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Exploring the relationship between cardiac awareness and balance

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Summary

Postural balance requires the interplay between several physiological signals. Indirect evidence suggests that the perception of signals arising from the autonomic nervous system might play a role (e.g. cardiac awareness). Here, we tested this hypothesis by investigating the relationship between postural control and cardiac awareness (i.e. interoception) in a sample of $N=70$ healthy individuals. Postural control was measured using a medical robotic device, while cardiac awareness was evaluated using the heartbeat counting task. A within-subject design included two platform configurations (static, unstable) and two visual feedback conditions (eyes open, eyes closed). For each condition, we measured the sway area and the range of oscillation of the platform, as well as the range of oscillation and the quantity of movement of participants' trunk. In the "platform unstable, eyes closed" condition, participants with higher cardiac awareness demonstrated a significantly smaller sway area and reduced oscillations of both the platform and their trunk. These findings hint at a potential link between interoception and postural control, suggesting that the perception of internal body signals might sustain balance.

Keywords Interoceptive accuracy, Postural balance, Postural control, Heartbeat counting Task

Balance has been defined as the ability to control the centre of the mass in association with the base of support[1]. Upright bipedal stance has been considered one of the most important evolutionary steps for humans, and it requires the orchestration between multiple physiological systems, such as the musculoskeletal, vestibular, proprioceptive, and visual ones[2,3], as well as information coming from somatosensory graviceptors in the human trunk[4]. The ultimate integration and regulation of all these multisensory signals entail the activation of a distributed network within the central nervous system (CNS), which engages circuits at cortical, brainstem, and spinal levels[3]. This computation also takes into account prior experiences and expectations, following which the body is able to react to changes that call for postural and balance adjustments[3]. Importantly, efficient balance control plays a pivotal role in everyday life as it provides postural equilibrium with respect to gravity and a proper alignment of body segments for actions with respect to the external world.

A growing body of evidence showed that the autonomic nervous system (ANS), particularly the sympathetic division, participates in maintaining balance routinely in response to posture changes as well as in postural control[3]. This is evidenced, for instance, by the role of visceral reflexes in maintaining an upright stance as well as by the autonomic responses to a loss of balance[3]. Such responses can be observed during balance challenges. For instance, receiving experimentally induced whole-body perturbations in healthy participants resulted in evoked electrodermal responses[5–7]. Interestingly, the amplitude of the electrodermal response to this temporary perturbation was associated to the challenge difficulty[5–7]. Furthermore, the modulation of balance by the ANS is not only linked to external stimuli (e.g. change in postural state) but also to the role of affect, meaning that conditions with emotional relevance involving both somatic and autonomic processing may alter postural outputs[8,9].

Signals from the ANS could be either implicit (e.g. slight vascular tone adjustments) or accessible to consciousness via distributed and specialized brain networks[3] (e.g. awareness of the increased heartbeat in response to physical exercise). The ability to perceive signals coming from the inside of the body and its visceral

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organs has been defined as interoception. Interoception is a multidimensional construct involving at least three dimensions[10]: (i) interoceptive accuracy, which is an objective measure of the ability to detect internal bodily signals, tested through counting or discriminating own heartbeats (i.e. cardiac awareness)[11,12], (ii) interoceptive sensibility, which is a measure of the subjective impression of how well individuals think they can perceive interoceptive signals, tested using self-report questionnaires[13,14], and (iii) interoceptive awareness, defined as metacognitive insight into one's own interoceptive accuracy performance (a subjective estimation of the confidence-accuracy correspondence[10]).

Interoception plays an important role in several complex cognitive functions and activities involving a mind-body interplay. However, only scarce, indirect evidence on the relationship between interoception and postural and balance control is available[15–20]. For instance, postural yoga practitioners (e.g. Ashtanga yoga) with higher interoceptive sensibility tended to achieve higher yoga expertise[17], whereas interoceptive sensibility moderated differences in postural control and cardiorespiratory variables during imagery involving interoceptive mental images as a function of hypnotisability[21]. Additionally, dancers, a category of professionals with robust balance and motor control, showed higher interoceptive accuracy than non-dancers, with senior dancers' interoceptive accuracy being higher than both junior dancers and non-dancers[15]. Interestingly, interoceptive accuracy can also be enhanced by specific body postures. Weineck and colleagues[16] showed that power posing (e.g. the adoption of an expansive and dominant bodily posture) compared to neutral posing significantly increased individuals' interoceptive accuracy at the heartbeat counting task in the short-term after two weeks of training compared to baseline. Finally, a study on a sample of patients with relapsing-remitting multiple sclerosis who underwent a physiotherapy program based on posture, proprioception, and balance, showed that higher interoceptive awareness correlated with better postural balance[22].

