Copyright Information

The effect of airway control on postural stability

Mary P. Massery

A dissertation submitted in partial fulfillment of the requirements for the degree of

Doctor of Science

Rocky Mountain University of Health Professions

2011

Specialty Program Authorized to Offer Degree: Advanced Neurology

ABSTRACT

Maintaining upright posture is a complex neuromotor process involving control of multiple factors including thoracic and abdominal pressures. Control of airflow by glottal structures, a primary determinant of thoracic pressure, should therefore be important for efficient 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 adult participants. Dependent measures were peak amplitude of displacement of the thorax and center of pressure (CoP). When the glottis was completely open (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: $P = 0.001$) across airway conditions and was greater at both extremes of glottal modulation (glottis closed and completely open). Perturbation of CoP was least during the partially opened glottal condition (counting) (Post hoc: all P

< 0.04). These results show that airway modulation effects postural control during upright perturbations. The thorax was most stable with a static breath-holding maneuver, but optimal control of CoP displacement was during the natural dynamic mid-range airway modulation of voicing. This study suggests that glottal control may be a relevant consideration during balance training.

Keywords: Postural control, glottis, balance reactions, thoracic pressure, voicing

INTRODUCTION

Maintenance of upright posture involves complex neuromotor processes. Although, considerable research into postural control strategies for the trunk has focused on the role of the abdominal and erector spinae muscles (24, 32), it has become apparent that control of pressures in the thoracic and abdominal cavities makes an important contribution. In addition to a contribution of abdominal muscles to this support, recent research has highlighted the role of other muscles that surround the abdominal cavity and thus influence cavity pressure in conjunction with their other functions such as respiration and continence. Those muscles include the diaphragm (1, 6, 20, 43), the intercostal (2, 26, 36) and the pelvic floor muscles (25, 37, 42). If control of cavity pressure is important for postural control of the trunk it follows that control of airflow by glottal structures, a primary determinant of thoracic pressure, 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, 40, 43). These studies show recruitment of the diaphragm as a component of postural adjustments associated with voluntary limb and trunk movements in a manner that is coordinated with its respiratory function. Human (19) and animal data (18) show that electrically evoked contraction of this muscle has a direct mechanical effect on control of the spine. The fundamental contribution of diaphragm to inspiration requires fine-tuned coordination of respiration and posture. This relationship is adaptable and depends on the contextual demands. When respiratory demand is increased by hypercapnea, the relative contribution of diaphragm to respiration is increased, and that to postural control is decreased (23). In quiet standing, respiratory movements of the trunk are compensated by small movements of the trunk and lower limbs to minimize perturbation to center of pressure (CoP) (22), but this is compromised in people with low back pain (10, 41) as are other functions that require coordination between respiration and posture in people with back pain (6, 9, 15, 27). During functional tasks such as walking, the coordination between respiration and postural demands varies as a function of speed and mode of locomotion (39). These studies and others

(3, 16, 29, 43) have firmly established respiration as a dynamic component of postural stability. A similar role for the glottis (vocal folds / airway structures) has not yet been described.

Although most neurophysiological and biomechanical research has focused on the role of modulation of IAP in postural control, equal importance should be placed on control of intra-thoracic pressure (ITP), which is likely to be essential for trunk control. ITP is dependent not only on activation of the thoracic muscles, but also on regulation of resistance to airflow (38). The glottis modulates the airway opening at the top of the trunk, supporting airway and ITP for tasks such as talking, coughing, and breathing, yet glottal control is rarely reported as an integral component of postural control (14, 31, 33, 34, 38). Past research has focused on glottal control during intense postural demands such as in weight lifting (7, 12, 17, 35, 38). We proposed that the glottal structures, in conjunction with activity of trunk muscles, contribute to dynamic stability of the trunk during low level demands such as being bumped in a crowd. We hypothesized that modulation of airway control would influence the efficacy of upright postural stability in response to postural perturbations. If true, we predicted that tasks that prevent airway constriction during a perturbation would compromise postural control of the trunk and body, resulting in a greater balance disturbance to thoracic and CoP position. In contrast, tasks that optimize airway constriction (e.g. glottal closure) should incur lesser perturbation. This study aimed to test this hypothesis in healthy participants.

