

Effect of airway control by glottal structures on postural stability

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Massery M, Hagins M, Stafford R, Moerchen V, Hodges PW. Effect of airway control by glottal structures on postural stability. *J Appl Physiol* 115: 483–490, 2013. First published June 13, 2013; doi:10.1152/jappphysiol.01226.2012.—Maintenance of upright posture involves complex neuromotor processes that include control of thoracic and abdominal pressures. Control of airflow by glottal structures is a primary determinant of thoracic pressure and may have a role in control of postural stability. This study aimed to investigate the effect of modulation of airway control on upright postural stability during postural perturbations. Standing balance was gently perturbed in the sagittal plane during 7 breathing/voicing tasks that ranged from completely closed (breath-hold), to partially opened (voicing) or completely open (sigh) glottal conditions in 11 healthy adults. Dependent measures were peak amplitude of displacement of the thorax and center of pressure (CoP). When the glottis was completely open during sigh, thoracic displacement in response to the perturbation was greater than in all other conditions, regardless of direction of perturbation (post hoc, all $P < 0.002$). The absolute amplitude of CoP displacement was greater with backward perturbation (main effect, Direction $P = 0.001$) and was greater at both extremes of glottal modulation (glottis closed and completely open) than when the glottis was partially opened during counting out loud (post hoc, all $P < 0.04$). These results show that airway modulation affects postural control during upright perturbations. The thorax was more stable when the glottis was engaged than when it was required to remain open, whereas control of CoP displacement appeared more optimal during the natural dynamic mid-range airway modulation of voicing. These data suggest that glottal control influences balance, and that glottal control strategies may be an important consideration for patients with breathing and/or balance disorders.

postural control; glottis; balance reactions; thoracic pressure; voicing

MAINTENANCE OF UPRIGHT POSTURE involves complex neuromotor processes. Although research related to postural control of the trunk has largely focused on the role of abdominal and erector spinae (ES) muscles (24, 33), control of pressures in the thoracic and abdominal cavities make an important contribution (14, 17). Recent research has highlighted the role of other muscles that influence intrathoracic (ITP) and intraabdominal (IAP) pressures such as the diaphragm (1, 6, 20, 49), intercostal (2, 26, 38), and pelvic floor muscles (25, 39, 44, 47, 48). If ITP and IAP are important for postural control of the trunk it follows that control of airflow by glottal structures, a primary determinant of ITP, should be important for efficient control of postural stability.

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The role of the diaphragm in postural control has been extensively explored in humans and animals (6, 8, 18, 20, 21, 43, 49). Human (19) and animal data (18) show enhanced mechanical support of the spine with electrically evoked diaphragm contraction. The diaphragm is recruited as a component of postural adjustments associated with limb and trunk movements, and this postural function is coordinated with respiratory function. The relationship between postural control and respiration is adaptable and depends on contextual demands. When respiratory demand is increased by breathing air with increased carbon dioxide, the relative contribution of the diaphragm to respiration is increased, and that to postural control is decreased (23, 27). In quiet standing, respiratory movements of the trunk are normally compensated by small movements of the trunk and lower limbs to minimize perturbation to the center of pressure (CoP) (22). However, this coordination between respiration and control of CoP is compromised in people with low back pain who have reduced compensatory trunk and limb movements and oscillation of the CoP with breathing (10, 45), and problems with other functions that require coordination between respiration and posture (6, 9, 16, 28). This coordination between respiration and control of CoP is also compromised in people with lung disease; expressed as decreased postural stability (27, 46). Respiration and postural demands are also coordinated during functional tasks such as walking (42). These studies and others (3, 16, 30, 49) have established integration of respiration with postural stability. Because pressures in the abdomen and thorax depend on the glottis (vocal folds/airway structures), and glottal function varies with respiratory tasks, the glottis is likely to affect postural control and balance, but this has received limited attention in postural research.

