THE EFFECT OF AIRWAY CONTROL BY GLOTTAL STRUCTURES ON POSTURAL STABILITY

M. Massery,1 M. Hagins,2 R. Stafford,3 V. Moerchen,4 P. W. Hodges3

1Graduate Program in Advanced Neurology Physical Therapy, Rocky Mountain University of Health Professions, Provo, UT, USA
2Department of Physical Therapy, Long Island University, Brooklyn Campus, Brooklyn, NY, USA
3NHMRC Centre of Clinical Research Excellence in Spinal Pain, Injury and Health, School of Health and Rehabilitation Sciences, The University of Queensland, Brisbane, Australia
4Department of Kinesiology, College of Health Sciences, University of Wisconsin-Milwaukee, Milwaukee, WI, USA

RUNNING HEAD: The Effect of Airway Control on Postural Stability

CORRESPONDING AUTHOR: Dr Paul Hodges, The University of Queensland, Centre of Clinical Research Excellence in Spinal Pain, Injury and Health, School of Health and Rehabilitation Sciences, Brisbane, Qld 4072 Australia
Tel: +61 7 3365 2008
e-mail: p.hodges@uq.edu.au
ABSTRACT

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 glottal control influences balance, and that glottal control strategies may be an important consideration for patients with breathing and/or balance disorders.
KEYWORDS: Postural control, glottis, balance reactions, thoracic pressure, voicing
INTRODUCTION

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 intra-thoracic (ITP) and intra-abdominal (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.

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 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 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) as well as 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. As 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 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 perturbations. 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 male/5 female, 21-41 (mean - 31) years) participated. Exclusion criteria included any major circulatory/neurologic/respiratory disorder, recent or current pregnancy, or recent muscle/joint pain. Data from 11 of the 12 participants was complete and used in analyses. Trunk motion data was not available for the remaining participant. The study was approved by the Institutional Medical Research Ethics Committee and conducted in accordance with the Declaration of Helsinki. Written informed consent was obtained before inclusion.

Ground reaction forces

Ground reaction forces were recorded with a force plate (Model FP4060, Bertec, Columbus, USA) to measure center of pressure (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 (Model HPS-M1-10, Hontko, Taipei, Taiwan) 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.

Surface Electromyography

Electromyographic (EMG) activity of the right obliquus externus abdominis (OE) and ES (Fig. 1) was recorded with surface electrodes (Noraxon, Scottsdale, USA) placed approximately parallel with the muscle inferior to 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 2000x using a Neurolog NL824 pre-amplifier and NL900D amplifier (Digitimer Ltd, 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 (Hans-Rudolf, Germany) was coupled to the mask via a filter (Fig. 1) to record airflow using a
differential pressure transducer (Model DP45-16, Validyne, England, UK) connected to a
carrier demodulator (Model MC1-10, Validyne, England, UK). The weight of the entire
apparatus was supported by an adjustable cable from the ceiling to minimize the
participant’s muscular effort to maintain the position of the device, and to ensure that the
apparatus would swing in a gentle horizontal arc with the participant during testing.

Intra-abdominal pressure (IAP)

IAP was recorded in 5 participants (4 had complete data that were used for
analysis as a result of the missing trunk motion data) using thin-film transducer (Gaeltec
Ltd, Isle of Skye, UK) attached to a nasogastric catheter (Figure 1F). Data were collected
along with CoP at 4 kHz. As 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 7 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 weight) 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 4 trials until they were comfortable with the perturbation and the response was observed to reach a steady-state. During the experiment, the participant’s balance was perturbed during the 7 breathing/voicing conditions described in Table 1. Participants were informed 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 non-voicing 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 conditions were assumed open as 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.
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 one hour.

**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, USA). Baseline CoP and thorax position was calculated as that 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). The amplitude of thoracic and CoP displacement were compared between the 7 airway conditions (Condition) and forward and backward (Direction) perturbations with separate repeated measures analyses of variance (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 as it is robust and tolerates small participant numbers and the result was
unaffected by analysis using non-parametric 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 the 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 x 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 eleven
participants, seven had their largest thorax displacement during the “Sigh”, and three
during “FRC-open”.

Center of Pressure (CoP) 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 participant 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 x 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 “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 “Max insp-hold” condition. ES EMG during the “Ah” was not different to 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 increased IAP adequately. 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 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 breath hold (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 2 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”), as well as “Normal breath.” As 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 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 to 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 stiffen the trunk adequately to limit thorax displacement, previous work indicates that greater trunk stiffness compromises the quality of postural control as it limits the capacity of trunk movement/damping to counteract the postural disturbance.
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 of counting, as apposed to the contrived “ah”; or 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 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 push 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 4 conditions, “Max insp-
hold”, “Ah”, “Counting” and “Sigh”, require a larger voluntary inspiratory effort (larger
lung volumes). OE and ES EMG was lower in the 3 quiet breathing (low lung volume)
conditions than in the 4 deep breathing (high lung volume) conditions. One exception
was “Ah” which had 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 if 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) to 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. Based on 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 the 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.
ACKNOWLEDGEMENTS

Funding was provided by the National Health and Medical Research Council (NHMRC) of Australia (ID1002190 and ID455863).