MATERIALS AND METHODS

Participants. 12 healthy participants (7 male/5female), 21-41 years-old (mean age 31.17) participated in this study. Participants were excluded from participation if they had a history of any major circulatory/neurologic/respiratory disorder, recent or current pregnancy, or recent muscle or joint pain. Data from 11 of the 12 participants was complete and therefore used in analyses. The study was approved by the Medical Research Ethics Committee of The University of Queensland (Australia) and conducted in accordance with the Declaration of Helsinki. Written informed consent was obtained from all participants before inclusion.

Ground reaction forces. Ground reaction forces to determine the trunk center of pressure measurements (CoP) were recorded with a force plate (Model FP4060, Bertec, Columbus, USA) (Figure 1A). CoP was calculated by dividing the moment (My) around the coronal axis by the vertical ground reaction force (Fz).

Surface Electromyography. Electromyographic (EMG) activity of the right obliquus externus abdominis (OE) and erector spinae (ES) muscles (Figure 1B) was recorded with surface electrodes (Noraxon dual electrodes #272, Noraxon, Scottsdale, USA) placed approximately parallel with the muscle fibers inferior to right costal margin of rib 8, and 2 cm lateral to L3, respectively. A ground electrode (Model 9160F, 3M, Pymble, NSW, Australia) was placed over the iliac crest. Skin was prepared with gentle abrasion. EMG data were band-pass filtered between 3 and 500 Hz (a notch filter at 50 Hz was used to remove electrical interference), amplified 2000 times, and sampled at 4 kHz using a Neurolog NL824 pre-amplifier and NL900D amplifier (Digitimer Ltd, Hertfordshire, England, UK). Samples were digitized using a Power 1401 data acquisition system and Spike2 (V6.09) software (Cambridge Electronic Design, Cambridge, England, UK).

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 (Figure 1D) to record horizontal linear displacement of the thorax. Data were collected along with the EMG at 4 kHz.

Pneumotachometer. Participants wore a nasal clip to ensure mouth breathing. They were fitted with an airtight oral nasal mask that was secured with a skull cap harness. The oral nasal mask was used rather than a mouthpiece to prevent the participants from biting down on the mouth piece as a possible postural stabilization strategy during testing. Participants were checked for air leaks, and the mask was readjusted if needed. A pneumotachometer (Hans-Rudolf, Germany) was coupled to the mask (Figure 1E) 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 oral 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 assure 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 and was used for analysis) using a single nasogastric catheter tube inserted via the nose (Figure 1F). The catheter was embedded with a thin-film transducer (Gaeltec Ltd, Dunvegan, Isle of Skye, Scotland, UK) that was placed in the stomach. Data were collected along with EMG at 4 kHz. Correct placement of the electrode was confirmed by noting increased pressure during a sniff test: during inspiration IAP increases in response to the descent of the diaphragm (21, 36). The catheter was secured in position with tape. IAP data were calibrated by immersion in a column of water.

Procedure. Participants stood on a force plate inside an aluminum enclosure (120 cm square and 110cm high, approximately "waist height" for most participants) (Figure 1). The participants' standing balance was perturbed during seven different airway conditions (Table 1) to investigate the response of the participant's postural stability to various airway constrictions. The specific breathing/voicing conditions were chosen to reflect normal variations in airway control; glottis closed (breath-holding), glottis partially opened (phonation), or glottis open (natural opening as in normal breathing or a forced opening as in a sigh).

Participants wore a rigid chest harness secured in place with Velcro straps (Figure 1C). Cables were attached to the harness anteriorly and posteriorly at the level of the xiphoid process. The cable height was adjusted (via pulleys) for each participant to maintain the cables parallel to the ground. The cables were connected via pulleys to electromagnets outside the aluminum enclosure (Figure 1C). Weights (3% of the participant's body weight) were attached to the anterior and posterior 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. Prior to the experiment, participants practiced up to 4 trials until they were comfortable with the perturbation task. During the experiment, the participant's balance was perturbed in a sagittal plane during the seven different breathing/voicing conditions described in Table 1. Participants were informed that during each trial the weight would drop from either the anterior or posterior cable, disturbing their standing balance in the sagittal plane. They were instructed to regain their starting standing posture as quickly as possible.

