Coupling Between Posture and Respiration Among the Postural Chain: Toward a Screening Tool for Respiratory-Related Balance Disorders

Yoann Lespert, Isabelle Rivals, Ros Kiri Ing, Louis Clavel, Thomas Similowski, Baptiste Sandoz, and Valérie Attali

***Abstract*— Alteration of posturo-respiratory coupling (PRC) may precede postural imbalance in patients with chronic respiratory disease. PRC assessment would be appropriate for early detection of respiratory-related postural dysfunction. PRC may be evaluated by respiratory emergence (REm), the proportion of postural oscillations attributed to breathing activity; assessed by motion analysis) as measured from the displacement of the center of pressure (CoP) (measured with a force platform). To propose a simplified method of PRC assessment (using motion capture only), we hypothesized that the REm can appropriately be measured derived from single body segment the postural oscillations of a single body segment rather than whole body postural oscillations. An optoelectronic system recorded the breathing pattern and the postural oscillations of six body segments in 50 healthy participants (22 women), 34 years [26; 48]. The CoP displacements were assessed using a force platform. One-minute recordings were made in standing position in four conditions by varying vision (eyes opened/closed) and jaw position (rest position/dental contact). The Sway Path and Mean Velocity of the CoP and of the representative point of each body segment were recorded. The REm was measured along the major and the minor axis of the 95% confidence ellipse of the CoP position (REm_MajorAxis$_{CoP}$; REm_MinorAxis$_{CoP}$) and of that of each body segment. SwayPath$_{CoP}$ and MV$_{CoP}$ varied widely across the four conditions (par<0.000001). These changes were related to the visual condition (p<0.000001) while the jaw position had no effect. The REm_MajorAxis$_{CoP}$ and the REm_MinorAxis$_{CoP}$ changed across conditions (p<0.05); this was related to vision while jaw induced changes only for the REm_MinorAxis$_{CoP}$. The SwayPath, the Mean Velocity and the REm of all body segments were significantly correlated to the CoP, but the highest correlations were observed for the thorax, the pelvis and the shoulder. PRC may be assessed from the postural oscillations of thorax, pelvis and shoulder. This should simplify the evaluation of respiratory-related postural interactions in the clinical environment, by using a single device to simultaneously assess postural oscillations on body segments, and breathing pattern. In addition, this study provides reference data for PRC and its sensory-related modulations on body segments along the postural chain.**

***Index Terms*— Posturo-respiratory coupling, multijoint postural chain, respiratory emergence, vision, jaw occlusion.**

I. Introduction

MAINTENANCE of an erect posture in humans imposes permanent adjustments of postural muscles that induce oscillations of the center of mass [1]. These oscillations reflect the subject's balance and are measured by the displacement

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of the projection of the center of mass on the ground, the so-called center of pressure (CoP) [2], [3]. Respiratory and postural systems are physiologically coupled. Firstly, many musculoskeletal structures that are dedicated to breathing are also dedicated to maintaining balance and movement. The diaphragm, the main inspiratory muscle, also has a postural stabilizing action during trunk rotation [4], upper limb motion [5] and repetitive postural task [6]. Secondly, because of the mechanical constraints it exerts on the thoracic spine, the rib cage is a crucial element of the postural chain [7]. The change in lung volume during breathing alters the orientation of the ribs relative to the spine [8] and is associated with large variations in thoracic kyphosis [9]. Breathing movements are thus responsible for rhythmic oscillations of the center of mass (and of the CoP) [10], [11], [12], [13], [14], [15] and trigger postural adaptations to maintain verticality [9]. In healthy subjects however, this "postural disturbance" of respiratory origin does neither cause balance impairment nor falls [14]. Rhythmic contractions of the spinal [14], [16] and of pelvic floor muscles [17] limit the postural oscillations linked to breathing by containing the CoP in the support polygon. This reflects a posturo-respiratory coupling (PRC) which is centrally adjusted [11], [15]. Respiratory-related postural dysfunction was suggested by clinical observations highlighting postural instability [18] and alteration of gait parameters [19] in patients with obstructive sleep apnea syndrome (OSAS), a chronic respiratory disease characterized by altered upper airway mechanics and control leading to repetitive collapses of the upper airways during sleep. As such, there is no specific recommendation for the management of OSAS-related postural dysfunction yet. However, it should be sought to adopt an early detection approach to prevent falls potentially leading to injury and accidental death, particularly in elderly [20]. Recently we reported in patients with OSAS and without apparent postural dysfunction, an increased PRC associated with balance perturbation on the stabilometric profile which suggests the existence of subclinical postural disease [21]. In this context, the PRC assessment would be appropriate for early detection and management of OSAS-related postural dysfunction. We had previously validated in healthy subjects [11] and in patients with OSAS [21] an experimental protocol to assess the PRC using an optoelectronic system coupled to a force platform. With a view to proposing a simplified method in routine clinical practice, we hypothesized that the evaluation of postural oscillations of a body segment would be representative of the global postural oscillations measured at the CoP. This approach will allow the use of a single device that will simultaneously assess breathing pattern, postural oscillations and PRC on specific body segments instead of CoP [22]. Indeed, the PRC is distributed throughout the postural chain from head to toe [11], [15] and thus may be estimated on any body segment. To validate this approach, the objective of this study was to identify the body segments on which the PRC assessment was the most representative of the PRC assessed on the CoP. To do so, we assessed the PRC and its adaptations along the postural chain according to visual afferents and jaw occlusion in fifty healthy subjects, using an optoelectronic system and a force plate to acquire breathing and postural oscillations of the body segments as well as the center of pressure.

II. Methods

A. Participants

Fifty healthy persons (22 women; median [1st -3^{rd} quartiles]; age: 34 years [26; 48]; height 1.72 m [1.65; 1.76]; weight 71kg [62; 78] and Body Mass Index (BMI) 24kg/m^2 [21; 26]) were included. They had no history of postural or respiratory disease and had normal lung volumes (including a measurement of Functional Residual Capacity using Helium dilution technique), according to the current recommendations of the European Respiratory Society [23]. All participants gave their written informed consent. This study was approved by the ethics committee (Comité de Protection des Personnes (CPP) Ile-de-France VI) under the number 2006-A00386-45.