If on the one hand these findings suggest the existence of a potential relationship between the conscious monitoring and appraisal of bodily signals and postural control, on the other hand a tailored study is absent, prompting a number of questions about this relationship. Specifically, whether better interoceptive accuracy (in terms of cardiac awareness) would also predict better balance control in the general population. Evidence on the topic is promising but scanty, without a proper evaluation of balance control (in all its components) in the tested individuals. Thus, in the current study, we explored the relationship between interoceptive accuracy and the different facets of postural controls (e.g. sway area and range of oscillation) via a medical robotic device in a large sample of healthy individuals. Concerning postural control measurement, participants were tested, in a within-subject design, in two platform configuration conditions (static, unstable) and two visual feedback conditions (eyes open, eyes closed). For each condition, we measured the sway area and the range of oscillation of the platform, as well as the range of oscillation and the quantity of movement of participants' trunk. Concerning interoception measurement, we opted for a measure of interoceptive accuracy to obtain a more objective evaluation of the ability to detect internal bodily signals, rather than using measures that only or partially rely on subjective impressions, self-report questionnaires (interoceptive sensibility), and subjective confidence judgements (interoceptive awareness). Specifically, we used the heartbeat counting task (HCT), which allows the measurement of the conscious perception of the heartbeat, an ANS signal. In the HCT, participants counted each heartbeat they felt by focusing exclusively on their own chest, while the actual number of heartbeats was recorded. Moreover, considering that both anxiety and depression could reflect altered interoceptive states due to the noisy amplification of self-referential interoceptive predictions[23–27], we also collected measures of anxiety and depression levels.

Based on the available literature, we expected that individuals with higher cardiac awareness also presented with better postural control. However, visual information is the preferred sensory modality during postural control and balance maintenance[28–31], and it becomes predominant when proprioception is attenuated[32–36]. Thus, we hypothesised that, when the visual external feedback is not available, relying on internal body signals to adjust the posture would be especially beneficial to the performance. Namely, being more aware of interoceptive signals would drive less dependency on exteroceptive information (e.g. information from sensory systems[28–30]). Therefore, we predicted that individuals with higher cardiac awareness had a better performance specifically when they had to maintain balance on an unstable platform with their eyes closed (i.e. in the most difficult condition), as compared to when they had their eyes open.

Results

$N=69$ healthy participants were tested in two Platform configurations of the medical robot device (Static, Unstable) with two levels of visual feedback (Eyes Open, Eyes Closed). For each condition, we obtained four outcome variables related to balance performance: two representative of the platform movements (i.e. the sway area and the range of oscillation of the Center of Pressure (CoP)) and two referred to the trunk movements (i.e. the range of oscillation and the quantity of movement of the trunk). At a visual inspection (see Table 1 for descriptive information) it is possible to appreciate that the condition Platform Unstable, Eyes Closed is the most difficult one, whereas the condition Platform Static, Eyes Open is the easiest, as expected.

In the HCT, participants were required to count silently each heartbeat they felt by focusing exclusively on their own chest, while the actual number of heartbeats was recorded via a professional pulse oximeter. The accuracy at this task was taken as a measure of interoceptive ability. In general, participants' mean accuracy (in percentage) at the HCT was 62% ± 31%.

Statistical analyses showed that participants with better interoceptive ability also had a better performance on the platform, particularly when it was unstable and in absence of visual feedback.

