was considered statistically significant (*$p < 0.05$).

2.7. Predictive ability using ROC analysis

ROC analysis was performed using SPSS (IBM SPSS Statistics 28.0.1.0) to determine the range of parameters which were both sensitive and specific in detecting posture and mobility. Prior to ROC analysis, all signals were filtered using a moving average filter with a window length of 15 samples to remove high frequency noise [12]. The spatial derivative was then calculated to highlight changes in the signal magnitude which were indicative of the postural changes and the postural adjustments which might have occurred during the static sitting postures. The derivatives of the COP and the inclination angles with respect to the sagittal and lateral planes were summed to reflect movements in both directions. The signals were then manually labelled, assigning '1' to the transitions between postures and '0' to the static postures. The area under the ROC curve (AUC) was then calculated for each signal to assess the sensitivity and specificity in discriminating between postural changes.

3. Results

3.1. Participants

Thirteen healthy volunteers (7M and 6F) took part in the study. They were aged between 20 and 38 years old (mean = 26.6 ± 4.1), with an average weight and height of 73.2 ± 12.1 kg and 174.2 ± SD 9.6 cm. The corresponding BMI ranged between 19.7 and 28.8 kg/m^2 (mean = 24.1 ± 3.0 kg/m^2).

3.2. Monitoring the biomechanical interactions

3.2.1. Interface pressure

All parameters estimated from the pressure distribution showed a high inter-subject variability across the postures, as shown in Fig. 4A and B for contact area and peak pressure gradient, respectively. Contact area data revealed that slump and forward lean postures were characterised by the highest inter-subject variability, ranging between 1034.2 and 1510.8 cm^2, and 1194.6 and 1724.4 cm^2, respectively, with the former showing the lowest contact area (median value = 1296.6 ± 308.4 (interquartile range)). Contact area was statistically smaller in slump ($p < 0.05$) compared to neutral position. By contrast, right lean posture showed the highest peak pressure gradients, which were significantly greater than neutral ($p < 0.05$).

3.2.2. *Internal seat pressure*

Internal pressure data revealed a larger minimum to maximum range in all postures at the right and left pelvic support air cells (Fig. 5B–C), showing a high inter-subject variability, as opposed to the thigh support air cell (Fig. 5A). A statistically significant difference was observed in the latter when the internal pressure values during the left and right lean postures were compared to neutral position ($p < 0.05$).

3.2.3. *Actimetry*

Actimetry data were able to differentiate the postures based on a combination of sagittal and lateral inclination angles, as depicted in Fig. 5A–B. Movements in the lateral plane (right and left lean) were statistically significantly different from the neutral position ($p < 0.05$). Similarly, movements in the sagittal plane (forward lean and slump) were statistically different from the neutral position ($p < 0.05$).

3.3. *Monitoring the physiological response*

The category responses from the ischial tuberosities for each of the participants are summarised in Table 1. Comparisons between right and left ischial tuberosities revealed similar trends in the data, although within individuals there were asymmetries in categorical responses. There was a high proportion of category 2 and category 3 responses with only some individuals exhibiting category 1 response in a few postures.

In some participants movements between postures clearly influenced the viability of the soft tissues. Fig. 3A demonstrates how an individual reacted at the right ischial tuberosity with category 2 and category 3 responses during neutral and right lean posture. During forward lean there is some recovery, with CO_2 decreasing to values similar to that of baseline (Category 2) and increasing in O_2 values during left lean and slump. By contrast, Fig. 3B shows an example of a Category 1 response throughout the test session, with approximately similar values to baseline of both CO_2 and O_2.

3.3.1. *Sensitivity and specificity of movement detection*

Table 2 summarises the AUC estimated for all the parameters. Not surprisingly, actimetry data showed the highest AUC value. Amongst the pressure data, COP showed the highest predictive ability with AUC >0.7 followed by the contact area with an AUC of 0.64. By contrast, internal