B. Experimental Protocol

An optoelectronic system for motion analysis (Vicon with Nexus 2.5, Oxford, UK) was used to assess the breathing pattern by optoelectronic plethysmography as previously described [11]. The subjects were equipped with 65 retroreflective markers, 41 on the thorax, four on the head, seven on each leg, and three on each foot (figure1). The CoP displacement was assessed using a force platform (BP 4051040-2K, AMTI, Watertown, USA) at the frequency of 100Hz, synchronized to the optoelectronic system. The optoeletronic system was also used to record postural oscillations of six body segments: ankles, knees, pelvis, thorax, shoulders, and head (figure 1). A representative point was defined for each body segment as the center of the line passing between the lateral and medial malleolus for the ankles; the center of the line passing between the lateral epicondyle of the femur and the medial condyle of the tibia for the knees; the barycenter of the four markers placed on the anterior and posterior iliac spines for the pelvis; the barycenter of the four markers of the head for the head; the eighth thoracic vertebra for the thorax; and the acromion for the shoulders. The participants were in a relaxed standing position barefoot on the force plate with their arms along their sides, looking straight ahead and staring at a far point at eye level. No specific respiratory instructions were given (natural breathing). Four conditions were studied according to the eyes being open (EO) or closed (EC) and the jaws being in resting position (JRP) or in an occlusion position with dental contact (JOC), namely EO-JRP, ED-JRP, EO-JOC and EC-JOC. After a habituation period of experimental conditions, four recordings of one minute (one for each condition) were made in random order. From each one-minute recording, we extracted 40 seconds for the analysis as previously described [11] (figure 1).

C. Data Processing

1) Stabilometric Profile and Body Segment Motion: The motion of the CoP and representative points of the body segments were similarly analyzed in a plane parallel to the ground. For each point, we evaluated the Sway Path (SwayPath) defined as the total distance traveled during the

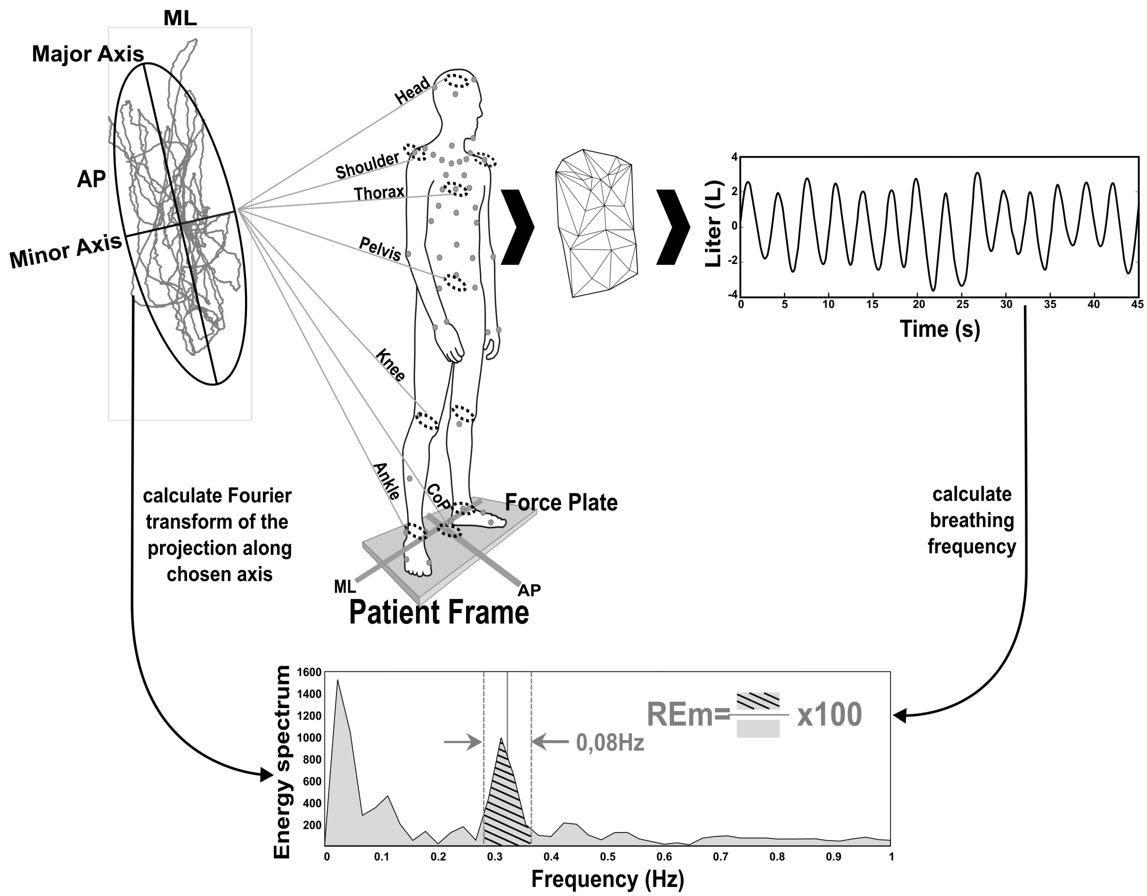

Fig. 1. **Experimental protocol and posture-respiratory coupling assessment.** Subject standing on the AMTI force plate in an optoelectronic system (Vicon) and patient frame; AP: anteroposterior; ML: mediolateral; Left graph: example of 95% confidence ellipse of point motion (CoP and body segment points) in patient frame; Right graph: chest wall volume variations was computed from the 41 markers placed on the trunk, extraction of breathing frequency (BF); Bottom graph: frequency of CoP or body segment point motion; respiratory emergence (REm) calculation from the energy from a 0.08 Hz wide subband centred on the breathing frequency.

acquisition, and the mean velocity (MV). We calculated CoP and body segment, the 95% confidence ellipse of their motion, anteroposterior (AP) and mediolateral (ML) ranges (figure 1). In addition, we evaluated the stochastic parameters using the critical point coordinates ΔR2c (magnitude) and ΔTcN (time) as previously described [24].