Specifically, when considering the outcome variable "CoP sway area (cm^2)", we found a significant interaction Platform Unstable, Eyes Closed x HCT [*ß = -198.10, 95% CI (-309.87, -85.93),* $p=0.001$], whereas all other interactions were not significant *(all ps > 0.93)*. In other words, the effect of the HCT score on the outcome variable "CoP sway area (cm^2)" decreases by 198 units in the most difficult condition (Platform Unstable, Eyes

	Platform Unstable		**Platform Static**	
Outcome variable	*Eyes Open*	*Eyes Closed*	*Eyes Open*	*Eyes Closed*
CoP sway area (cm^2)	14.18 (21.61)	272.05 (220.56)	1.23 (0.82)	3.38 (2.34)
CoP range of oscillation of Platform (cm)	3.93 (2.21)	16.72 (6.70)	1.38 (0.44)	2.41 (0.72)
Trunk quantity of movement (deg/s^2)	0.07 (0.03)	0.16 (0.06)	0.05 (0.02)	0.05 (0.02)
Trunk range of oscillation (deg)	2.64 (0.95)	7.11 (2.63)	2.00 (0.89)	2.33 (1.00)

Table 1. Descriptive statistics of the outcome variables. Note. Descriptive statistics of each outcome variable are mean (SD), separated by platform configurations (static, unstable) and visual feedback conditions (eyes open, eyes closed). CoP = Center of Pressure.

Outcome variable	**ß**	**95% CI**	***p*-value**
CoP sway area (cm^2)			
Platform Unstable, Eyes Closed * HCT	-198.10	-309.87; -85.93	**0.001**
Platform Static, Eyes Closed * HCT	-0.56	-113.44; 106.11	0.98
Platform Unstable, Eyes Open * HCT	-4.16	-118.74; 104.63	0.93
CoP range of oscillation of Platform (cm)			
Platform Unstable, Eyes Closed * HCT	-5.52	-9.00; -2.04	**0.002**
Platform Static, Eyes Closed * HCT	-0.25	-3.69; 3.10	0.89
Platform Unstable, Eyes Open * HCT	-1.24	-4.64; 2.22	0.48
Trunk quantity of movement (deg/s^2)			
Platform Unstable, Eyes Closed * HCT	-0.01	-0.04; 0.01	0.31
Platform Static, Eyes Closed * HCT	-0.01	-0.04; 0.01	0.32
Platform Unstable, Eyes Open * HCT	0.01	-0.02; 0.03	0.65
Trunk range of oscillation (deg)			
Platform Unstable, Eyes Closed * HCT	-2.00	-3.34; -0.66	**0.004**
Platform Static, Eyes Closed * HCT	0.12	-1.23; 1.39	0.87
Platform Unstable, Eyes Open * HCT	0.06	-1.31; 1.37	0.94

Table 2. Linear mixed-effect models results. Note. For each model, Beta (ß) values, 95% confidence intervals (CI) and *p*-values are reported. Reference level: Platform Static, Eyes Open. CoP = Center of Pressure; HCT = Heartbeat Counting Task. * indicates the interaction; p-value in bold are < 0.05.

Closed) as compared to the easiest condition (Platform Static, Eyes Open). Also for the outcome variable "CoP range of oscillation of Platform (cm)" we found a significant interaction Platform Unstable, Eyes Closed x HCT *[ß = -5.52, 95% CI (-9.00, -2.04)*, $p = 0.002$], whereas all other interactions were not significant *(all ps > 0.48)*, indicating a positive relationship between interoceptive accuracy and performance on the platform in the absence of visual inputs.

The same reasoning applies to "Trunk range of oscillation (deg)" where, once again, we found a significant interaction Platform Unstable, Eyes Closed x HCT *[ß = -2.00, 95% CI (-3.34, -0.66)*, $p = 0.004$], whereas all other interactions were not significant *(all ps > 0.87)*. However, this was not true for the outcome variable "Trunk quantity of movement (deg/s^2)", for which we did not find any significant results *(all ps > 0.31)*. In Table 2, complete results of the linear mixed-effect models are reported.

Finally, considering that both anxiety and depression could reflect altered interoceptive states, we also collected measures of anxiety and depression. Participants' mean STAI-XS score was 36 ± 7.95, their mean STAI-XT score was 41.13 ± 9.66, and their mean BDI-II score was 6.33 ± 5.61. However, the above linear mixed-effect models results held also when repeating the analyses by controlling for anxiety and depression levels (see Table S1 in the Supplementary Information).

To sum up, the present results are in line with our hypothesis that participants with better interoceptive accuracy would have a better performance on the platform, and specifically in the condition in which the platform was unstably tilting based on their movements while they had their eyes closed.