Immediately prior to testing each condition, the participants practiced the specific breathing task (instructions for each condition listed in Table 1). For the non-voicing conditions, a pneumotachometer tracing on the oscilloscope was used to confirm that the instruction for the glottal task resulted in the expected performance. A smooth sinusoidal wave confirmed an uninterrupted airflow for the open glottal conditions (“Normal breath”, “FRC-open”, “Sigh”), and a sharp angle followed by 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 a list of random numbers. Weights were dropped 20 times (10 times in each direction) during the 7 breathing/voicing conditions for a total of 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 subsequent trial, participants were provided with verbal feedback as required to regain their neutral marked position prior to the next trial. Participants were allowed to rest between conditions as needed.

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). Baseline position was calculated as the CoP / thorax position immediately prior to the perturbation averaged over 50ms. The peak amplitude of the displacement of each parameter after the perturbation was identified automatically using custom software. Data were normalized to the maximal displacement for each subject across all 7 conditions. All displacement values were thus expressed as a percentage of each subject's maximal displacement.

If present, changes in displacement of the thorax and CoP in response to the perturbation in the 7 conditions could be explained by differences in a range of factors including the airway constriction as well as IAP and trunk muscle activity. In order to determine whether differences in the IAP and trunk muscle activity were responsible, the mean amplitude of these variables for 50 ms prior to the perturbation was calculated and normalized across all 7 conditions, as with the thoracic and CoP displacement data.

Statistical analyses were performed with Statistica (version 9). Repeated measures analyses of variance (RM-ANOVA) with post hoc analyses (Duncan's test) were performed on amplitude of both thoracic and CoP displacement between the 7 conditions. IAP and trunk muscle EMG just prior to perturbation was compared between conditions with RM-ANOVAs. The relationship between IAP, and OE/ES EMG and the amplitudes of thoracic and CoP displacement were analyzed using Pearson's correlation. Significance level was set at $p < 0.05$.

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. The peak amplitude of displacement was affected by the 7 breathing/voicing conditions (Main effect condition: $P < 0.0001$). Consistent with our hypothesis, the two conditions with a forced open-glottis allowing unimpeded airflow ("Sigh" and "FRC-open") were associated with greater thoracic displacement in response to the perturbations than any other condition, regardless of the direction of perturbation (Figure 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 also exceed that in "Count" and "Norm exp-hold" conditions (Post hoc: $P < 0.06$). There was no difference between the other conditions. Of the eleven participants, seven had their largest thorax displacement during the "Sigh" condition, and three had their largest displacement during the "FRC-open" condition. There was no interaction effect of direction by condition.

Center of Pressure (CoP) displacement of the body. In contrast to the thorax displacement, the absolute amplitude (amplitude without reference to direction) of CoP displacement was different between directions (Main effect direction: $P = 0.001$) (Figure 3). When the posterior weight dropped and the participant was pulled forwards (forward perturbation) toward the remaining anterior weight, there was a smaller displacement of CoP. The effect of the breathing condition on CoP displacement was the same for both perturbation directions (Interaction Direction x Condition: $P = 0.76$). In both directions, "Sigh" (an open glottis condition) and "Max insp-hold" (a glottis closed condition) were associated with a greater CoP displacement than that induced by perturbation during "Count" (a 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. To assess whether trunk-readiness influenced the thoracic and whole body postural stability reaction to the perturbations, EMG and IAP data for each condition were analyzed immediately prior the onset of the perturbation. Peak obliquus externus abdominis (OE) EMG differed between the 7 breathing conditions (Main effect condition: $P = 0.035$) (Figure 4). Immediately prior to the perturbation, normalized OE EMG mean amplitude was higher for “Max insp-hold” than “Normal breath”, “Norm exp-hold” and “FRC-open” conditions (Post hoc: $P < 0.05$). There was no difference between other conditions. Although the greatest OE EMG amplitude was recorded during one of the conditions with the lowest trunk displacement, there was no significant correlation between OE EMG prior to perturbation and thoracic or CoP displacement (Table 2).