2) Breathing: The chest wall volume was computed from the 41 markers placed on the trunk and the respiratory profile was extracted as previously described [11]. Artefacts were manually removed by an expert pulmonologist and the start of inspirations and expirations were identified. The breathing frequency (BF), the inspiratory time (Ti), the expiratory time (Te) and the cycle total time (Ttot) were extracted. We calculated the Ti/Ttot and Te/Ttot ratio.

3) Posturo Respiratory Coupling: The PRC was assessed by calculating the respiratory emergence (REm) on the displacement of the CoP and each body segment point, projected on the AP axis, as previously described [11]. The REm is the percentage of the postural oscillations related to breathing. Briefly, we extracted the energy from a 0.08 Hz wide subband centered on the respiratory rate (local energy) from the spectrum signal of the CoP. Then the ratio between the local energy and the total energy of the spectrum was calculated. REm values theoretically range between 0 and 100% but are generally observed between 10-20% in healthy subjects [11], [13]. The higher the value of REm, the greater the postural perturbation related to breathing.

D. Statistical Analysis

The analysis was performed using MATLAB Version 9.10.0.1684407 (R2021a) and R version 4.0.3 (2020-10-10). All data are presented as median with inter-quartile interval and a p-value <0.05 was considered as significant for all tests. Normality was tested using Shapiro-Wilk's test. To detect the variables of the CoP and segment points that were most affected by the changes in vision and jaw, they were all screened using several nonparametric and parametric tests. The significance of the overall effect of vision and jaw occlusion across the four experimental conditions (EO-JRP, EC-JRP, EO-JOC and EC-JOC) was assessed using the aligned rank test, which is a more powerful variant of Friedman's non parametric test [25] The corresponding p-values are denoted by p_{ar}. To evaluate the significance of the separate effects of vision, jaw occlusion and of their interaction, a repeated measure analysis of variance (ANOVA) with two within-subjects factors was performed, with a prior standardization within subjects. The corresponding p-values (p_{vision}^{anova},p_{jaw}^{anova} $p_{interaction}^{anova}$) are provided with the

Huyn and Feldt correction for departure from sphericity tested with Mauchly's test. Since it turned out that jaw occlusion had little effect, the significance of the effect of vision alone in resting position was also evaluated by comparing the EO-JRP and EC-JRP conditions on the raw data with Wilcoxon's non-parametric paired sign-rank test (p_{vision}^{signr}). The linear associations between the CoP and each of the body segments points on Rem, Sway Path, Mean Velocity, ΔR2c and ΔTcN values were evaluated using the ANCOVA based repeated measures correlation of Bakdash and Marusic [26] in its nonparametric version using bootstrap (1000 bootstrapped samples) with the associated rmcorr R package (https://cran.r-project.org/web/packages/rmcorr/).

III. Results

A. Stabilometric Profile and Body Segments Motion

High magnitude variations were observed across conditions on $SwayPath_{CoP}$ and MV_{CoP} ($p_{ar} < 0.000001$) (table I). These variations were related to the change in visual condition, $SwayPath_{CoP}$ and MV_{CoP} increasing with eyes closed ($p_{vision}^{anova} < 0.000001$) while the jaw position had no effect (table I). Similar results were observed for $SwayPath_{Thorax}$ and MV_{Thorax}, $SwayPath_{Pelvis}$ and MV_{Pelvis}, $SwayPath_{Shoulders}$ and $MV_{Shoulders}$, and $SwayPath_{Head}$ and MV_{Head}, $SwayPath_{Knee}$ and MV_{Knee}, with an effect of high magnitude only for shoulders, thorax and head (table I). The visual-related change between EO-JRP and EC-JRP conditions for both SwayPath and MV was confirmed by the non-parametric analysis for CoP, Shoulders, Thorax, Pelvis and Head body segments ($p_{vision}^{signr} < 0.01$ for all comparisons) (figure 2 and table I). For Range_MajorAxis and Range_MinorAxis of the COP and all body segments, there was no or little overall effect of vision and jaw position (Table II). The coordinates of the critical point varied significantly with the visual condition for the CoP and for all body segments excepted for the ankle, while the jaw position had little effect (Table II).

B. Breathing

The magnitude of the change in Ti, Te and BF across conditions was low and not significant (par ns), however, there was an effect of vision with a significant increase of Ti in the eyesclosed condition ($p_{vision}^{anova} = 0.008$) while the jaw position had no effect (table I).

C. Posturo Respiratory Coupling

REm_MajorAxis and REm_MinorAxis were differently affected by vision and jaw conditions. There was a significant overall change on $REm\_MajorAxis_{CoP}$ across conditions ($p_{ar} = 0.001$), which was also observed on $REm\_MajorAxis_{Thorax}$ ($p_{ar} = 0.0002$), $REm\_MajorAxis_{Shoulders}$ ($p_{ar} < 0.0001$), $REm\_MajorAxis_{Pelvis}$ ($p_{ar} = 0.003$) and $REm\_MajorAxis_{Head}$ ($p_{ar} < 0.0001$), without change on REm_MajorAxis for knee and ankle. The change in $REm\_MajorAxis_{CoP}$ was related to vision ($p_{vision}^{anova} <= 0.0003$) while jaw position had no effect (table I). According to the non-parametric analysis in the jaw resting position, there was a non-significant increase