Discussion

Maintaining balance is a compound ability that requires the processing and integration of different information, including visual, proprioceptive, vestibular, and musculoskeletal signals[2], as well as signals coming from somatosensory graviceptors in the human trunk[4]. Such information is ultimately integrated and regulated in distributed and specialized brain networks in the central nervous system (CNS), so that the body is able to react to changes that call for postural and balance adjustments[3]. Growing evidence shows the emerging role of Autonomic Nervous System (ANS) signals, particularly those belonging to its sympathetic division, in participating routinely in balance and postural control[3]. One crucial aspect of the ANS signals processing seems to pertain to their conscious perception, namely interoception. Interoception, here broadly defined as the ability to perceive signals coming from the inside of the body and its visceral organs[10,37] may contribute as well to postural control[3]. However, despite a much larger amount of evidence suggesting its contribution to a high number of psychological and cognitive processes involving the body[28,38,39], its role in balance and postural control has been scarcely explored. Although indirect, previous evidence suggests that higher levels of interoception is associated with better postural control in both populations with motor control expertise (e.g. professional dancers and yoga practitioners[11,15]) and pathological populations such as patients with relapsing-remitting multiple sclerosis[18].

To fill this gap, in the present study we specifically explored the correlation between interoception, in terms of cardiac awareness, and postural control. To this aim, we enrolled 70 healthy participants in an experiment requiring maintaining the balance standing on either a static or an unstable platform while their eyes were open or closed. For each condition, we collected different measures of postural control, consisting of *the sway area of the CoP*, *range of CoP oscillation*, *range of trunk oscillation* and *quantity of trunk movement*. We also collected participants' interoceptive accuracy through the Heartbeat Counting Task (HCT)[12]. Moreover, considering that both anxiety and depression levels could reflect altered interoceptive states due to the amplification of self-referential interoceptive predictions[23–27], we also collected a measure of anxiety (both state and trait) and a measure of depression.

We found that higher interoceptive accuracy was indeed associated with better balance and postural control. Interestingly, this relationship emerged in response to the platform unstable tilting (unstable condition) depending on the participants' weight shift in the absence of the visual input (eyes closed), suggesting that, when the visual external feedback is not available, relying on internal body signals to adjust the posture can be beneficial to the performance. Specifically, it has been already suggested that, in the absence of visual or auditory spatial orientation cues (i.e. eyes are closed and there is no relevant sound source, as in the present case), individuals would maintain balance of the body lean in space via signals from the otholiths, the vestibular semicircular canal, proprioception, and somatosensory graviception, so that the body can react against the gravity by modulating the muscular tone[4,40]. Thus, based on our findings, we additionally suggest that being more aware of interoceptive signals would drive less dependency on exteroceptive information (e.g. information from vision[28,29]), when external inputs are unavailable. Moreover, the above results held even when correcting for participant's level of anxiety and depression, thus we can exclude that they might have had a role in participants' performance on the platform.

One could speculate that interoception acts as a "conscious bridge" between the postural control and the ANS adjustments occurring in case of postural instability, following multisensory integration in a distributed brain network involving areas such as superior parietal, posterior parietal, temporo-parietal, temporo-occipital, premotor, and insular cortices[41]. This network is supposed to be at the basis of self-awareness, subserving the complex integration of signals coming from different sources (external and internal)[41]. Concerning the role of the ANS, Sibley and colleagues[3] hypothesised three potential functions of this system in postural control. First, the ANS might intervene as a low-level error detector, so that it would participate in the balance correction following instability detection. Second, the ANS might participate in adjusting postural control in preparation for expected or upcoming postural destabilisations, signalled by distributed and specialized brain networks, or in response to perturbations. Third, the ANS modulation might occur concurrently with sensorimotor control, namely, with autonomic signals being integrated by cerebral networks into sensorimotor activity in order to regain postural stability[3]. How could we inscribe interoceptive signals into this framework? We speculate tentatively that interoception might participate as a mediator of ANS adjustments on postural control and balance. Specifically, interoception could support postural control by boosting the adjustments made by the ANS, after being integrated with the other multisensory signals in specific brain networks, so that individuals with higher interoceptive abilities would get a magnified perception of the ANS signals. The better the interoceptive ability, the higher the conscious perception of the ANS changes in response to postural imbalance, the better the postural control. This idea would make contact with all three possibilities postulated by Sibley and colleagues[3]: interoception might, thus, boost ANS signals to correct a postural error, or to magnify ANS signals to fine tune balance control in the anticipation of a perturbation, or to heighten ANS online signals integration into sensorimotor activity orchestrated for balance and postural maintenance. In other words, participants who are better at detecting their own internal body information would be in turn better at balance and postural control through a better perception of ANS adjustments that need to take place. However, these speculations must be taken cautiously, as we did not modulate the potential effect of the ANS signals on postural control and balance, but only looked at the co-occurrence of better cardiac awareness and better performance.