Although research has focused on modulation of IAP in trunk control, control of ITP is likely to be important. ITP depends not only on activation of the thoracic muscles, but also on regulation of airflow resistance (40). The glottis modulates airway opening, supporting the airway and ITP for tasks such as talking, coughing, and breathing, yet glottal control is rarely reported in relation to postural control (14, 32, 34, 35, 40). Although postural control is commonly evaluated by investigation of the recovery of balance after a perturbation, most work has focused on glottal control during high-level postural demands such as weight lifting (7, 12, 17, 37, 40). We proposed that glottal structures would also contribute to dynamic stability of the trunk during the lower-level demands of recovery after perturbation to balance (e.g., akin to balance recovery after being bumped in a crowd). Our central hypothesis was that modulation of airway control would influence the efficacy of upright postural stability in response to postural perturba-

tions. That is, we predicted that the modification of the state of the trunk (pressure, glottal opening, trunk muscle activity, etc.) at the moment of a perturbation as a result of variation in breathing task, would affect the ability to counteract the perturbation. If true, we further hypothesized that tasks that prevent airway constriction (e.g., mandatory glottal opening) during a perturbation would result in greater disturbance to thorax and CoP position, whereas tasks that optimize airway constriction (e.g., glottal closure) would incur lesser perturbation. This study aimed to test these hypotheses in healthy participants.

MATERIALS AND METHODS

Participants. Twelve healthy individuals [7 men/5 women, age 21–41 yr (mean, 31 yr)] participated. Exclusion criteria included any major circulatory, neurologic, or respiratory disorder; recent or current pregnancy; or recent muscle/joint pain. Data from 11 of the 12 participants were complete and used in analyses. Trunk motion data were not available for the remaining participant. The study was approved by The University of Queensland Institutional Medical Research Ethics Committee and conducted in accordance with the Declaration of Helsinki. Written informed consent of participants was obtained before inclusion in the study.

Ground reaction forces. Ground reaction forces were recorded with a force plate (FP4060; Bertec, Columbus, OH) to measure CoP displacement. CoP was calculated as the moment (My) around the coronal axis divided by the vertical ground reaction force (Fz). Data were collected with a Power 1401 data acquisition system and Spike2 (V6.09) software (Cambridge Electronic Design, Cambridge, UK) at 4 kHz.

Horizontal linear displacement of the thorax. A linear wire potentiometer (HPS-M1-10; Hontko, Taipei, Republic of China) was attached to the posterior aspect of a chest harness (Fig. 1) to record horizontal linear displacement of the thorax. Data were collected with the CoP data at 4 kHz.

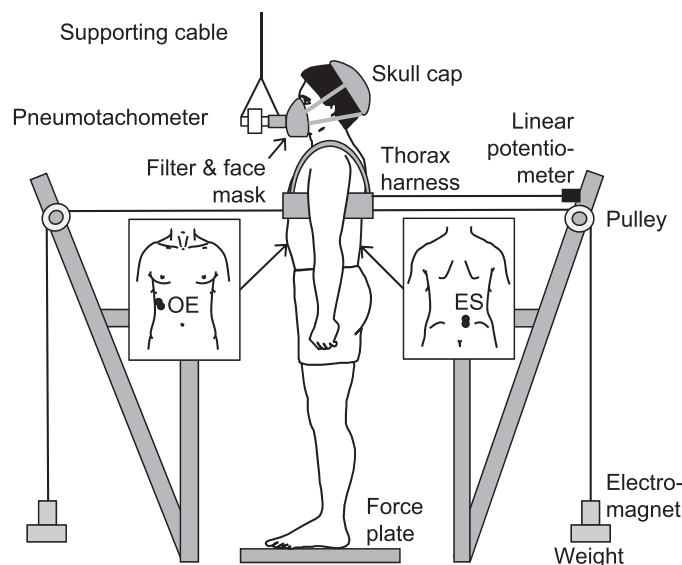


Fig. 1. Experimental set up. Perturbation was applied to the trunk by release of the weight (by release of the electromagnet) from one side causing the trunk to be pulled in the opposite direction by the remaining weight. Displacement of the trunk and center of pressure (CoP) were recorded with a linear potentiometer and force plate, respectively. Insets: placement of the surface electromyographic electrodes for the obliquus externus abdominis (OE) and erector spinae (ES) muscles.

Surface electromyography. Electromyographic (EMG) activity of the right obliquus externus abdominis (OE) and ES (Fig. 1) was recorded with surface electrodes (Noraxon, Scottsdale, AZ) placed approximately parallel with the muscle inferior to the right costal margin (rib 8), and 2 cm lateral to L3, respectively. A ground electrode (3M; Pymble, Australia) was placed over the iliac crest. EMG data were band-pass filtered between 3 and 500 Hz (50 Hz notch filter to remove electrical interference), amplified 2,000× using a Neurolog NL824 preamplifier and NL900D amplifier (Digitimer, Hertfordshire, UK), and sampled at 4 kHz with CoP data.

