Effect of precision aiming on respiration and the postural-respiratory synergy

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**Abstract**

Precision manual tasks require a stable postural background which might be facilitated by respiratory modulations. We investigated the influence of performing a manual precision aiming task on respiratory rate and dynamics, and the coherence between respiration and center of pressure (COP) fluctuations (i.e., the postural–respiratory synergy). Participants aimed a pointer at targets of different sizes while seated or standing. Respiratory rate increased during the aiming period compared to a pre-task phase, but did not vary as a function of aiming difficulty. Recurrence quantification analysis revealed an increased incidence of slowly changing periods of chest movements during the most difficult aiming condition, which required the highest level of manual precision. Aiming, irrespective of difficulty, led to increases in the regularity of the respiratory pattern. Increases in respiratory rate during aiming were accompanied by an increased level of coherence for the seated but not the standing posture, suggesting that task demands affect the organization of coordination across the postural-respiratory synergy. Functional demands of the task likely shape the effectiveness of compensation for respiration during precision aiming.

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The primary function of respiration is to meet the body's metabolic demands. However, respiration also has implications for neuromotor control. The most extensively studied kind of respiratory–motor interaction has been locomotor–respiratory coupling [4]. Besides that phenomenon, respiration serves as a global background for balance and movement, influencing the stability and precision of focal hand movements [15]. Compared to locomotor–respiratory coupling, coordination between respiration, postural stability, and fine motor control has not been extensively studied.

Respiratory movements of the chest can influence postural stability by either mechanically perturbing the body or through neuromuscular crosstalk [10]. Previously, a postural-respiratory synergy (PRS) was hypothesized to compensate for these potentially destabilizing effects of respiration on balance control [3,6,9]. Compensation for respiratory movements of the chest occurs via active control of segmental rotations about the joints of the lower limbs [6,9] and passive, viscoelastic properties of the muscles and connective tissues of the postural chain [7,8].

Interactions between motor control and respiration are especially apparent when performing fine motor tasks that require a high degree of precision (threading a needle or performing surgery). Voluntary modulations of respiration such as temporary breath holding or shallow breathing might facilitate motor performance in such situations by stabilizing the body. Anecdotal evidence suggests that such respiratory modulations are commonplace, but the prevalence and nature of respiratory modulations have not been widely studied. Performance of precision manual tasks also induces adaptive and compensatory changes in postural control (as measured by the variability as well as dynamics of the center of pressure [COP]) [2,17]. In light of the links between respiration, balance, and movement, these task-specific changes in the COP might be accompanied by changes in respiratory rate, volume, or dynamics (i.e., the pattern of breaths across time).

The aims of this study were to determine whether the rate or dynamics of respiration change when performing an aiming task requiring high manual precision, and, if so, to determine the relation between these modulations and postural control. We expected respiratory rate to increase while performing the aiming task compared to a pre-task, based on previous studies showing that tasks requiring concentration are associated with increased metabolic demand [5]. However, despite the overall increase in respiratory rate, the increased precision demands of the aiming task were hypothesized to induce short periods of breath holding and consequently relatively slower breathing rate so that respiratory movements would not interfere with aiming performance—a possible strategy to minimize unnecessary movement. We used recurrence quantification analysis (RQA) to quantify these periods of slowly changing respiratory movement using the trapping time measure described below [14]. We quantified the amount of spectral coherence between respiration and the anterior–posterior (AP) COP at the dominant frequency of respiration as a measure of the activity of the PRS, following Hodges et al. [9]. Low coher-
ence reflects a stronger PRS synergy that minimizes the influence of respiration on the COP more effectively. Increased respiratory activity (e.g., greater rate or inspiratory volume) poses a greater challenge for the postural system [3,6,11]. Because performance on the aiming task was expected to increase respiratory rate compared to the pre-task, we hypothesized that coherence would increase during aiming compared to the pre-task. We expected this effect of task performance on coherence would be greater when performed by seated participants compared to standing participants, since the PRS is less effective when seated—the lower limbs cannot as effectively compensate for respiratory movements in this position [3,12,19], although the spinal column can potentially compensate and participants might be able to use their feet (which were in contact with the floor) to brace the body against respiratory perturbations. Finally, based on previous results [2,17], we expected that aiming task performance would be associated with decreased COP variability.