The present results are also well inscribed in the construct of bodily self-awareness[41], namely, the feeling that conscious experiences are bound to the self and are experiences of a unitary entity[42,43]. The multidimensional nature of bodily self-awareness includes the experience of owning a body, feeling the body in space, and the agency over one's own actions; moreover, it entails the multisensory integration of vestibular, visual, tactile, and proprioceptive stimuli[44,45], as well as the ability to feel engaged by information coming from the inside of the body (interoception) and noticing subtle changes[14,41,46]. The brain is continuously updated by bodily signals with a map of the internal physiological state, as well as with information on the position and orientation of the body relative to gravity within its supporting base during stationary position, in voluntary movement, and in response to external perturbations, thanks to the activity of the vestibular system[44,45], among others. All these signals are strictly tied to each other and integrated to build a representation of the body as well as to our awareness of it[41]. Whenever motor and sensory processing is altered, or in the event of an external perturbation, the accuracy and regulation of movements, including postural control, unstable balance, and coordination, as well as the individual's capacity to safely navigate their surroundings are hindered[19,47,48]. It thus becomes crucial to have an optimal online system that can inform about the adjustments made, i.e. interoception, so that we can efficiently support postural balance in case of uncertainty. In this way, the better one is at consciously perceiving signals coming from the internal body, especially when other sensory systems are unavailable (e.g. vision), the more they are able to maintain a coherent representation of the body, thus better controlling balance and posture.

Overall, it is reasonable to speculate that just as varying levels of interoceptive accuracy are associated with different postural and balance outcomes, changes in interoceptive accuracy during mind-body interventions (such as meditation[16] and yoga[14,15,18]) could reflect the effectiveness of such interventions[19,21,32]. Future studies, possibly also including clinical populations, are needed to better investigate this matter and to shed new light on this complex and multidimensional interaction and its underpinning mechanisms. Postural control and balance problems constitute a major healthcare issue in our increasingly older society. Falls are an important cause of morbidity and mortality and the leading cause of fatal and nonfatal injuries among older adults. Our results suggest a possible relationship between balance/postural control and interoception. If these results were confirmed, this would have important clinical implications, especially from a rehabilitation perspective; indeed, in this view, tailored interventions aimed at improving interoceptive accuracy could be useful to improve postural control and consequently reduce the risk of falls and all its medical, social, and economic consequences, in clinical and healthy elder populations. Specifically, future studies could evaluate the effect of interventions aimed at augmenting the interoceptive accuracy of people presenting with balance deficits.

Limitations of the study

The primary limitation of this study lies in the measurement of cardiac awareness. Several studies have shown that the HCT is not an ideal measure of interoceptive accuracy. For instance, the performance at this task could be only an estimation of interoception, rather than a real heartbeat counting[49]. Indeed, despite instructing participants to rely only on the heartbeat felt from their chest and that zero is a plausible answer if they did not feel any heartbeats (as we did in the present case), one cannot be entirely sure that they did not adopt guessing strategies[50]. However, despite these shortcomings, these critiques are not universally embraced[51]. Indeed, the HCT has been used in several fMRI studies and has been found to correlate with activity in the insula, the primary interoceptive cortex. Additionally, higher scores at the HCT have been reported to correlate with measures of interoceptive sensibility, such as the subscales of the Multidimensional Assessment of Interoceptive Awareness[14]. Thus, the HCT still offers the largest amount of data (e.g. physiological and neural correlates) on interoceptive accuracy across different populations and contexts to compare our results with[52]. Overall, this also highlights the limitation of not directly measuring ASN activity in the present study, which future research should address. Direct ANS measurements could provide valuable insights into physiological responses underlying sway and trunk stability. Incorporating such measures in future studies would help clarify the link between ANS activity and balance control mechanisms.

Materials and methods

Data and code availability

Preprocessed data available from the corresponding authors upon reasonable request.