Respiratory measurement. Participants wore a nasal clip to ensure mouth breathing and were fitted with an airtight oral nasal mask secured with a skull-cap harness. This was preferred to a mouthpiece, which may have incurred biting for postural stabilization. The mask was checked for air leaks and adjusted if needed. A pneumotachometer (3813, Hans-Rudolf, Shawnee, KS) was coupled to the mask via a filter (Fig. 1) to record airflow using a differential pressure transducer (DP45-16; Validyne Engineering, Northridge, CA) connected to a carrier demodulator (MC1-10; Validyne Engineering). The weight of the entire apparatus was supported by an adjustable cable from the ceiling to minimize participants' muscular effort to maintain the position of the device, and to ensure that the apparatus would swing in a gentle horizontal arc with participants during testing.

Intraabdominal pressure. IAP was recorded in five participants (four had complete data that were used for analysis as a result of the missing trunk motion data) using thin-film transducer (Gaeltec, Isle of Skye, UK) attached to a nasogastric catheter (Fig. 1). Data were collected along with CoP at 4 kHz. Because inspiration increases IAP due to diaphragm descent (21, 38), correct transducer placement was confirmed by increased IAP during a sniff. The catheter was secured to the nose with tape. IAP was calibrated by immersion in a column of water.

Procedure. Participants stood on a force plate inside an aluminum enclosure (120 cm square and 110 cm high; approximately waist height for most participants) (Fig. 1). Standing balance was perturbed during seven different airway conditions (Table 1) to investigate the effect of various airway constrictions on postural stability. The breathing/voicing conditions were chosen to reflect normal variations in airway control; glottis closed (breath-holding at large and small lung volumes), glottis partially opened (phonation of “ah” and counting out loud), or glottis open (natural opening as in normal breathing, mandatory opening as in a sigh, and maintenance of an open glottis at low lung volume).

Participants wore a rigid chest harness secured in place with Velcro straps (Fig. 1). Cables were attached to the harness anteriorly and posteriorly at the level of the xiphoid process and connected via pulleys to electromagnets. Cable height was adjusted (via pulleys) to maintain the cables parallel to the ground. Weights (~3% body wt) were attached to the electromagnets. This weight was identified in pilot trials to be sufficient to gently perturb the participant when released unexpectedly from one side, but rarely caused the participant to take a recovery step or to grab the aluminum enclosure to recover balance. Participants practiced up to four trials until they were comfortable with the perturbation and the response was observed to reach a steady state. During the experiment, a participant's balance was perturbed during the seven breathing/voicing conditions described in Table 1. Participants were informed that a weight would drop from either the anterior or posterior cable, disturbing their standing balance in the sagittal plane. They were instructed to regain their initial posture as quickly as possible.

Immediately prior to testing each condition, the participants practiced the breathing task (see Table 1). For the nonvoicing conditions, airflow was displayed on an oscilloscope to confirm the expected performance. A smooth sinusoidal waveform confirmed an uninterrupted airflow for the open glottal conditions [normal breath, functional residual capacity (FRC), open, sigh], and a flat line confirmed a closed glottal condition (max insp-hold, norm exp-hold). Voiced