Erector spinae (ES) EMG was also affected by the 7 breathing conditions (Main effect condition: $P = 0.0002$) (Figure 5) with significantly higher mean amplitude for the conditions with higher starting lung volume conditions (“Max insp-hold”, “Count” and “Sigh”) than the lower lung volume conditions (“Normal breath”, “Norm exp-hold” and “FRC-open”) (Post hoc: all $P < 0.03$). The only exception was

“Ah” which is a high lung volume condition but was significantly lower than “Max insp-hold” condition. “Ah” was not lower than any other condition ($P < 0.03$). Again 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 and poor statistical power.

DISCUSSIONS AND CONCLUSION

This study examined the impact of airway modulation on upright postural control and demonstrated that the status of the glottis appears to influence the quality of postural control. Conditions in which the glottis was maintained open (“Sigh” and “FRC-open”) prevented the airway from constricting in response to a perturbation. When perturbed the thoracic and CoP displacements were largest in the “Sigh” of all 7 conditions and could not be otherwise explained by activation or lack thereof of the trunk muscles. Conversely, the “Max insp-hold” condition allowed full glottal closure after a full inspiratory effort and showed the least thoracic displacement (greater postural stability). However, the CoP response in the “Max insp-hold” condition was unanticipated, as it showed postural instability similar to the “Sigh” condition. The most stable CoP condition was the mid-range, partially open glottal condition of “Counting.” These findings show that the glottis plays an active role in postural stability.

Breath-holding strategies have been reported with strenuous postural demands such as weight lifting (4, 7). Hemborg et al (17) investigated IAP and its relationship to breath support, abdominal strength and weight-lifting in healthy individuals, weight lifters and people with low back pain, and found that neither an abdominal muscle strengthening program alone, nor a specific respiratory pattern increased IAP adequately. Instead, the highest IAPs were generated by neuromotor strategies that involved glottal closure to stabilize the diaphragm and abdominal muscles. Recent research confirmed breath-holding (glottal closure) as a natural breath response to heavy loads (12). Further, the role of breathing at the opposite end of postural demand, has shown that at minimal workloads (quiet stance), the trunk and lower limbs compensate for breathing movements, primarily in the sagittal plane, in order to dynamically maintain CoP for balance (3, 16, 22, 29). The present work extends these concepts demonstrating that glottal control plays a role in thoracic and whole body postural stability.

Whereas most studies of respiration and postural control investigate displacement of the CoP (3, 10, 15, 16, 22, 27, 29), this study included peak thoracic displacement as an additional measure of balance disturbance, and found that the behavior of the thorax and whole-body CoP behaved differently in several conditions. This warrants further discussion.

We hypothesized that the airway would naturally constrict when balance is challenged in order to assist in increasing trunk pressures to meet the increased postural demand. Orlikoff (38) provided supporting evidence in 20 healthy men and women who lifted 0, 3, 5 and 7 kg dumbbells with extended arms while performing 2 different voicing tasks. In both the sustained vowel (/a/) and the rapid repeating syllable (/pi/) condition, airway resistance and glottal constriction increased as the postural demand increased, yet the airway remained patent. To test our hypothesis, we manipulated the airway rather than postural demand. In the forced open-glottal conditions of “Sigh” and “FRC-open”, the airway was intentionally prevented from constricting. Consistent with our hypothesis, this was associated with greater thoracic displacement than any other condition, the findings of which are compatible with Orlikoff (38) - glottal constriction is necessary to meet higher postural loads. Conversely, the thorax was more posturally stable with the glottis closed (“Max insp-hold” and “Norm exp-hold”) and with the glottis only partially opened (“Ah” and

“Counting”), as well as “Normal breath.” There were no differences in thoracic displacement between the glottis-closed and glottis partially-open conditions. This may be explained by our use of gentle perturbations (akin to being bumped in a crowd) and greater disturbances may have highlighted further differences. As trunk muscle EMG and IAP were not directly related to thoracic displacement it appears that engagement of the vocal folds and airway structures was important to control the cranial thoracic outlet, effectively functioning as a pressure valve. The type of engagement, e.g. voicing vs. breath-holding, does not appear as important as the engagement itself.

Thoracic displacement was not affected by the direction of the 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 (potentiometer attached at the level of the xiphoid process). 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. The base of support for CoP has a larger base anteriorly (the feet) than posteriorly, thus it was not surprising that CoP displacement was greater with backward perturbations. Although thorax displacement will be influenced by whole body displacement, the equal displacement of thorax in each direction implies difference in angular motion at the hip and low spine with each direction (hip/lumbar motion to enable similar displacement despite limited CoP displacement in the anterior direction). There were no comparable studies for this aspect of our study.