Subjects details

Seventy healthy volunteers participated in the study. One participant was excluded from the dataset as it was an extreme outlier (+ 3SD) across several variables (i.e. “CoP sway area (cm^2)” Platform Unstable, Eyes Open and Platform Unstable, Eyes Closed; “CoP range of oscillation of platform (cm)” Platform Unstable, Eyes Open; “Trunk range of oscillation (deg)” Platform Unstable, Eyes open; see below for details). Thus, the final sample included 69 participants, 33 males [age: range 18–54 years (M = 29.18, SD = 10.79); education: range 12–18 years (M = 15.28, SD = 1.61); body mass index (BMI): range 18–33 (M = 22.93, SD = 3.39)] and 36 females [age: range 19–59 years (M = 29.19, SD = 11.64); education: range 8–19 years (M = 15.38, SD = 2.63); BMI: range 19–37 (M = 24.22, SD = 4.47)]. All participants were right-handed according to the Edinburgh Handedness Inventory[53], native Italian speakers, had normal or corrected-to-normal vision and had no previous history of mental, neurological and/or musculoskeletal illness. Before starting the experiment, all participants gave their written informed consent. No part of the study procedures or analyses was pre-registered prior to the research being conducted. The Ethical Committee of the ASST “Grande Ospedale Metropolitano” Niguarda approved the experimental procedures, which were performed in accordance with the Declaration of Helsinki.

Experimental tasks

Heartbeat counting task Interoceptive accuracy was evaluated using the Heartbeat Counting Task (HCT), based on previous publications[10,12,54]. Participants were instructed to focus exclusively on their own chest and to silently count each heartbeat they felt from the time they heard a “start” acoustic signal to when they heard a “stop” acoustic signal; “start” and “stop” acoustic signals were provided by a computer and they both sounded similar to the bursting of a balloon. Meanwhile, the experimenter noted down the actual number of heartbeats recorded via a professional pulse oximeter (Shyonda) connected to the participant’s left index finger. Participants were also reassured that reporting a count of zero if they did not feel any heartbeats was acceptable. This task was repeated six consecutive times using six different time windows of 25, 30, 35, 40, 45, and 50 s submitted in a randomized order across participants. Based on a previous study[10], an interoceptive accuracy score was derived for each time window using the following formula: *1 – ((number of real beats – number of reported beats)) / ((number of real beats + number of reported beats) / 2)*. The so-obtained six different scores (one for each time window) were then averaged to obtain the interoceptive accuracy score of each participant. Thus, the HCT score can vary between 0 and 1: the closer to 1 (i.e. 100% accuracy), the better the interoceptive accuracy.

Postural control assessment Hunova® by Movendo Technology srl[55–57] is a robotic CE-marked device composed of two electromechanical platforms: one under the feet and one under the seat. These platforms have two rotational degrees of freedom as described in a recent paper[57] and are equipped with a six-axis force-torque sensor that allows the estimation of the centre of pressure (CoP) while an optical incremental encoder allows measuring the inclination of the platform itself on the two axis (y axis - anteroposterior and x axis - mediolateral direction)[58–61]. The device is integrated with a wearable motion sensor based on an inertial measurement unit (IMU) applied to the participants' trunk, which allows to measure body inclinations and accelerations in space. Testing was performed in a bi-podalic configuration[58] with participants standing on the platform in their comfortable upright position and wearing the IMU sensor on their sternum. They were positioned on the platform with the heels distanced by approximately 2 cm and the forefoot by about 4 cm, forming an angle of 30° between the feet. Participants were tested both in static and unstable[56,61,62] – i.e. not static – situations, by providing different environments that could challenge reactive and anticipatory postural response and postural adjustment. Thus, the within-subjects experimental design involved two conditions (Static, Unstable) with two levels of visual feedback each (Eyes Open, Eyes Closed). In the Static condition the platform is fixed, and participants must stand still and maintain the balance by fixing a distal point ("*Static balance with eyes open")* or maintain their balance with eyes closed ("*Static balance with eyes closed")*. In the Unstable condition the platform is unstably tilting in response to the weight shift of the subject, thereby stirring in random directions depending on participants' movements and oscillations[56,61,62]. The parameters of the platform control followed standard protocols used by Hunova, also used in other publications[56,61,62]. Participants must maintain their balance by fixing a distal point ("*Unstable balance with eyes open*") or maintain their balance with eyes closed ("*Unstable balance with eyes closed")*. The distal point was displayed in the centre of the screen, which is part of the Hunova device, placed at a distance of 1 m, while being adjusted in height based on participants' height. All participants performed each of the four conditions three times, consecutively, for a total of 12 trials per subject. Each trial lasted 30 s, with a 15-second pause in between. For each condition, the three trials were averaged before being entered in the analyses to allow for variability reduction across conditions. Conditions were administered in a counterbalanced order. The total duration of the experimental session was approximately 20 min. The assessment session provided the experimenter with a series of measurements related to the postural control, which were used as dependent variables in the present study. These variables are among those most consistently measured in studies using this device[56,61,62]. Since several of such variables are redundant, we selected the most representative ones by opting for two indices referred to the platform and two indices referred to the person. Specifically, the outcome variables related to balance performance obtained for each trial were: (i) *Center of Pressure (CoP) variables*: sway area (the 95% confidence ellipse area of the statokinesiogram) and range of oscillation (the maximum amplitude of the CoP displacement); (ii) *Trunk variables*: range of oscillation (the maximum angular displacement of the torso measured in degrees) and quantity of movement (the variability of the oscillations of the torso around the initial position measured as the standard deviation of the accelerations). All these indicators are proportional to the instability of the subjects: the higher the values, the smaller the ability of the subject ability to maintain balance.