Table 1. *Definition and instructions for breathing/voicing conditions*

Breathing Condition	Abbreviation	Airflow at Time of Perturbation	Glottis Position During Perturbation	Justification for Condition	Instruction to Participants
Maximal inhalation plus breath-hold	Max insp-hold	No	Closed	Breath-holding is a natural form of trunk stabilization (12, 14). Healthy individuals naturally take in a deeper breath prior to lifting a heavier load than a lighter load (13). The greater lung volume while breath-holding results in greater intraabdominal pressure.	“Take in the biggest breath you can. Then hold your breath until the weight drops.”
/Ah/voicing	Ah	Yes	Partially open*	Voicing a vowel sound requires the vocal folds to actively adduct and partially restrict the airway to control expiratory flows to produce sound via Bernoulli’s effect (5). This requires mid-range control of the glottis. The partially opened glottis condition results in a longer exhalation phase than a completely open airway exhalation.	“In a normal, full speaking voice, say ‘ah’ for as long as you can until the weight drops.”
Natural breathing	Normal breath	Yes	Open	Natural breathing uses a passive open airway without conscious effort. It was included to observe a natural rather than contrived responses associated with other conditions tested here.	“Breathe normally. Do not take deep breaths. Do not take shallow breaths. Don’t hold your breath. Just breathe normally until the weight drops.”
Counting out loud	Count	Yes	Partially open*	As during /ah/ voicing condition, counting partially obstructs the airway (40). Unlike /ah/, counting is a natural use of voicing rather than contrived.	“Count out loud to seven in a normal, full speaking voice until the weight drops. Do not talk softly. Do not shout. Just use your normal full voice.”
Normal expiration plus breath-hold	Norm exp-hold	No	Closed	Functional residual capacity (FRC), the end of a natural breath, is the natural end resting position of the chest (50). The inward elastic recoil forces of the lungs is equal to the outward forces of the chest wall, thus the respiratory muscles do not exert a force to maintain this position (50). Closing the airway at FRC will trap approximately half the volume of air in the lungs compared with the Max insp-hold condition in which participants inhaled a maximal effort.	“Take an easy breath in. Exhale normally. Then hold your breath until the weight drops.”
Normal expiration plus airway open (no breath hold)	FRC-open	No	Open	Like the Norm exp-hold condition, normal exhalation with the airway open uses the homeostatic state of FRC. However, in this condition, participants leave the airway open rather than closing the glottis.	“Take an easy breath in. Exhale normally. Pause. Keep your airway open until the weight drops by thinking that you could exhale for a few seconds more if you needed to.”
Sigh (/H/ sound)	Sigh	Yes	Open	/H/ is an unvoiced sound (29, 31). Air is passively forced out through the open glottis, preventing participants from regulatory expiratory flows and, by extension, thoracic pressures, even though participants start with large lung volumes.	“Take a deeper breath than normal and then say ‘ha’ like a sigh. Do not push the air out. Let the air fall out like a normal sigh until the weight drops.”

*To produce sound, the vocal folds actively constrict the airway, thus the glottis is only partially open.

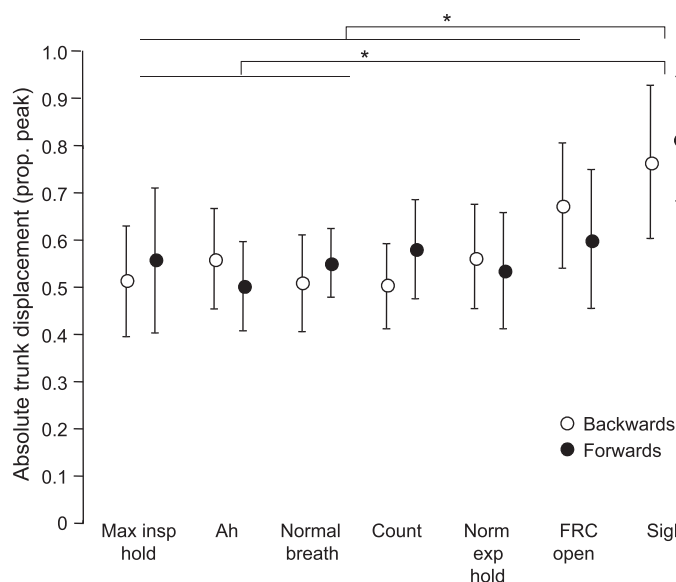


Fig. 2. Peak horizontal linear displacement of the thorax in response to perturbation in both directions. Absolute thoracic displacements are presented as the proportion of the largest displacement across trials. Absolute displacement of the thorax did not differ between forward and backward perturbations. The largest displacements were recorded in the sigh and FRC open conditions, which required an open glottis. Abbreviations for breathing conditions are listed in Table 1. * $P < 0.05$.

conditions were assumed open because the production of sound requires a patent airway. Both the order of conditions and the direction of perturbation were randomized using random numbers. Weights were dropped 20 times (10 times in each direction) during the 7 breathing/voicing conditions (140 trials per participant). The neutral upright posture was self-selected by the participant for the first trial, and the position of the linear potentiometer was marked at this point. After each trial participants were provided with verbal feedback to regain their neutral marked position prior to the next trial. Participants were allowed to rest briefly for ≤ 1 min between conditions as needed. Data collection was typically complete in less than 1 h.

Data analysis. The primary outcome measures of postural stability were the peak amplitude of thoracic displacement (linear potentiometer) and CoP displacement (ground reaction force) in response to the perturbations. Data were exported for processing to Matlab (MathWorks, Natick, MA). Baseline CoP and thorax position were calculated as those immediately prior to the perturbation, averaged over 50 ms. Peak amplitude of the displacement after the perturbation was identified automatically using custom software. Data were expressed as a percentage of the maximal displacement for each subject across all conditions.