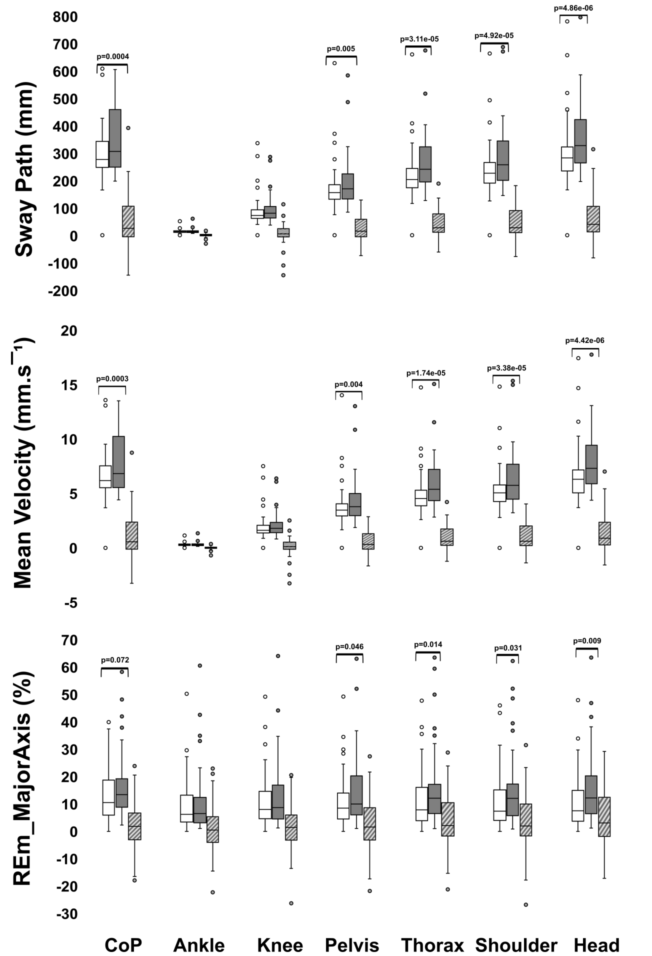

Fig. 2. **Effect of vision on stabilometric and posturo-respiratory coupling variables on body segments and on the CoP.** REm_MajorAxis: respiratory emergence along the major axis of the 95% confidence ellipse of the position of the CoP or of the point representative of a body segment. Comparison between EO-JRP (eyes opened-rest position of the jaw; in white) and ECJRP (eyes closed-rest position of the jaw; in dark grey) conditions. Individual differences between EO-JRP and EC-JRP conditions (in hatched light grey); p-value of Wilcoxon's non-parametric paired sign-rank test (p_{vision}^{signr}).

of $REm\_MajorAxis_{CoP}$ with the eyes closed (difference 1.8 [−3.1; 6.7]; $p_{vision}^{signr} = 0.072$). A significant increase due to vision was however observed for $REm\_MajorAxis_{Thorax}$ (difference 2.1 [−1.7; 10.5]; $p_{vision}^{signr} = 0.014$), $REm\_MajorAxis_{Shoulders}$ (difference 2.0 [−1.7; 10.0]; $p_{vision}^{signr} = 0.031$), $REm\_MajorAxis_{Pelvis}$ (difference 1.6 [−3.2; 8.6]; $p_{vision}^{signr} = 0.046$) and $REm\_MajorAxis_{Head}$ (difference 3.1 [−1.9; 12.4]; $p_{vision}^{signr} = 0.009$) (figure 2 and table I). Regarding the REm_MinorAxis there was a significant overall change across conditions for the CoP ($p_{ar} = 0.019$), which was also observed on the ankle, knee and shoulder ($p_{ar} < 0.05$ for all comparisons; table I). In addition, significant changes related to jaw were observed on $REm\_MinorAxis_{CoP}$, $REm\_MinorAxis_{Thorax}$ and $REm\_MinorAxis_{Shoulders}$ (table I).

D. Correlations Between CoP and Segments

Thorax, pelvis and shoulder were the body segments which best correlated to the CoP for SwayPath, MV, critical point coordinates and REm (figure 3).