DISCLOSURES

This work is not associated with any potential conflict of interest, financial or otherwise.
REFERENCES


FIGURE LEGENDS

**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 show the placement of the surface EMG electrodes for the obliquus externus abdominis (OE) and erector spinae (ES) muscles.

**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 difference between forward and backward perturbations. The largest displacements were recorded in the conditions that required an open glottis: “Sigh” and “FRC-open”. Abbreviations used for breathing conditions are listed in Table 1. * - P<0.05.

**Fig. 3.** Peak displacement of the center of pressure (CoP) 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 was greater 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. (A) Obliquus externus abdominis and (B) erector spinae 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.
Table 1. Definition and instructions for breathing/voicing conditions

<table>
<thead>
<tr>
<th>Breathing condition</th>
<th>Abbr.</th>
<th>Airflow at time of perturbation</th>
<th>Glottis position during perturbation</th>
<th>Justification for condition</th>
<th>Instruction to participants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximal inhalation</td>
<td>Max</td>
<td>No</td>
<td>Closed</td>
<td>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 IAP.</td>
<td>“Take in the biggest breath you can. Then hold your breath until the weight drops.”</td>
</tr>
<tr>
<td>plus breath-hold</td>
<td>insp-hold</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>/Ah/ voicing</td>
<td>Ah</td>
<td>Yes</td>
<td>Partially open†</td>
<td>Voicing a vowel sound requires the vocal folds to actively adduct and partially restrict the airway in order 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.</td>
<td>“In a normal, full speaking voice, say “ah” for as long as you can until the weight drops.”</td>
</tr>
<tr>
<td>Natural breathing</td>
<td>Normal</td>
<td>Yes</td>
<td>Open</td>
<td>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.</td>
<td>“Breathe normally. Do not take deep breaths. Do not take shallow breaths. Don’t hold your breath. Just breathe normally until the weight drops.”</td>
</tr>
<tr>
<td></td>
<td>breath</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Condition</td>
<td>Count</td>
<td>Yes</td>
<td>Open</td>
<td>Description</td>
<td>Example</td>
</tr>
<tr>
<td>-----------------------------------------------</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
<td>-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>---------</td>
</tr>
<tr>
<td>Counting out loud</td>
<td>Yes</td>
<td></td>
<td>Partially open†</td>
<td>As during /ah/ voicing condition, counting partially obstructs the airway (40). Unlike /ah/, counting is a natural use of voicing rather than contrived.</td>
<td>“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.”</td>
</tr>
<tr>
<td>Normal expiration plus breath-hold</td>
<td>No</td>
<td></td>
<td>Closed</td>
<td>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 to condition “Max insp hold” where the participants inhaled a maximal effort.</td>
<td>“Take an easy breath in. Exhale normally. Then hold your airway until the weight drops.”</td>
</tr>
<tr>
<td>Normal expiration FRC-open‡</td>
<td>No</td>
<td></td>
<td>Open</td>
<td>Like condition “Norm exp-hold”, normal exhalation with the airway left open uses the homeostatic state of FRC. However, in this condition the participants leave their airway open rather than closing their glottis.</td>
<td>“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.”</td>
</tr>
<tr>
<td>Normal expiration plus airway open (no breath hold)</td>
<td>Sigh</td>
<td>Yes</td>
<td>Open</td>
<td>/H/ is an unvoiced sound (29, 31). Air is passively forced out through the open glottis preventing the participants from regulatory expiratory flows and by extension, thoracic pressures even though the participants start with large lung volumes.</td>
<td>“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.”</td>
</tr>
</tbody>
</table>

† In order to produce sound, the vocal folds actively constrict the airway, thus the glottis is only partially open.
‡ Functional residual capacity (FRC); Abbr. – abbreviation.
Table 2. Correlation coefficients (R² values) for relationship between EMG and the amplitude of thoracic and CoP displacement

<table>
<thead>
<tr>
<th></th>
<th>Peak thoracic displacement (Backward)</th>
<th>Peak thoracic displacement (Forward)</th>
<th>Peak COP displacement (Backward)</th>
<th>Peak COP displacement (Forward)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OE EMG</td>
<td>0.01</td>
<td>0.02</td>
<td>0.12</td>
<td>0.17</td>
</tr>
<tr>
<td>ES EMG</td>
<td>0.0004</td>
<td>0.07</td>
<td>0.12</td>
<td>0.08</td>
</tr>
</tbody>
</table>
Fig. 2

Absolute trunk displacement (prop. peak)

- Max insp hold
- Ah
- Normal breath
- Count
- Norm exp hold
- FRC open
- Sigh

O Backwards
● Forwards
Fig. 4

A. Obliquus externus abdominis

B. Erector Spinae

EMG amplitude (prop. peak)

Max insp hold  Ah  Normal breath  Count  Norm exp hold  FRC open  Sigh

Backwards  Forwards

* Indicates significant differences.