Statistical analyses were performed with Statistica (version 9, Statsoft, Tulsa, OK). The amplitude of thoracic and CoP displacement were compared between the seven airway conditions (condition) and forward and backward (direction) perturbations with separate repeated measures ANOVA and post hoc analyses using Duncan's multiple range test. Significance was set at $P < 0.05$.

Because differences in perturbation to the thorax and CoP between conditions might be explained by differences in IAP or trunk muscle EMG activity between breathing conditions rather than airway constriction, the mean amplitude of these variables for 50 ms prior to the perturbation was calculated and expressed as a percentage of the peak across conditions. IAP and OE/ES EMG just prior to perturbation were compared between Conditions and Directions using separate ANOVAs. We used the ANOVA because it is robust and tolerates small participant numbers and the result was unaffected by analysis using nonparametric tests. The relationship between OE/ES EMG and

the amplitudes of thoracic or CoP displacement was investigated by calculation of Pearson's correlation coefficients (this was not analyzed for the IAP data because of the small number of participants with this recording).

RESULTS

Horizontal linear displacement of the thorax. When the thorax was moved horizontally by the release of the weight attached to the thoracic vest, there was no difference in absolute amplitude of displacement between forward and backward perturbations (main effect, direction $P = 0.87$), but the direction was opposite. Consistent with our hypothesis, the two conditions in which participants were required to maintain an open glottis allowing unimpeded airflow (sigh and FRC open) were associated with greater thoracic displacement in response to the perturbations than most (FRC open) or all (sigh) other conditions, regardless of the direction of perturbation (main effect, condition $P < 0.0001$; interaction, condition \times direction $P = 0.54$) (Fig. 2). The sigh, which is associated with an open, relaxed airway, resulted in a thoracic displacement that was larger than all other conditions (post hoc all $P < 0.002$). Displacement following perturbation in the condition with the glottis voluntarily held open at FRC (FRC open) was greater than that recorded in the max insp-hold, ah, and normal breath conditions ($P < 0.05$), but less than the sigh. Although not significant, there was a tendency for displacement in the FRC open condition to exceed that in count and norm exp-hold conditions (post hoc $P < 0.06$). There was no difference between other conditions. Of the 11 participants, 7 had their largest thorax displacement during the sigh, and 3 during FRC open.

Center of pressure displacement. In contrast to thorax displacement, the absolute amplitude of CoP displacement differed between directions (main effect, direction $P = 0.001$) (Fig. 3). When the posterior weight dropped to pull the partic-

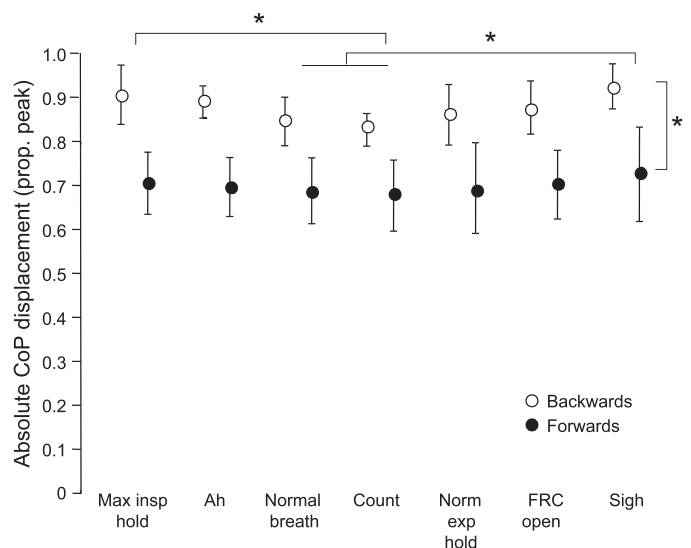


Fig. 3. Peak displacement of C of the body in response to perturbation in both directions. Absolute CoP displacements are presented as the proportion of the largest displacement across trials. Absolute CoP displacement was greater with backward perturbation and with the glottis either fully open or closed after a full inspiration (sigh and max insp-hold, respectively) than partially open in the natural counting task. Abbreviations used for breathing conditions are listed in Table 1. * $P < 0.05$.