Questionnaires and scales To control for possible level of anxiety that may modulate interoception skills[23–25], we asked participants to fill in the State-Trait Anxiety Inventory X (STAI-X)[63], a psychological inventory based on a 4-point Likert scale and consisting of 40 self-report questions. It measures two types of anxiety: state anxiety, or anxiety about an event (STAI-XS), and trait anxiety, or anxiety level, as a personal characteristic (STAI-XT). A cut-off of 39–40 is normally used for detection of clinically significant symptoms of anxiety[64].

To control for possible level of depression that may also affect interoceptive abilities[24,26,27], we also administered the Beck Depression Inventory-II (BDI-II;[65,66]), a 21-item self-report questionnaire evaluating the presence and the severity of several aspects of depression symptoms on a 4-point Likert scale. A total score of 0–13 is considered minimal range depression, 14–19 is mild depression, 20–28 is moderate depression, and 29–63 is severe depression[67].

Quantification and statistical analysis

Procedure The entire experimental procedure was performed in a single day for each participant. After checking for eligibility, participants gave their informed consent to participate in the study. First, participants performed the HCT to assess their interoceptive accuracy[10]. Testing took place in a quiet semi-dark room to avoid any possible source of distraction. Then, participants underwent a robotic-assisted evaluation of balance and postural control using Hunova® by Movendo technology srl[68]. Balance evaluation was carried out in the rehabilitation centre of the Spinal Unit in ASST "Grande Ospedale Metropolitano" Niguarda in Milan. Finally, participants filled in questionnaires and scales and answered to a series of demographic questions, including information about sex, age, education.

Statistical analysis To investigate the relationship between interoceptive accuracy and balance and postural control we fitted linear mixed-effect models with Platform configuration and visual feedback (Static, Eyes Open; Static, Eyes Closed; Unstable, Eyes Open; Unstable, Eyes Closed), the HCT continuous score, and their interactions as models' predictors. We also added to each model age, gender, and BMI as covariate to adjust for possible confounding on balance performance[69]; a random intercept for each subject, in the form of 1|subject, was added to account for the intrasubject correlation produced by the different measurements carried out on the same participants. The different indexes of balance and postural control measured by the Hunova® platform were modelled as the dependent variable of each model[70]. More in details, these indexes were: (i) "CoP sway area (cm^2)", (ii) "CoP range of oscillation of Platform (cm)", (iii) "Trunk range of oscillation (deg)", and (iv) "Trunk quantity of movement (deg/s^2)". To verify that the assumptions of the linear mixed models were not violated, we checked that the residuals of the models were normally distributed by visually examining Q–Q plots. As the residual distributions of the models were not normal, non-parametric bootstrap with 5,000 replicates) was applied to estimate 95% Confidence Intervals (CI) and *p*-value based on distribution's quantiles. Data analysis was conducted using R.

Data availability

Preprocessed data available from the corresponding authors upon reasonable request.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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