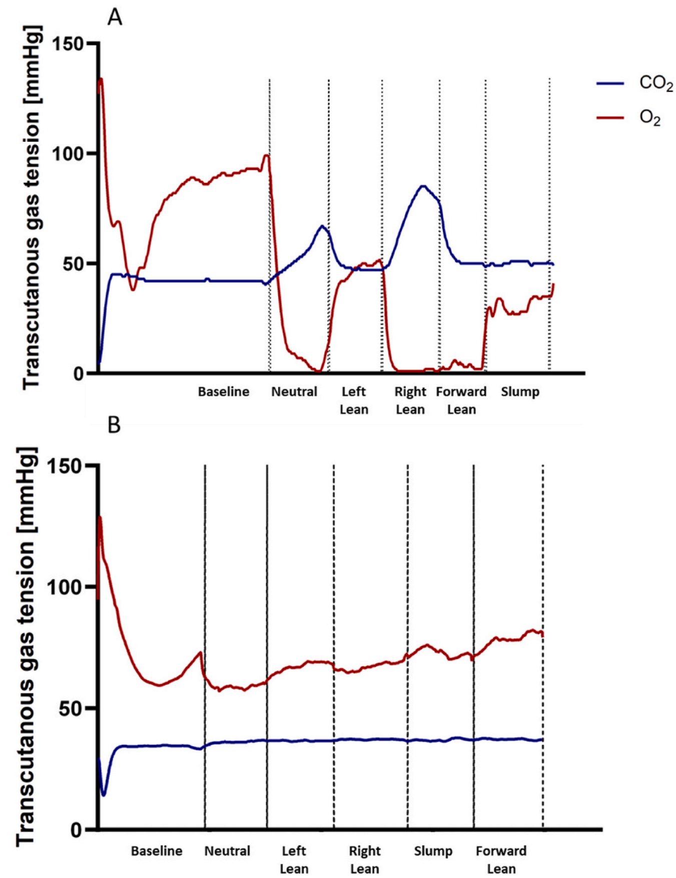

Fig. 3. Transcutaneous tissue gas tensions at the right ischial tuberosity from (A) Participant 5 who exhibited Category 2 and 3 responses during the test session (B) Participant 2 who exhibited a Category 1 response throughout the test session.

Table 1
Summary of the transcutaneous category responses at ischial tuberosities, according to Chai and Bader 2013 criteria [19].

Participant	Posture order	IT	Optimal	Left Lean	Right Lean	Slump	Forward Lean
1	Neutral, Left Lean, Right Lean, Sump, Forward Lean	Left	2	2	2	1	1
		Right	1	1	1	1	1
2	Neutral, Left Lean, Right Lean, Forward Lean, Slump	Left	3	3	2	2	2
		Right	2	3	2	2	2
3	Neutral, Forward Lean, Slump, Left Lean, Right Lean	Left	2	2	2	2	2
		Right	3	3	1	1	1
4	Neutral, Slump, Forward Lean, Left Lean, Right Lean	Left	3	3	3	3	2
		Right	3	3	3	3	3
5	Neutral, Left Lean, Forward Lean, Right Lean, Slump	Left	2	2	3	2	3
		Right	2	3	3	1	1
6	Neutral, Left Lean, Forward Lean, Slump, Right Lean	Left	3	2	3	3	3
		Right	3	3	3	2	1
7	Neutral, Forward Lean, Slump, Right Lean, Left Lean	Left	3	3	3	3	3
		Right	3	3	3	2	2
8	Neutral, Slump, Forward Lean, Left Lean, Right Lean	Left	2	2	3	2	3
		Right	2	2	3	2	3
9	Neutral, Forward Lean, Left Lean, Slump, Right Lean	Left	2	3	3	2	2
		Right	2	3	3	3	2
10	Neutral, Left Lean, Right Lean, Forward Lean, Slump	Left	3	2	3	3	3
		Right	3	3	3	3	3
11	Neutral, Forward Lean, Slump, Left Lean, Right Lean	Left	3	2	3	3	2
		Right	3	2	2	3	2
12	Neutral, Slump, Left Lean, Right Lean, Forward Lean	Left	3	2	2	2	3
		Right	3	2	3	2	3
13	Neutral, Right Lean, Forward Lean, Slump, Left Lean	Left	3	3	3	3	2
		Right	3	3	3	3	3

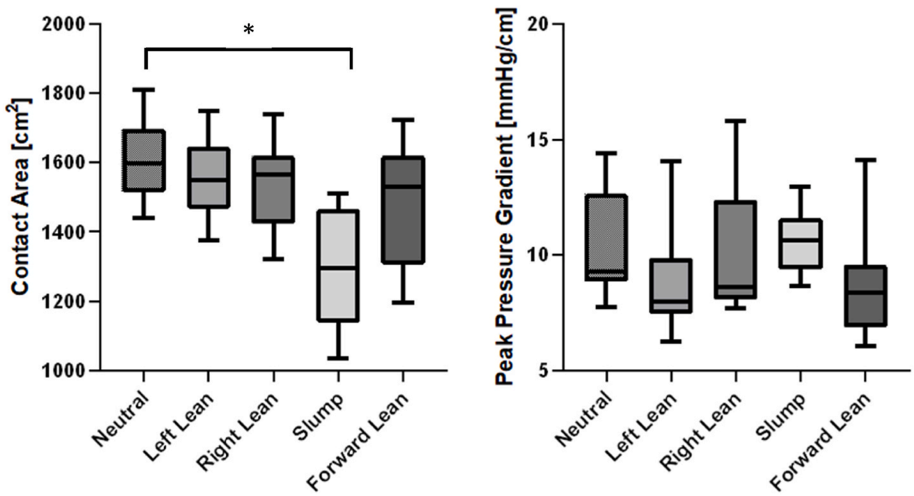

Fig. 4. Box and Whisker plot of contact area (A) and peak pressure gradient (B) during neutral, left and right lean, slump and forward learn.