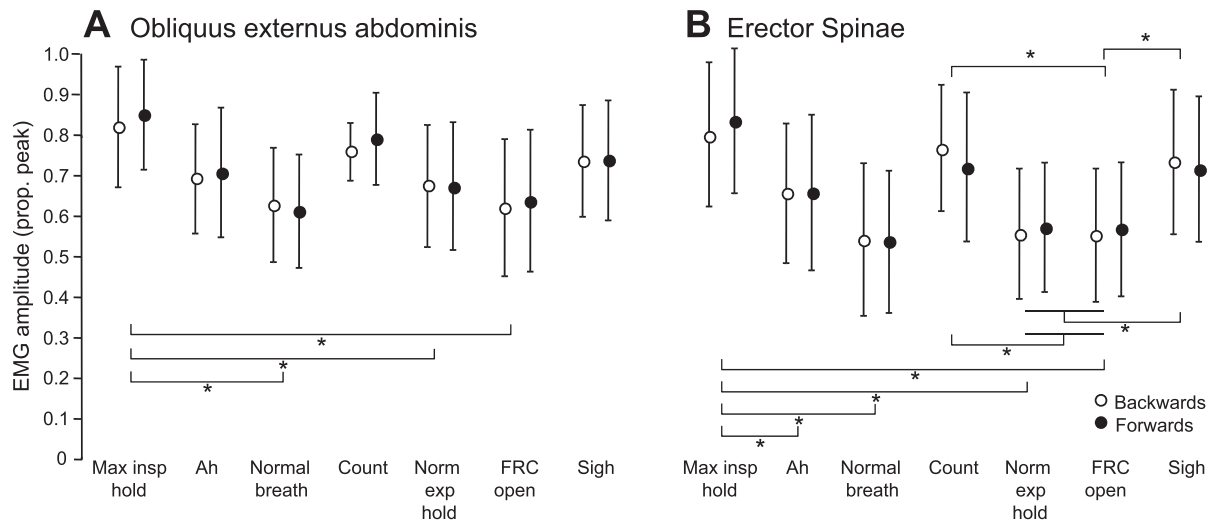


Fig. 4. OE (A) and ES (B) root mean square electromyographic activity just prior to loading, averaged over 50 ms and expressed as a proportion of the largest amplitude across trials. Abbreviations used for breathing conditions are listed in Table 1. * $P < 0.05$.

ipant forward toward the remaining anterior weight, there was a smaller CoP displacement than during the backward perturbation. The effect of the airway control on CoP displacement was the same for both perturbation directions (interaction, direction \times condition $P = 0.76$). Sigh (open glottis condition) and max insp-hold (glottis closed condition) were associated with a greater CoP displacement than that induced by perturbation during count (partially open condition), which was associated with natural modulation of airflow resistance and no conscious attempt to influence glottal closure (post hoc all $P < 0.04$). CoP displacement was also greater in sigh than normal breath conditions (post hoc $P = 0.03$). There was no difference between other conditions.

EMG and IAP at time of perturbation onset. OE EMG amplitude immediately before the perturbation was greater for max insp-hold than for normal breath, norm exp-hold, and FRC open conditions (main effect, condition $P = 0.035$; post hoc $P < 0.05$; Fig. 4A). There was no difference between other conditions (post hoc all $P > 0.05$). Although OE EMG amplitude was greatest during one of the conditions with the smallest trunk displacement, there was no significant correlation between OE EMG and thoracic or CoP displacement (Table 2).

ES EMG amplitude immediately before the perturbation was greater for the conditions that were expected to have a higher starting lung volume (max insp-hold, count, and sigh) than the lower lung volume (normal breath, norm exp-hold, and FRC open; main effect, condition $P = 0.0002$; post hoc all $P < 0.03$; Fig. 4B). The only exception was ah, which is expected

to start with a high lung volume but had lower ES EMG than the max insp-hold condition. ES EMG during the ah was not different from any other condition (post hoc all $P < 0.03$). There was no correlation between ES EMG and thoracic or CoP displacement (Table 2).

In the subset of participants with IAP recordings ($n = 4$) there was no difference in IAP amplitude immediately before perturbation between the breathing/airway conditions (main effect, condition $P = 0.09$). However, this must be interpreted with caution due to the small number of participants.

DISCUSSION

This study examined the impact of airway modulation on upright postural control and demonstrated that the status of the glottis influences the quality of postural control. Consistent with our hypothesis, when the glottis was maintained open using sigh or FRC open maneuvers, thus preventing the airway from constricting, the perturbation to the thorax/CoP was greater than in all/some of the other conditions that involved varying degrees of airway closure. Unexpectedly, the perturbation to CoP in the max insp-hold condition with maximal airway closure was not different to the condition with airway opening (sigh). Both of these conditions were less stable than the counting task that involved partial opening of the glottis in a natural manner. Taken together, these findings show that airway closure plays a role in postural stability, but some aspects of postural control can be compromised by both extremes of complete opening or closure of airway.