The peak CoP displacement differed in some conditions from the thoracic displacements, which was not fully consistent with our hypothesis. Consistent with our hypothesis, the forced open-glottal condition (“Sigh”) was the most challenging situation in terms of both thoracic and CoP displacement. However, the CoP response to the glottal closed condition of “Max insp-hold” differed from the thoracic displacement outcomes. In the CoP displacement, the “Max insp-hold” condition imposed a challenge equal to the open airway “Sigh” condition. Prior research has established that patients with low back pain have excessive spinal stiffness and less compensation for normal respiratory balance disturbances resulting in less effective postural control strategies (9, 10, 15, 27). Furthermore, if the stiffness of the trunk is increased, the quality of postural control is compromised as this limits the capacity of the trunk to compensate for postural disturbances (11). Thus, greater stiffness of the body in the “Max insp-hold” condition may explain the greater postural disturbance in this condition. Perhaps, the ideal postural control needs mid-range control; neither too stiff nor to flexible. The “Max insp-hold” condition would simulate the stiff trunk, and the “Sigh” condition would simulate the flexible or floppy trunk. Neither strategy was effective for minimization of disturbances to CoP in response to a gentle perturbation. Mid-range glottal control (“Counting”) was the most effective dynamic postural strategy for minimization of CoP disturbance, more so than “Ah”, although not significantly different. Perhaps the common voicing pattern of counting was better matched with the natural balance response than the contrived voicing condition of “Ah.”

The thorax was most stable with a static breath-holding maneuver, but the CoP was most capable of absorbing thoracic disturbances and maintaining CoP position stable with a dynamic mid-range airway modulation (voicing) rather than a static, breath-holding strategy during light postural disturbances that were similar to everyday balance challenges. Studies that demonstrate the dynamic balance between the stability and mobility needs of the trunk and breathing (8, 22) support our results. 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 presented with a challenging postural task.

However, it would appear that to optimize dynamic control of CoP, a mid range glottal control technique such as talking may be more effective.

The changes in thoracic and CoP displacement with airway closure conditions could not be explained by changes in trunk readiness immediately prior to the perturbation (~50ms). “Sigh”, which was associated with the greatest thoracic and CoP displacement, would have had to have had less OE and ES activation than other conditions (providing less support) to account for the greater postural instability. However, OE activity during “Sigh” was not different to that recorded in any other condition, and ES activity was greater during “Sigh” than during 3 other conditions (“FRC-open”, “Normal exp-hold” and “Normal breath”). Further, there was no correlation between EMG of either muscle and the displacement variables. A limitation of this study is that EMG data did not include post-perturbation responses.

Of interest, “FRC-open”, “Normal exp-hold” and “Normal breath” all involve low lung volume breathing patterns (quiet breathing). The other 4 conditions, “Max insp-hold”, “Ah”, “Counting” and “Sigh”, require a larger voluntary inspiratory effort (larger lung volumes). OE and ES activity 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 activation than “Max insp-hold.” Perhaps OE and ES are needed to co-contract during higher lung volume breaths to stabilize the trunk (14). Specific lung volume measurements were not controlled during this study. Further research is needed to determine if there is a critical lung volume threshold where glottal control becomes more important to postural stability.

Clinical relevance and suggestions for further research

Our findings suggest that without the ability to recruit glottal structures as part of dynamic postural control, balance strategies would inherently be disadvantaged. An ideal clinical population for further research would be patients with open tracheostomies (an obligatory open-glottal condition) versus patients who have speaking-valve attachments to their tracheostomy tubes that restore the use of the vocal folds for airway modulations. Based on our findings, we would anticipate that patients with the ability to modulate their airways (speaking-valve group) would have better postural control than those with tracheostomies that do not restore this function. Our findings may also help to explain common clinical breath-holding strategies used by patients with balance impairments. The thorax will be more stable, but may not afford the dynamic control necessary to efficiently control CoP.

Conclusion.

Airway modulation does effect postural control during upright perturbations. These data highlight that consideration of glottal control is likely to be important to consider during balance training.