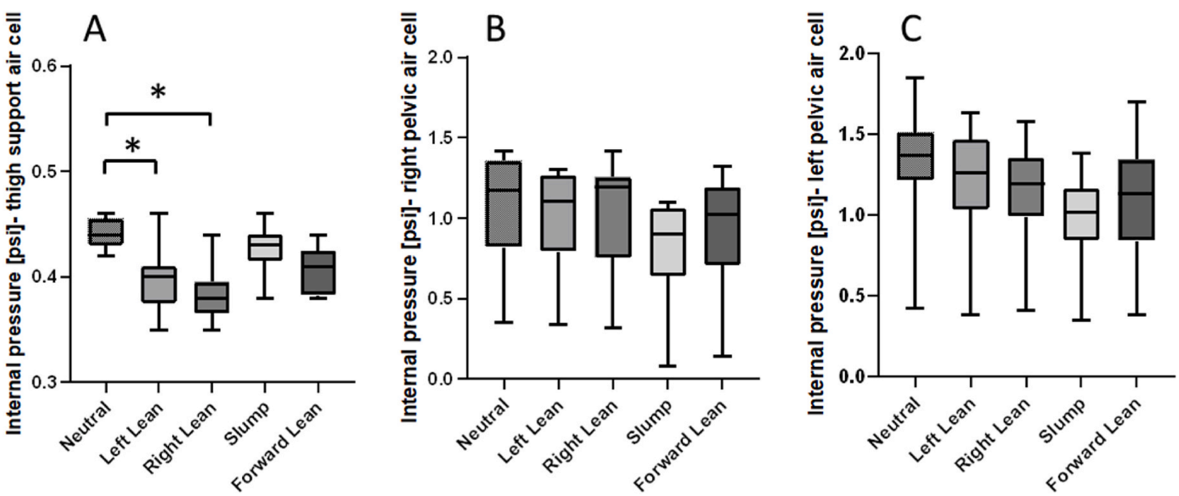

Fig. 5. Box and Whisker plot of the internal pressure of the thigh support (A), left and right pelvic support (B and C) air cells.

Table 2
AUC of the interface pressure, internal pressure and actimetry data calculated from the ROC analysis.

Source	Parameter	AUC
Interface Pressure	COP	0.72
	Contact Area	0.64
	Peak Pressure Gradient	0.60
Internal Pressure	Thigh support	0.58
	Left pelvis	0.58
	Right Pelvis	0.57
Actimetry	Inclination angles	0.73

pressure data showed the lowest predictive ability with AUC <0.6. The signals which provided the best sensitivity and specificity of movement detection were then projected onto the principal component dimensional space.

4. Discussion

The present study investigated the biomechanical and physiological performance of a closed loop dynamic sitting system (Aergo PS, Aergo Health), in a young cohort of healthy volunteers. The results revealed that interface pressures data e.g. contact area and actimetry devices could accurately detect postural movements, with the chair adjusting to new postures during the test protocol. Both interface pressure and internal pressure data were characterised by a high inter-subject variability (Figs. 4 and 5), with contact area statistically smaller in slump position ($p < 0.05$) and peak pressure gradients during right lean were significantly higher ($p < 0.05$), when compared to neutral posture respectively.

Inclination angle data showed a clear differentiation of sagittal and lateral postures (Fig. 6). This is in agreement with previous studies which showed that actimetry can discriminate changes in sitting posture in the two planes, in particular during the slump and lateral lean [12, 18].

Tissue perfusion varied between participants and postures (Table 1 and Fig. 3), revealing in a few cases that movements provided tissue reperfusion (Fig. 3B). By contrast, in some individuals there was a significant compromise to the $TcPO_2$ levels, which was associated with an increase in $TcPCO_2$ (Category 3 response). Previous research has been conducted to assess the physiological response of soft tissues to periodic repositioning as a strategy for pressure ulcer prevention [17,19]. However, this has been mainly conducted in lying, with a few studies investing sitting postures. Two studies of interest [18,20] investigated the local physiology at the ischial tuberosities during a range of sitting postures on a cohort of healthy volunteers. In agreement with their findings, our results showed that movements between postures influenced the viability of the soft tissues, with some individuals showing