Breath control and postural control. Breath-holding has been reported during strenuous postural demands such as weight lifting (4, 7). In a study of IAP and its relationship to breath support, abdominal strength, and weight lifting, Hemborg et al. (17) found that neither abdominal muscle strengthening nor a specific respiratory pattern adequately increased IAP. The highest IAP was generated by neuromotor strategies that involved glottal closure to stabilize the diaphragm during abdominal muscle contraction. Recent research confirmed breath-holding (glottal closure) as a natural breath response to heavy loads (12). The present work extends this finding to demonstrate that more subtle modulation of

Table 2. Correlation coefficients (R^2 values) for relationship between EMG amplitude of thoracic and CoP displacement

	Peak Thoracic Displacement (Backward)	Peak Thoracic Displacement (Forward)	Peak CoP Displacement (Backward)	Peak CoP Displacement (Forward)
OE EMG	0.01	0.02	0.12	0.17
ES EMG	0.0004	0.07	0.12	0.08

CoP, center of pressure; EMG, electromyography; OE, obliquus externus abdominis; ES, erector spinae.

airflow restriction at the glottis plays a role in thoracic and whole body postural stability. This would be consistent with recommendation to expire during lifting rather than hold the breath (37). Whereas most studies of respiration and postural control investigate displacement of the CoP (3, 10, 15, 16, 22, 27, 28, 30), this study included peak thoracic displacement as an additional measure of balance disturbance, and found different behavior of the thorax and whole body CoP.

We predicted that restriction of airflow would mechanically assist the system to increase trunk pressures for postural control. Orlikoff (40) studied the interaction between airway resistance/glottal constriction and postural control by manipulation of postural demand (lifting 0, 3, 5, and 7 kg dumbbells with extended arms) and measurement of airway resistance during two voicing tasks, a sustained vowel (/a/) and rapid syllable (/pi/) repetition. Airway resistance and glottal constriction increased in conjunction with increased postural demand, yet the airway remained patent. The present study evaluated the converse situation by manipulation of the airway control and measurement of changes in quality of postural control. Consistent with our hypothesis and the observations of Orlikoff (40), thoracic displacement increased in the mandatory open-glottal conditions of sigh and FRC open. Conversely, the thorax was more posturally stable with the glottis closed (max insp-hold and norm exp-hold) or partially opened (ah and counting), and at normal breath. Because there was no difference in the effect of the perturbation to the thorax (and therefore the quality of thoracic stabilization) between these tasks, the type of engagement (e.g., voicing vs. breath-holding) does not appear as important as the engagement itself for low-level postural disturbances.

The amplitude of thoracic displacement was similar between directions of perturbation. This contrasted with CoP displacement, which showed greater displacement (postural instability) with backward perturbations. The thoracic displacement measured the upper body's movement in response to a balance disturbance to the mid chest. The base of support for the thorax (the pelvis) allows similar anterior and posterior movement and pulled the thorax equally forward or backward in response to the small perturbation, thus there was no effect of direction for thoracic displacement. However, the CoP displacement measured the entire body's response to the thoracic disturbance and depends largely on control of the ankle muscles. The base of support for CoP has a larger base anteriorly (the feet) than posteriorly and depends on control of the larger dorsal gastrocnemius muscle. Thus it was not surprising that CoP displacement was greater with backward perturbations. This has been reported in other work (51). Although thorax displacement will be influenced by whole body displacement, the equal displacement of the thorax in each direction can only occur with differences in angular motion at the hip and lower spine with each direction (hip/lumbar motion to enable similar displacement despite limited CoP displacement in the anterior direction).

Conditions with large CoP displacement did not always correspond with similar observations for thoracic displacement. Although the mandatory open-glottal condition (sigh) induced large displacement of both thoracic and CoP displacement, the effect of complete glottal closure (max insp-hold) was opposite for CoP and thoracic displacement; thoracic displacement was least in this condition, but CoP displacement was equal to that in trials with the open airway (sigh). This discordance may be due to the complex interrelationship between trunk stiffness and postural