Forty students participated for course credit. There were 10 men and 10 women in the standing group and 12 men and 8 women in the sitting group. The average age in the standing group (M = 22.35, SD = 4.41) was slightly higher than in the sitting group (M = 19.17, SD = 1.85), t(38) = 2.71, p = 0.01. All participants signed a consent form approved by the local Institutional Review Board.

Respiratory movements of the chest were sampled at 1000Hz using a Biopac (Biopac Systems, Inc., Goleta, CA) TSD-201 respiratory effort transducer and RSP100C amplifier. Data were band-pass filtered with cut-off frequencies of 0.05 and 1 Hz. The belt containing the transducer was placed around the rib cage at the level of the xiphoid process. An AMTI AccuSway+ force platform (AMTI Water- town, MA) was used to obtain COP time series at 100 Hz. For the sitting condition, the force platform was placed on a chair. Participants sat so that the plate provided support for roughly 2/3 of the distance between the ischium and knee, and placed their feet on the floor. It is important to note that comparisons between the whole-body COP signal from the standing condition and the upper-body COP from the sitting condition must be qualified because the signals are qualitatively different; seated participants placed their feet on the floor, so the force platform did not capture all aspects of postural motion in that condition. After completion of this experiment, subsequent testing using two force platforms suggested that vertical ground reaction forces at the feet equaled approximately 5–6% of the body mass of seated participants.

A Nintendo Wii-remote connected to a PC running Darwin Remote software was used for the manual aiming task. Customized Matlab code was used to present the task and measure performance. The location of the current aim was presented by a visible red dot (0.15° visual angle) on a 24-in. LCD monitor with a 60 Hz refresh rate placed at eye level 170 cm away from participants.

Participants aimed the remote at targets of three different sizes (0.2°, 0.5°, and 0.8° visual angle) manipulated as a within-subjects factor. Each trial (120 s) consisted of three phases. During the first 30 s participants aimed the remote toward the center of the screen without explicit precision instructions. This pre-task period was immediately followed by the aiming task. Participants pointed at targets that appeared on the screen one at a time and pressed the remote’s B button to “hit” them. The instruction was to aim as accurately as possible before pressing the button and attempt to press only once per target. Each target appeared for 2 s. If participants successfully hit the target before 2 s elapsed, it turned green and remained on the screen for the rest of the 2 s before disappearing. If participants did not hit the target within 2 s, it disappeared. After the previous target disappeared, a new one appeared at a random location. Thirty targets were successively displayed during the 60 s task phase. Immediately afterward, the screen turned blank again and participants pointed toward the center of the screen for 30 s. Each difficulty condition was repeated twice. Six total trials were performed with 30–60 s breaks between trials. Participants performed this task in one of two postures manipulated as a between-subjects variable: Seated or standing. In both postures, participants were asked to minimize unnecessary movements.

**Average respiration measures.** Measures from the respiratory effort transducer were normalized to have a zero mean and unit SD. Respiratory rate was calculated as 60/inter-breath interval and expressed in breaths per minute (BPM).**

**Recurrence rate and trapping time.** Recurrence quantification analysis [RQA; 21] is based on recurrence plots, which provide visualizations of the repetition (recurrence) of trajectories along a reconstructed attractor. RQA requires the identification of a time delay and embedding dimension from the measured signal [16,21]. Time delay was calculated for each trial individually using the average mutual information (AMI) function, and embedding dimension was estimated using the global false-nearest-neighbor algorithm (FFN; 1% tolerance) [11]. Delay values averaged 11.22 samples (SD = 4.22). An embedding dimension of 8 was used for each trial. RQA radius was selected (without normalization of the distance matrix) for each trial so as to keep the recurrence rate (RR; the proportion of the number of recurrent points to the total number of possible recurrences) at 2% using a Theiler window of 10 samples.