TABLE I

VARIATION OF STABILOMETRIC, BREATHING AND POSTURO-RESPIRATORY COUPLING VARIABLES ACCORDING TO VISION AND JAW OCCLUSION

	EO-JRP	EC-JRP	EO-JOC	EC-JOC	p_{ar}	p_{vision}^{signr}	p_{vision}^{anova}	p_{jaw}^{anova}	$p_{interaction}^{anova}$
				Sway Path (mm)					
CoP	278.8 [252.0; 346.0]	307.1 [249.5; 460.9]	278.3 [231.6; 383.6]	348.9 [282.0; 451.1]	5.70E-08	0.0004	1.04E-07	0.144	0.104
Ankle	12.8 [10.4; 16.4]	13.0 [9.7; 16.4]	12.4 [9.8; 17.1]	13.4 [10.3; 17.8]	0.743	0.828	0.753	0.585	0.665
Knee	73.6 [63.0; 94.2]	80.8 [63.1; 105.1]	76.7 [61.3; 99.0]	88.9 [67.9; 104.1]	0.004	0.066	0.005	0.540	0.317
Pelvis	156.6 [136.3; 185.9]	170.0 [133.1; 224.8]	154.0 [124.7; 190.1]	186.0 [146.9; 243.0]	1.04E-06	0.005	5.92E-06	0.357	0.154
Thorax	204.3 [175.2; 244.9]	242.1 [195.5; 324.3]	208.3 [165.7; 260.8]	250.7 [197; 313.8]	6.46E-11	3.11E-05	2.72E-10	0.962	0.187
Shoulder	228.5 [193.8; 267.8]	258.5 [201.1; 345.7]	222.7 [174; 287.4]	285.6 [215.8; 330.9]	1.46E-10	4.92E-05	2.95E-10	0.669	0.165
Head	284.1 [242.2; 324.2]	328.6 [265.0; 424.2]	287.5 [226.5; 349.4]	344.4 [285.4; 453.2]	9.78E-13	4.86E-06	4.71E-12	0.943	0.341
				Mean Velocity (mm/sec)					
CoP	6.2 [5.6; 7.5]	6.8 [5.5; 10.2]	6.2 [5.1; 8.5]	7.8 [6.3; 10.0]	4,47E-08	0.0003	7,98E-08	0.144	0.101
Ankle	0.3 [0.2; 0.4]	0.3 [0.2; 0.4]	0.3 [0.2; 0.4]	0.3 [0.2; 0.4]	0.741	0.828	0.759	0.575	0.666
Knee	1.6 [1.4; 2.1]	1.8 [1.4; 2.3]	1.7 [1.4; 2.2]	2.0 [1.5; 2.3]	0.003	0.060	0.005	0.538	0.314
Pelvis	3.5 [3.0; 4.1]	3.8 [3.0; 5.0]	3.4 [2.8; 4.2]	4.1 [3.3; 5.2]	9.60E-07	0.004	5.59E-06	0.363	0.154
Thorax	4.5 [3.9; 5.4]	5.4 [4.3; 7.2]	4.6 [3.7; 5.8]	5.6 [4.4; 7]	4.60E-11	1.74E-05	1.18E-10	0.943	0.190
Shoulder	5.1 [4.3; 5.8]	5.7 [4.5; 7.7]	4.9 [3.9; 6.4]	6.3 [4.8; 7.4]	1.12E-10	3.38E-05	1.73E-10	0.661	0.162
Head	6.3 [5.3; 7.2]	7.3 [5.9; 9.4]	6.4 [5.0; 7.8]	7.7 [6.3; 10.1]	2.42E-12	4.42E-06	5.90E-12	0.926	0.400
				REm Major Axis (%)					
CoP	10.9 [6.0; 18.9]	13.4 [8.8; 19.2]	9.1 [4.4; 13.8]	16.2 [10.1; 22.1]	0.001	0.072	0.0003	0.956	0.910
Ankle	6.4 [3.5; 13.2]	6.5 [3.1; 12.4]	5.6 [2.7; 12.6]	8.9 [4.5; 17.2]	0.224	0.696	0.061	0.350	0.295
Knee	8.2 [4.9; 15.2]	8.7 [4.5; 16.9]	6.2 [3.2; 10.5]	10.1 [5.0; 20.0]	0.110	0.299	0.063	0.976	0.429
Pelvis	8.7 [4.8; 14.0]	10.0 [6.0; 20.3]	6.9 [4.1; 13.5]	13.3 [7.1; 22.2]	0.003	0.046	0.003	0.714	0.3
Thorax	7.9 [4.2; 16.4]	12.1 [6.5; 17.2]	7.1 [3.2; 13.1]	15.0 [7.0; 21.5]	0.0002	0.014	1.27E-05	0.851	0.254
Shoulder	7.7 [4.1; 15.4]	12.0 [5.7; 17.3]	6.1 [2.9; 10.3]	12.8 [8.0; 21.2]	2.80E-05	0.031	1.22E-06	0.926	0.020
Head	7.7 [3.9; 15.6]	12.2 [6.5; 20.2]	7.0 [3.5; 15.3]	13.8 [7.7; 23.0]	1,86E-06	0.009	5,45E-06	0.402	0.049
				REm Minor Axis (%)					
CoP	7.5 [5.3; 11.5]	8.9 [5.5; 13.5]	8.8 [5.8; 12.8]	10.6 [6.6; 15.3]	0.019	0.149	0.012	0.022	0.905
Ankle	10.8 [6.4; 15.0]	11.3 [7.7; 14.0]	9.0 [5.1; 14.1]	12.1 [8.9; 16.6]	0.003	0.927	0.017	0.849	0.064
Knee	8.9 [6.1; 13.6]	10.2 [7.2; 16.0]	9.3 [6.1; 13.5]	13.1 [8.4; 17.1]	0.022	0.253	0.001	0.480	0.405
Pelvis	8.6 [5.9; 13.6]	10.8 [6.9; 14.5]	9.5 [6.0; 13.5]	12.7 [7.4; 18.5]	0.052	0.342	0.013	0.214	0.553
Thorax	8.5 [5.7; 17.6]	12.2 [9.0; 15.1]	10.7 [6.1; 15.4]	13.6 [7.8; 20.7]	0.063	0.443	0.051	0.028	0.414
Shoulder	8.6 [5.4; 14.2]	12.3 [9.1; 16.4]	11.5 [7.1; 15.3]	13.9 [8.2; 21.7]	0.002	0.023	0.005	0.011	0.872
Head	10.3 [5.8; 17.5]	12.6 [9.2; 17.0]	11.2 [7.1; 15.7]	13.3 [9.0; 21.7]	0.050	0.163	0.006	0.446	0.562
				Breathing profile					
Ti	2.0 [1.6; 2.3]	2.0 [1.7; 2.5]	1.9 [1.7; 2.3]	2.1 [1.7; 2.5]	0.426	0.222	0.008	0.668	0.684
Te	2.0 [1.8; 2.5]	1.9 [1.6; 2.3]	1.9 [1.6; 2.4]	2.0 [1.7; 2.3]	0.516	0.253	0.716	0.687	0.061
BF	16.0 [13.1; 18.2]	15.2 [12.8; 18.5]	16.6 [13.3; 19.1]	15.5 [13.0; 17.7]	0.275	0.942	0.241	0.926	0.115
Ti/ToT	0.5 [0.5; 0.5]	0.5 [0.5; 0.6]	0.5 [0.5; 0.5]	0.5 [0.5; 0.5]	0.361	0.074	0.167	0.675	0.149
Te/ToT	0.5 [0.5; 0.5]	0.5 [0.4; 0.5]	0.5 [0.5; 0.5]	0.5 [0.5; 0.5]	0.361	0.074	0.167	0.675	0.149

Table I : EO: eyes opened; EC: eyes closed; JRP: jaw in rest position; JOC: jaw in occlusion; Ti: inspiratory time; Te: expiratory time; CoP: center of pressure; REm: Respiratory Emergence measured on Major and Minor Axis of the 95% confidence ellipse of the position of the CoP or the representative point of a body segment. Results are expressed as median and interquartile interval; par: p-value of aligned rank test for the overall effect of vision and jaw occlusion; p_{vision}^{signr}: p-value of Wilcoxon's sign-rank test comparing the EO-JRP and EC-JRP conditions; p_{vision}^{anova}, p_{jaw}^{anova}, $p_{interaction}^{anova}$: p-value of effects of respectively vision, jaw occlusion and of their interaction tested with a repeated measure ANOVA. Gray box for $p<0.05$