control. Although airway closure may adequately stiffen the trunk to limit thorax displacement, previous work indicates that greater trunk stiffness compromises the quality of postural control because it limits the capacity of trunk movement/damping to counteract the postural disturbance (11). For example, patients with low back pain have greater spine stiffness, and this is associated with less effective postural control strategies (9, 10, 15, 28). Taken together, these data imply that ideal postural control needs mid-range control: neither too stiff nor too flexible. The max insp-hold condition would produce a stiffer trunk, and the sigh condition would produce a more flexible trunk. Neither strategy was effective for minimization of disturbances to CoP in response to a gentle perturbation. Mid-range glottal control (counting) was a more effective dynamic postural strategy for minimization of CoP disturbance with less displacement than the two extreme conditions. This may be because counting is a more familiar/natural task as apposed to the contrived ah; or it may be explained by the short duration of airflow in counting as apposed to the long sustained airflow in the ah task. These alternatives require further investigation. Considering the thoracic and CoP displacement findings together, a breath-holding strategy would appear to be effective for ensuring the stability of the thorax, hence the logic for use of breath-holding when the primary demand is thoracic stability such as lifting a heavy object (14) or pushing a heavy door. However, it would appear that to optimize dynamic control of CoP, a mid-range glottal control technique such as talking may be more effective.

Consideration of possible alternative mechanisms. Quality of postural control can be compromised by excessive trunk muscle activity (36, 41). However, in this study the changes in thoracic and CoP displacement with airway closure could not be explained simply by differences in trunk muscle EMG or IAP recorded immediately prior to the perturbation (~50 ms). Although ES/OE EMG differed between conditions, the changes were not correlated with changes in the displacement of the thorax or trunk following perturbation. As an example, for trunk muscle activity to explain greater CoP and thoracic displacement in the sigh condition, this task would need to be associated with less OE/ES EMG than the other conditions. However, OE EMG did not differ between conditions and ES EMG was higher than three other conditions (FRC open, normal exp-hold, and normal breath) that had less thoracic displacement. Whether components of the response of these muscles after the onset of perturbation were related to thoracic or CoP displacement was not examined. IAP did not differ between conditions for the four participants included in this study and therefore cannot explain the differences in the effect of perturbation.

Of interest, FRC open, normal exp-hold, and normal breath are expected to involve low lung volumes (quiet breathing), whereas the other four conditions, max insp-hold, ah, counting, and sigh, require a larger voluntary inspiratory effort (larger lung volumes). OE and ES EMG were lower in the three quiet breathing (low lung volume) conditions than in the four deep-breathing (high lung volume) conditions. One exception was ah, which had a lower ES EMG than max insp-hold. Perhaps OE and ES co-contract during higher lung volume breaths to stabilize the trunk (14). Lung volume was not measured in this study, and further research is needed to determine whether there is a threshold lung volume at which glottal control becomes important for postural stability.

Clinical relevance and suggestions for further research. Our findings suggest that balance strategies are likely to be disadvantaged if the ability to recruit glottal structures as part of dynamic postural control is compromised. This would be clinically meaningful for patients with a tracheostomy or damage/paralysis of the glottal structures. Clinical research to extend these findings should compare postural control between patients with open tracheostomies (obligatory open-glottis) and patients who have speaking-valve attachments to their tracheostomy tubes (e.g., Passy Muir Valves, Irvine, CA) that restore the use of the vocal folds for airway modulation. On the basis of our findings, we would anticipate that patients with speaking valves would have better postural control than those with open tracheostomies. Such a clinical study could further test the interpretation of our data. Our findings may also help explain breath-holding strategies often used by patients with balance impairments that are observed clinically. Although this may stabilize the thorax, it may constrain the dynamic control necessary to efficiently control CoP. Balance training may be more effective if it actively incorporates glottal control as part of a rehabilitation program. This warrants further study.

Conclusion. These results show that airway modulation affects postural control during even minor upright perturbations. Thoracic stability and dynamic CoP control strategies differed. Mandatory glottal opening decreased stability in both strategies, whereas glottal closure decreased stability in only the CoP strategy. These data suggest that glottal control influences balance, and that glottal control strategies may be an important consideration for patients with breathing and/or balance disorders.

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DISCLOSURES

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AUTHOR CONTRIBUTIONS

Author contributions: M.M., M.H., R.S., V.A.M., and P.W.H. conception and design of research; M.M., R.S., and P.W.H. performed experiments; M.M., R.S., and P.W.H. analyzed data; M.M., M.H., R.S., V.A.M., and P.W.H. interpreted results of experiments; M.M. and P.W.H. prepared figures; M.M. and P.W.H. drafted manuscript; M.M., M.H., R.S., V.A.M., and P.W.H. edited and revised manuscript; M.M., M.H., R.S., V.A.M., and P.W.H. approved final version of manuscript.

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