We used trapping time (TT; 14) to capture short periods of relative slowing of the respiratory chest movements, which could result from transient periods of breath holding. TT gauges the amount of time a system remains in a specific region of the attractor. Recurrence plots were created from the normalized respiratory time series over each 120 s trial using the parameters described above and then divided into four windows corresponding to the pre-task (0–30 s), early-task (30–60 s), late-task (60–90 s), and post-task (90–120 s) phases. Recurrence rate and TT for the early and late task phases were computed over the respective 30 s windows and then averaged to obtain an overall measure of the dynamics in the task phase, because time series length could affect the results if these measures had been computed over 60 s of data from the task phase, resulting in invalid comparisons to the shorter pre- and post-task phases.

**Coherence.** We calculated the coherence between the respiratory signal and AP-COP at the dominant frequency of respiration (detected as the largest peak in the respiratory power spectrum) for each phase of each trial: pre-task, early task, late task, and post-task. Coherence (Matlab’s mscohere function) was calculated using a 512-point Hamming window with 50% overlap. FFT length was 512 points resulting in a frequency bin size of 0.19 Hz. We chose these parameters based on the length of the analyzed COP segments (2500 points) per segment.

**COP Variability.** The local standard deviation (SDL) of the AP-COP was computed to quantify COP variability. SDL [17] is the within-trial average of the standard deviation (SD) computed over non-overlapping, 1 s data windows. SDL is less affected by slow drift than the SD of the entire COP time series, and captures fine-grained COP variation.

Dependent measures were averaged across the two trials per difficulty condition to obtain mean values for the pre-task, task, and post-task phases. For each measure a three-way mixed-design analysis of variance (ANOVA) with stance (sit vs. stand) as a between-subjects factor and aiming difficulty (targets of 0.2°, 0.5°, and 0.8° visual angle) and trial phase (pre-task, task, and post-task) as within-subjects factors was first conducted. To evaluate task difficulty hypotheses, we conducted planned stance > aiming difficulty mixed-factors ANOVAs for the task phase. Tukey-corrected post-hoc F-tests were conducted following the overall analysis. The significance level was set at 0.05.

Participants hit significantly fewer targets as target size decreased, F(2,76) = 106.72, p < 0.001. The smallest, most difficult
targets had fewer hits ($M = 23.88, SD = 3.64$) than medium-sized targets ($M = 28.60, SD = 1.67$) which had fewer hits than large targets ($M = 29.58, SD = 0.58$), $F(1,139) = 132.42, p < 0.001$, and $F(1,39) = 15.86, p < 0.001$, respectively. Stance and the stance × difficulty interaction were not significant.

Respiratory rate. There was a main effect of trial phase on respiratory rate (Fig. 1, top), $F(2,76) = 37.49, p < 0.001$. Respiratory rate was significantly greater in the task phase ($M = 20.54$ BPM, $SD = 3.42$) than the pre-task ($M = 17.84, SD = 3.11$) and post-task ($M = 18.76, SD = 3.29$) phases, $F(1,119) = 104.31, p < 0.001$, and $F(1,119) = 76.07, p < 0.001$, respectively. Respiratory rate remained higher in the post-task than in the pre-task, $F(1,119) = 22.82, p < 0.001$. There was a stance × task phase interaction such that respiratory rate in the pre- and post-task (but not during the task phase) was lower in the seated than the standing condition, $F(2,76) = 3.33, p = 0.04$. The planned one-way ANOVA comparing respiratory rate across the three aiming difficulty conditions within the task phase was not significant, $F(2,76) = 1.33, p > 0.05$. Stance and the stance × difficulty interaction were not significant.

Recurrence rate. There was a main effect of trial phase on RR (Fig. 1, middle), $F(2,76) = 18.58, p < 0.001$. RR was greater in the task phase ($M = 5.04, SD = 1.29$) than in the pre-task ($M = 3.40, SD = 1.94$) and post-task ($M = 3.44, SD = 1.34$), $F(1,119) = 44.10, p < 0.001$, and $F(1,119) = 81.78, p < 0.001$, respectively. The pre- and post-tasks did not differ ($p > 0.05$). The planned one-way ANOVA revealed an effect of aiming difficulty within the task phase, $F(2,76) = 7.43, p = 0.001$. The difficult condition had higher RR ($M = 5.45, SD = 1.39$) than the medium ($M = 4.88, SD = 1.22$) and easy conditions ($M = 4.79, SD = 1.19$), $F(1,119) = 9.79, p = 0.006$, and $F(1,119) = 12.18, p = 0.002$, respectively. The easy and medium conditions were similar ($p > 0.05$).