IV. DISCUSSION

This study is seemingly the first to provide standards for the distribution of PRC along the postural chain. It shows that the assessment of PRC modulations measured on thorax, pelvis and shoulder are the most representative of the PRC measured on the CoP. In healthy subjects, the removal of visual afferents

TABLE II

RANGE OF THE 95% CONFIDENCE ELLIPSE OF POSITION AND CRITICAL POINT COORDINATES ACCORDING TO VISION AND JAW OCCLUSION

	EO-JRP	EC-JRP	EO-JOC	EC-JOC	p_{ar}	p_{vision}^{signr}	p_{vision}^{anova}	p_{jaw}^{anova}	$p_{interaction}^{anova}$
Range Major Axis (mm)									
CoP	25.1 [19.8; 32.7]	26.1 [18.0; 35.0]	23.6 [17.8; 38.2]	27.4 [18.4; 38.3]	0.140	0.215	0.117	0.324	0.295
Ankle	0.8 [0.7; 1.3]	0.8 [0.6; 1.4]	0.9 [0.6; 1.7]	1.0 [0.6; 1.4]	0.411	0.420	0.594	0.471	0.771
Knee	9.9 [7.1; 13.5]	9.9 [6.3; 13.9]	10.2 [6.9; 14.8]	10.8 [7.1; 15.5]	0.749	0.661	0.276	0.268	0.443
Pelvis	24.8 [18.1; 30.8]	23.7 [16.4; 31.8]	22.6 [17.5; 33.6]	26.4 [17.7; 35.5]	0.693	0.776	0.452	0.267	0.338
Thorax	31.8 [24.0; 39.6]	30.6 [24.0; 44.4]	30,6 [22.9; 42.0]	33.8 [23.0; 45.1]	0.531	0.460	0.164	0.352	0.675
Shoulder	33.4 [26.8; 44.1]	34.4 [27,9; 48,9]	32.2 [23.4; 48.0]	36.4 [25.1; 49.3]	0.334	0.286	0.107	0.642	0.608
Head	38.8 [32.6; 50.3]	41.4 [32.0; 55.7]	37.1 [28.9; 56.6]	44.1 [32.2; 56.9]	0.165	0.233	0.053	0.663	0.486
Range Minor Axis (mm)									
CoP	7.5 [5.0; 9.3]	7.4 [4.5; 8.9]	6.7 [5.3; 9.1]	6.9 [5.0; 9.8]	0.765	0.437	0.456	0.619	0.220
Ankle	0.4 [0.3; 0.6]	0.4 [0.3; 0.5]	0.4 [0.3; 0.6]	0.5 [0.3; 0.6]	0.610	0.540	0.443	0.343	0.929
Knee	3.0 [2.1; 4.2]	3.1 [1.6; 3.9]	2.9 [2.0; 4.3]	3.0 [2.0; 4.6]	0.700	0.169	0.372	0.948	0.301
Pelvis	5.9 [3.8; 8.3]	6.0 [3.2; 7.8]	5.7 [3.6; 8.1]	5.6 [3.4; 8.7]	0.420	0.166	0.156	0.460	0.270
Thorax	8.9 [6.0; 12.3]	8.2 [6.0; 10.9]	8.0 [6.5; 9.6]	7.8 [6.2; 11.8]	0.708	0.291	0.329	0.939	0.188
Shoulder	9.1 [6.5; 13.0]	9.3 [6.5; 11.1]	8.6 [6.9; 10.9]	8.9 [6.4; 10.8]	0.570	0.273	0.507	0.387	0.488
Head	12.0 [9.7; 16.5]	12.3 [9.4; 16.0]	11.8 [9.1; 15.4]	12.7 [8.6; 16.4]	0.603	0.460	0.818	0.940	0.742
ΔR2c (mm2)									
CoP	17.3 [10.3; 38.5]	26.6 [14.5; 67.6]	16.1 [7.0; 32.6]	29.8 [19.5; 66.8]	3.61E-06	0.0002	2.17E-07	0.522	0.353
Ankle	0.0 [0.0; 0.1]	0.0 [0.0; 0.0]	0.0 [0.0; 0.0]	0.0 [0.0; 0.1]	0.226	0.138	0.073	0.643	0.441
Knee	0.7 [0.6; 0.9]	0.7 [0.6; 0.9]	0.7 [0.6; 0.8]	0.8 [0.6; 0.9]	0.059	0.160	0.032	0.670	0.188
Pelvis	17.6 [6.8; 26.6]	17.6 [9.1; 38.8]	10.8 [4.6; 26.3]	21.5 [13.2; 50.3]	0.0007	0.023	0.0004	0.546	0.180
Thorax	27.9 [12.6; 50.4]	34.3 [20.3; 77.4]	20.3 [11.7; 40.9]	47.3 [26.3; 75.2]	7.08E-06	0.002	2.21E-07	0.484	0.201
Shoulder	34.4 [15.3; 66.4]	42.2 [23.4; 95.4]	23.5 [13.9; 48.7]	55.4 [33.3; 93.8]	1.59E-07	0.0005	4.51E-08	0.479	0.175
Head	39.7 [23.8; 87.5]	66.7 [36.5; 137.3]	35.0 [21.4; 61.8]	82.7 [48.4; 129.7]	9.22E-09	6.05E-05	5.48E-0	0.419	0.217
ΔTcN (sec)									
CoP	0.6 [0.4; 0.8]	0.6 [0.5; 0.8]	0.5 [0.4; 0.6]	0.6 [0.5; 0.7]	0.0002	0.157	0.0004	0.019	0.374
Ankle	0.6 [0.5; 0.8]	0.6 [0.5; 0.8]	0.5 [0.4; 0.7]	0.7 [0.5; 0.8]	0.028	0.958	0.028	0.820	0.082
Knee	0.7 [0.6; 0.9]	0.7 [0.6; 0.9]	0.7 [0.6; 0.8]	0.8 [0.6; 0.9]	0.067	0.515	0.049	0.122	0.435
Pelvis	0.8 [0.7; 1.1]	0.8 [0.7; 1.0]	0.7 [0.6; 0.9]	0.9 [0.8; 1.0]	0.016	0.509	0,049759	0.089	0.180
Thorax	0.9 [0.7; 1.2]	0.9 [0.8; 1.1]	0.8 [0.7; 0.9]	0.9 [0.8; 1.1]	0.007	0.286	0.015	0.077	0.291
Shoulder	0.9 [0.7; 1.2]	0.9 [0.8; 1.1]	0.8 [0.7; 1.0]	1.0 [0.8; 1.1]	0.009	0.332	0.023	0.121	0.300
Head	0.9 [0.6; 1.0]	0.8 [0.7; 1.0]	0.7 [0.7; 0.9]	0.9 [0.8; 1.0]	0.006	0.106	0.002	0.133	0.586