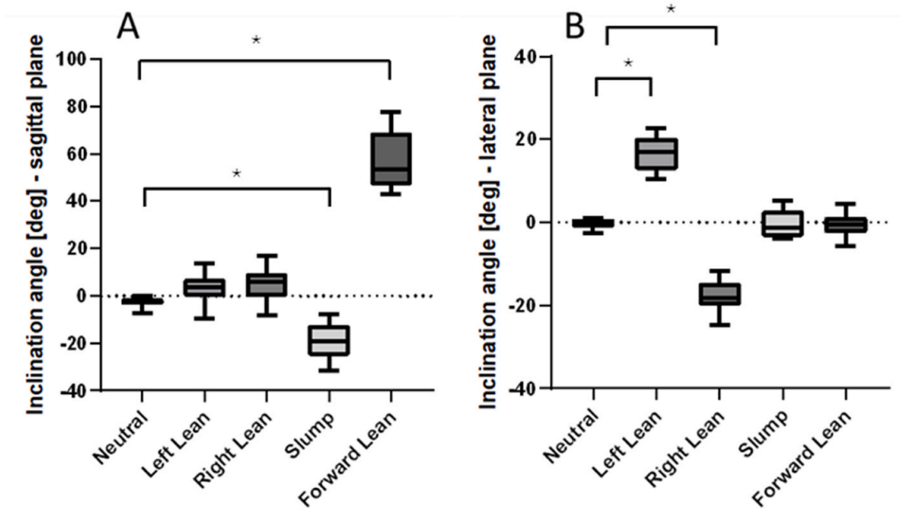

Fig. 6. Box and Whisker plot of sagittal (A) and lateral (B) plane inclination angles during neutral, left and right lean, slump and forward learn.

category 2 and 3 responses during specific postures. However, direct comparison is difficult due to the nature of the support surface e.g. viscoelastic and air cell cushions as opposed to rigid foam.

ROC analysis revealed interface pressure parameters e.g., contact area and COP the most accurate in detecting postural changes events (AUC >0.6) (Table 2). This is in agreement with the results of our previous study [12] where both pressure parameters showed the highest predictive ability in discriminating posture events in lying. Actimetry data revealed a relatively limited discriminative potential (AUC = 0.73), which could be associated to the randomisation of the postures. Previous studies explored a combination of pressure and actimetry data to monitor seated behaviours [11], finding a weak correlation between interface pressure parameters and inclination angles of the trunk. By contrast, our approach uses the spatial derivative to highlight meaningful variations in the signals magnitude [13].

Previous research have extensively examined the effect of different cushions and sitting postures in both heathy [18,21] and vulnerable individuals [7–11]. A recent study of interest [21] investigated the effects of inflation/deflation patterns of a designed air-cell cushion on the interface pressure and blood perfusion of healthy individuals, during a static neutral posture. Their results showed that the average interface pressure under the ischial tuberosities did not change during the inflation/deflation sequence, with tissue viability showing recovery. However, the study only considered short period of monitoring and utilised pressure parameters such as peak and average pressures to characterize the biomechanical response at the seat interface.

The present study involved a cohort of able-bodied individuals, which limits the generalisation of the findings to specific sub-population groups deemed to be at risk of developing pressure ulcers. In addition, each posture was only adopted for a relatively short period of time (10 min) which limits the evaluation of biomechanical and physiological responses over extended periods, which represents one of the key factors in PU development. Another limitation of the study is represented by the fact that the chair in its responsive move is set with a threshold which automatically triggers the inflation and deflation patterns to movements. Further research here is needed to identify the optimal threshold sensitive to specific movements. In addition, the pressure distribution at the ischial tuberosities might have influenced by the presence of the transcutaneous tissue gas electrodes. These were applied to the skin with a fixation ring, which was surrounded using a silicon ring to minimise pressure gradients.

The transferability of the results to other seating systems maybe limited due to the specific nature in which the Aergo system employs its close loop technology. However, parallels can be drawn with other support surfaces which use a similar principle by adjusting the internal pressures based on back pressures of air cells [22]. With the advent of cheaper sensing technology and more advanced computing power, this can provide opportunities for devices such as Aergo, which have intelligent capabilities.

The present study demonstrated that pressure monitoring and actimetry technologies can inform individual posture and mobility. This, combined with support technology in the form of pressure sensitive air cell, can identify individual postures, putting the basis for technical innovation where the air cells automatically create movement patterns and establish support requirements, for comfortable, continuous transition of postural support and proactive relief of pressure points. Further research utilising combined biomechanical and physiological responses is needed to establish postural patterns and tissue response, relative to an individual tolerance [17,23,24]. This could be translated to a variety of clinical situations and vulnerable patients, who require postural support and will aid in the self-management of their posture and mobility.

5. Conclusion

This study evaluated the biomechanical and physiological response of a closed loop dynamic sitting system (Aergo PS, Aergo Health), which in its responsive mode adjusted the internal pressure of the air cells to individual movements, supporting neutral sitting postures. We observed that interface and internal pressure, and actimetry data can provide a means to assess repositioning strategies. However, ischial tuberosities remain a vulnerable site, with ischemic events observed in a number of the participants.

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Declaration of competing interest

All authors declare no conflict of interest.

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