Trapping time. There was a main effect of trial phase on TT (Fig. 1, bottom), $F(2,76) = 5.34, p = 0.01$. TT decreased in the post-task compared to the pre- and task-phases, $F(1,119) = 7.58, p = 0.01$, and $F(1,119) = 6.14, p = 0.03$, respectively. The planned one-way ANOVA within the task phase found a significant effect of aiming difficulty, $F(2,76) = 5.21, p = 0.01$. The most difficult condition had higher TT ($M = 3.49, SD = 0.60$) than the medium ($M = 3.26, SD = 0.62$) and easy conditions ($M = 3.29, SD = 0.63$), $F(1,39) = 12.36, p < 0.001$, and $F(1,39) = 5.98, p < 0.01$, respectively. The medium and easy aiming conditions were equivalent ($p > 0.05$).

Coherence: Postural-respiratory coupling. As expected, there was a main effect of stance on coherence between respiration and the AP-COP, $F(1,38) = 28.04, p < 0.001$ (Fig. 2). Coherence was significantly greater for seated ($M = 0.42, SD = 0.30$) than standing participants ($M = 0.16, SD = 0.10$). As expected, there was also a main effect of task phase, $F(2,76) = 23.38, p < 0.001$. Coherence increased during the task phase ($M = 0.38, SD = 0.30$) compared to the pre-task ($M = 0.22, SD = 0.20$) and post-task ($M = 0.26, SD = 0.25$), $F(1,119) = 57.02, p < 0.001$, and $F(1,119) = 29.50, p < 0.001$, respectively, and post-task coherence was higher than in the pre-task, $F(1,119) = 6.04, p = 0.04$. However, the significant phase × stance interaction, $F(2,76) = 16.70, p < 0.001$, indicated that the task-phase increase in coherence was only significant for participants who were seated (pre-task: $M = 0.30, SD = 0.24$; task: $M = 0.60, SD = 0.28$; post-task: $M = 0.37, SD = 0.30$); for standing participants there was no significant effect of task phase (pre-task: $M = 0.14, SD = 0.14$; task: $M = 0.17, SD = 0.09$; post-task: $M = 0.16, SD = 0.10$).

COP variability. SD$_t$ of the AP-COP was significantly greater when standing ($M = 11.94$ mm, $SD = 3.05$ mm) than seated ($M = 2.29, SD = 1.02$), $F(1,38) = 323.65, p < 0.001$. There was a main effect of trial phase on SD$_t$, $F(2,76) = 5.37, p < 0.001$. SD$_t$ was lower in the task phase ($M = 6.60, SD = 4.83$) than the pre-task ($M = 7.88, SD = 5.59$) and post-task ($M = 10.16, SD = 5.84$), $F(1,119) = 26.72, p < 0.001$, and $F(1,119) = 7.56, p < 0.01$, respectively. Pre- and post-task SD$_t$ did not differ ($p > 0.05$). There was a stance × phase interaction, $F(2,76) = 3.63, p < 0.03$. Simple effects analysis showed that SD$_t$ decreased during task performance in the standing but not the seated condition, $F(2,38) = 4.58, p = 0.02$, and $F(2,38) = 1.73, p = 0.19$, respectively. There was no effect of aiming difficulty during the task phase ($p > 0.05$).

The main objective of this study was to determine the extent and nature of interplay among respiration, postural control, and fine motor control. The results revealed a complex but clear set of relations among these processes. The main results were that (1) respiratory rate increased during task performance but did not change with changes in precision requirements, (2) respiratory chest movements became more regular during aiming, especially for the difficult condition (higher RR), and showed more slowly varying dynamics (increased TT) in the most difficult aiming condition, (3) coherence between respiration and the AP-COP increased during the aiming task only for seated but not standing participants, and (4) SD$_t$ of the AP-COP when standing was lower during task performance than during the pre- and post-task phases.