Table II: EO: eyes opened; EC: eyes closed; JRP: jaw in rest position; JOC: jaw in occlusion; CoP: center of pressure; Range Major Axis and Range Minor Axis: ranges following major and minor axis of the 95% confidence ellipse of the position of the CoP or of the representative point of a body segment; Results are expressed as median and interquartile interval; par: p-value of aligned rank test for the overall effect of vision and jaw occlusion; p_{vision}^{signr}: p-value of Wilcoxon's sign-rank test comparing the EOJRP and EC-JRP conditions; p_{vision}^{anova} $p_{jaw}^{anova}$$p_{interaction}^{anova}$: p-value of effects of respectively vision, jaw occlusion and of their interaction tested with an repeated measure ANOVA. Gray box for p<0.05.

induced modulations of the PRC while changes in jaw position had little effect.

A. Physiological Modulations of the PRC

Optimal balance in standing position is constantly adjusted based on the integration of multiple sensory information [27]. In our subjects, we observed significant changes in the stabilometric profile when closing eyes, while the jaw position had little effect. Similar findings were previously reported in healthy subjects [27], [28]. Our large sample also confirmed that the REmCoP ranged between 5 and 20% in the reference condition (eyes opened and jaw at rest), which was comparable to values reported previously in smaller studies [11], [13]. Not described before, we observed that the removal of visual afferents triggered an increase of the PRC. Vision and breathing are centrally connected, as illustrated by the ability of visuorespiratory manipulations to interfere with bodily self-consciousness [29]. We hypothesize that, in our experiment,

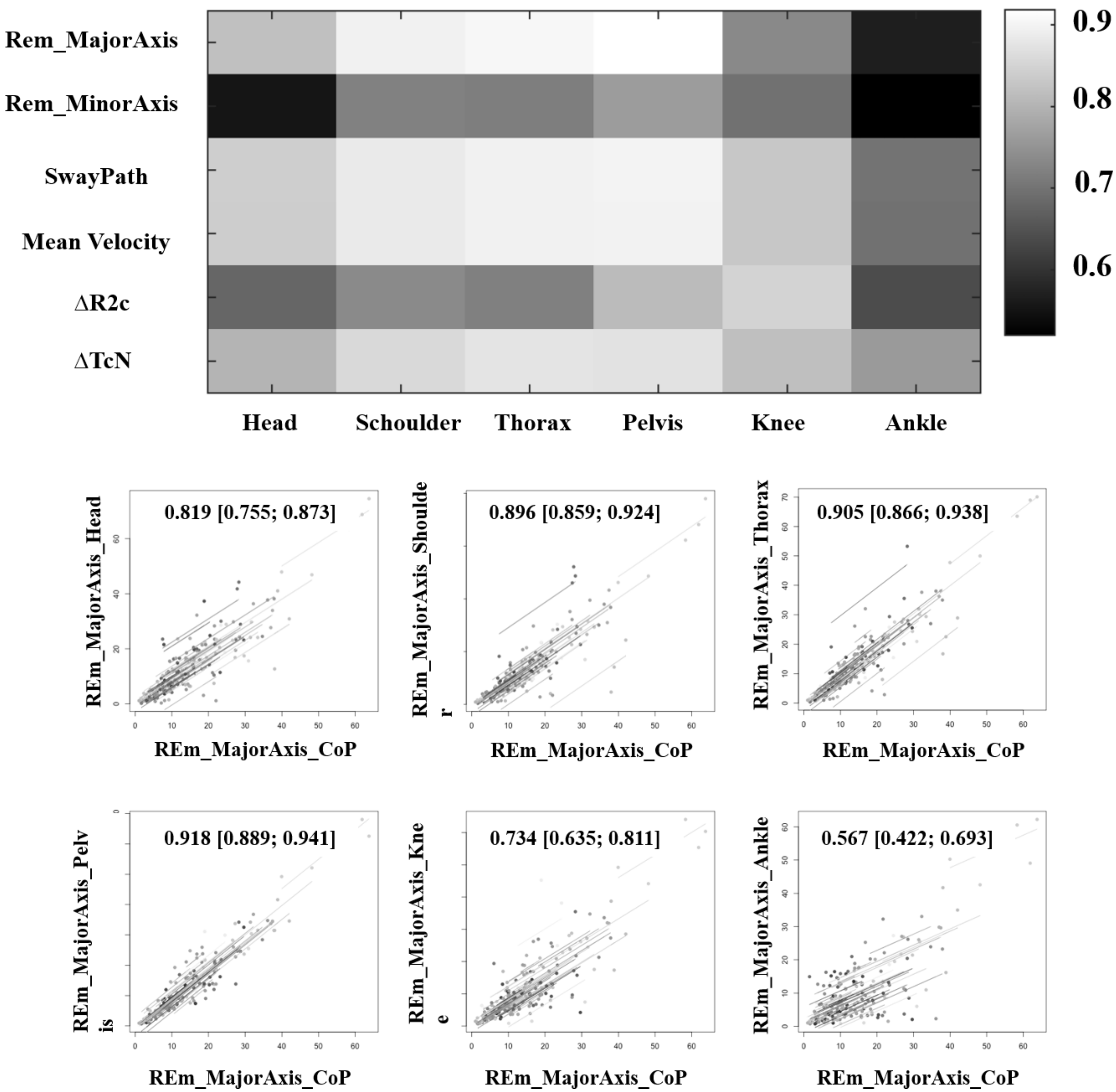

Fig. 3. **Correlations between CoP and body segments on stabilometric and posturo-respiratory variables.** Top Correlations between CoP and body segments for respiratory emergence along the major axis (REm_MajorAxis) and the minor axis (REm_MinorAxis) of the 95% confidence ellipse of the position of the CoP or of the representative point of each body segment; Sway Path (SwayPath); mean velocity (MV); and the critical point coordinates ΔR2c (magnitude) and ΔTcN (time).

removing visual feedback could have modified the baseline visuo-respiratory interaction, thereby modifying bodily self-consciousness [29] with possible consequences on balance and PRC. This hypothesis is supported by the occurrence of breathing pattern changes when visual afferent are removed (increase in Ti). It is also indirectly supported by closing eyes induced variations of the critical point coordinate in the stochastic analysis of the CoP and body segment motions which suggest that a visual-dependent central regulation of balance was triggered [24]. We therefore submit that our results support the existence of a central PRC modulation depending on visual afferents.

B. Segmental Analysis of the PRC Towards a Simplified Assessment Method

Our experimental protocol using an optoelectronic system coupled to a force platform to assess the PRC based on the CoP oscillations [11], [21], constitutes a limitation for clinical use. In the perspective of a transfer of our approach to routine practice, and based on the fact that the PRC is distributed along the postural chain [11], [15], we proposed to assess the PRC through the postural displacements a of body segments. This study helped to identify the three segments of interest: “shoulder” “pelvis” and “thorax” exhibited a behavior closest to that of the CoP with respect to stabilometric and PRC values. These results appear particularly interesting in the perspective of the development of a contactless airborne ultrasound device capable of simultaneously assessing breathing pattern and PRC displacements to study respiratory-related postural disturbancies in the clinical field [22].

C. Implication for Early Detection of Postural Dysfunction in Chronic Respiratory Disease

The PRC is centrally controlled which is attested by the existence of “anticipatory postural adjustments” (cortical in nature) of the diaphragm in its role in maintaining posture and balance [30]. The central control of the PRC is also supported by its alteration in patients with cortical stroke [31]. In addition this hypothesis is supported by the existence of “attentional competition” in dual-task situations between balance and breathing [11] and between locomotion and breathing [32]. Finally, cortical structures (motor, premotor and supplementary motor areas) that are involved in movement initiation and preparation are also involved in breathing control [33] and presumably in the PRC control [11]. A pathological adaptation of the respiratory-related cortical networks has been described in chronic respiratory diseases such as COPD [34] and OSAS [35], for which alteration of balance and gait have also been reported [18], [36], [37]. This abnormal respiratory-related cortical activity could be one of the main mechanisms leading to the altered PRC and balance we reported in OSAS patients without apparent postural dysfunction [21]. In addition, increased cortical respiratory activity has been associated with increased consumption of cognitive resources, in healthy humans under inspiratory load [38] and in patients with congenital central hypoventilation [39], which may itself be responsible of postural dysfunction through a mechanism of “attentional competition”. Thus PRC alteration would precede clinical manifestations of imbalance in patients with chronic respiratory disease, particularly in OSAS [18], [19] and COPD [36], [37] and PRC assessment would help to detect early postural dysfunction.

D. Potential Effect of Vision and Jaw Occlusion in Patients With Chronic Respiratory Disease

Our study provides reference data for PRC and its sensory related modulations. We chose to focus on the effects of vision and jaw occlusion, which are likely to vary in a standing position, the condition in which we recorded the subjects. Based on these results it appears that adding a visual challenge would help to sensitize the PRC assessment in patients. Conversely, jaw occlusion had little effect on PRC in our healthy participants. However, we observed a change in REm_MinorAxis for the CoP, as well as for the thorax and the shoulder. The jaw occlusion was associated in previous studies to changes in the stabilometric profile of healthy subjects when challenging the balance control (unstable platform and/or fatigue) [28]. Hyperventilation [13] and or misalignment linked to hyperinflation (COPD) [36] or cervical spine extension (OSAS) [21] may also be challenging in patients. In addition, an altered stabilometric profile and an altered PRC on the minor axis of the 95% confidence ellipse of the position of CoP, were reported in a previous study in OSAS patients. In this context, PRC modulations are expected not to be negligible under jaw occlusion, particularly on the minor axis of the 95% confidence ellipse of the position of the CoP and of two body segments of interest (thorax and shoulder), but this remains to be evaluated in patients.

E. Limitations

We acknowledge that the critical point coordinate may be subject to certain variability [40] and for this reason we used the stochastic variables only for a sensitivity analysis. We acknowledge that we have not established a link between clinical postural dysfunction, gait alteration or falls previously reported in patients with chronic respiratory disease, and PRC alteration, a question which remains to be addressed in future studies. In this study we used our experimental protocol using an optoelectronic system to assess the PRC. We acknowledge that our results remains to be validated using the airborne ultrasound device which constitutes a perspective of the present study [22].

V. Conclusion

This study indicates that posturo-respiratory coupling assessment should be possible by measuring the Respiratory Emergence from the shoulder, pelvis and thorax body segments. Adding a visual challenge is expected to sensitize this evaluation. This should simplify the assessment of respiratory-postural interactions in clinical practice in patients with chronic respiratory disease

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Declaration of Competing Interest

Dr. SIMILOWSKI reports personal fees for consulting and teaching activities from ADEP Assistance, AstraZeneca France, Chiesi France, KPL consulting, Lungpacer Inc., OSO-AI, TEVA France, Vitalaire, all outside the submitted work. Dr. ATTALI reports personal fees for consulting from Bioprojet and Resmed outside the submitted work. The others authors declare no conflict of interest with respect to the research.

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