Increases in respiratory rate during task performance most likely occurred due to increased metabolic demand and arousal due to concentration on the task. While the energetic demands of the task were probably small, there are subtle energy demand increases even during performance of cognitive tasks [5]. Increased metabolic demand can accompany heightened arousal, and activity of the sympathetic nervous system is likely to require increased metabolic support to sustain those physiological processes.

The increase in precision requirements during the aiming task phase led to subtle changes in respiratory dynamics (increased TT and RR) while respiratory rate was unaffected by task difficulty. Hitting the most difficult targets required fine motor control of the fingers and hands. The RQA results suggest that respiratory chest
movements under these conditions showed more periods of breath holding (increased TT) and became more regular (increase in RR). These modulations of respiratory dynamics could have reduced the severity of or increased the predictability of respiration-related perturbations of hand position to facilitate performance in this challenging task [15]. Increases in the regularity of respiratory chest movements may reflect reactive tuning [13] in response to novel task constraints that require the system to operate in a new stable state.

Increases in respiratory parameters such as rate or volume are typically associated with larger COP displacements [3,6,11]. Previous research has largely focused on identifying characteristics of postural responses to increased respiratory movements in the absence of any behavioral goal apart from remaining upright [6,9]. Earlier studies that observed increases in the degree of coupling between respiration and the COP manipulated respiratory rate by metronome pacing [11,19] or by introducing respiratory dead space to increase volume [9]. Those manipulations do not directly introduce any relevant behavioral consequences apart from remaining upright [20], so it is likely that there was no functional need to effectively engage the PRS since the respiratory changes were unlikely to threaten postural stability to the point of inducing a fall or a step.

In the present study, the aiming task introduced an additional functional constraint on postural stability. For participants who performed the task while standing, the increase in respiratory rate during the task phase was not accompanied by an increase in coherence between respiration and the AP-COP, and SDh of the AP-COP was lower during the task phase than during the pre- and post-task phases. These results suggest that the PRS can compensate for the increased influence from the respiratory system when there is a functional benefit in supporting fine motor control and when multiple joints of the leg are available to provide compensations. We propose that increased respiratory activity does not invariably and automatically lead to a weaker PRS synergy as suggested before [6,9]. Instead, the strength of the PRS during standing appears to be modulated by the behavioral context.

The compensatory mechanisms engaged to reduce respiratory perturbations to postural stability rely on both active motor control strategies [6,9] and passive, viscoelastic, dampening properties of the postural chain [7,8]. It is difficult to assess whether compensation was primarily active or passive in this experiment. One possibility is that concentration on the task promoted overall “stiffening” or “freezing” of the postural chain (as suggested by the decreased SDh) due to increased muscle tension [cf. 18]. In the absence of any active regulatory processes, the likely result would have been an increase in the perturbing role of breathing, because muscle stiffening reduces postural steadiness [8]. However, the decrease in SDh occurred despite the increase in respiratory rate, suggesting an active modification of postural control to offset that potential perturbation in order to facilitate the fine motor control demands of the aiming task [2].

In contrast to the standing condition, participants who performed while seated did exhibit an increase in coherence between respiration and the AP-COP, and did not exhibit a decrease in SDh during the task phase. Jointly, these results suggest that there may be fewer possibilities for postural reorganization while sitting, since many of the joints that could participate in compensating for respiration are effectively immobilized. However, sitting did not disrupt aiming task performance, so the limited ability to compensate may not have had functional consequences. In addition, our participants’ feet touched the floor when participants were seated, so it is possible that they may have used the legs and feet to brace the torso against respiratory modulations. As noted previously, comparisons of COP measures between the standing and seated conditions must be qualified by the qualitative differences in the COP signal between those two conditions.
This study revealed a complex interplay between respiration, postural control, and precision motor control. Performing the precision aiming task led to increases in respiration rate and regularity. The potentially disturbing effects of respiration were attenuated by compensatory changes in the dynamics of respiratory chest movements and by the task-specific activity of the PRS. In future studies on the impact of supra-postural behavioral goals on postural control processes, it may be important to consider the role of respiration and its connections to the postural system.

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References