REFERENCES

1. **Al-Bilbeisi F**. Diaphragm recruitment during nonrespiratory activities. *Am J Respir Crit Care Med* 162: 456-459, 2000.
2. **Butler JE**. Drive to the human respiratory muscles. *Respir Physiol Neurobiol* 159: 115-126, 2007.
3. **Caron O, Fontanari P, Cremieux J, Joulia F**. Effects of ventilation on body sway during human standing. *Neurosci Lett* 366: 6-9, 2004.
4. **Davis PR, Troup JDG**. Pressures inthe trunk cavities when pulling, pushing and lifting *Ergonomics* 7: 465 - 474, 1964.
5. **Deem JF, Miller L**. *Manual of Voice Therapy, ed. 2*. Austin,TX: PRO-ED, Inc, 2000, p. 13-14.
6. **Ebenbichler GR, Oddsson LI, Kollmitzer J, Erim Z**. Sensory-motor control of the lower back: implications for rehabilitation. *Med Sci Sports Exerc* 33: 1889-1898, 2001.
7. **Fink BR**. The Curse of Adam: Effort Closure Of The Larynx. *Anesthesiology* 39: 325-327, 1973.
8. **Gandevia SC, Butler JE, Hodges PW, Taylor JL**. Balancing acts: respiratory sensations, motor control and human posture. *Clin Exp Pharmacol Physiol* 29: 118-121, 2002.
9. **Grenier SG, McGill SM**. When exposed to challenged ventilation, those with a history of LBP increase spine stability relatively more than healthy individuals. *Clin Biomech (Bristol, Avon)* 23: 1105-1111, 2008.
10. **Grimstone SK, Hodges PW**. Impaired postural compensation for respiration in people with recurrent low back pain. *Exp Brain Res* 151: 218-224, 2003.
11. **Gruneberg C, Bloem BR, Honegger F, Allum JH**. The influence of artificially increased hip and trunk stiffness on balance control in man. *Exp Brain Res* 157: 472-485, 2004.
12. **Hagins M, Lamberg EM**. Natural breath control during lifting tasks: effect of load. *Eur J Appl Physiol* 96: 453-458, 2006.

13. **Hagins M, Pietrek M, Sheikhzadeh A, Nordin M**. The effects of breath control on maximum force and IAP during a maximum isometric lifting task. *Clinical Biomechanics* 21: 775-780, 2006.
14. **Hagins M, Pietrek M, Sheikhzadeh A, Nordin M, Axen K**. The effects of breath control on intra-abdominal pressure during lifting tasks. *Spine* 29: 464-469, 2004.
15. **Hamaoui A, Do M, Poupard L, Bouisset S**. Does respiration perturb body balance more in chronic low back pain subjects than in healthy subjects? *Clinical Biomechanics* 17: 548-550, 2002.
16. **Hamaoui A, Gonneau E, Le Bozec S**. Respiratory disturbance to posture varies according to the respiratory mode. *Neurosci Lett* 475: 141-144, 2010.
17. **Hemborg B, Moritz U, Lowing H**. Intra-abdominal pressure and trunk muscle activity during lifting. IV. The causal factors of the intra-abdominal pressure rise. *Scand J Rehabil Med* 17: 25-38, 1985.
18. **Hodges P, Kaigle Holm A, Holm S, Ekstrom L, Cresswell A, Hansson T, Thorstensson A**. Intervertebral stiffness of the spine is increased by evoked contraction of transversus abdominis and the diaphragm: in vivo porcine studies. *Spine* 28: 2594-2601, 2003.
19. **Hodges PW, Eriksson AE, Shirley D, Gandevia SC**. Intra-abdominal pressure increases stiffness of the lumbar spine. *J Biomech* 38: 1873-1880, 2005.
20. **Hodges PW, Gandevia SC**. Activation of the human diaphragm during a repetitive postural task. *J Physiol (Lond)* 522 Pt 1: 165-175, 2000.
21. **Hodges PW, Gandevia SC**. Changes in intra-abdominal pressure during postural and respiratory activation of the human diaphragm. *J Appl Physiol* 89: 967-976, 2000.
22. **Hodges PW, Gurfinkel VS, Brumagne S, Smith TC, Cordo PC**. Coexistence of stability and mobility in postural control: evidence from postural compensation for respiration. *Exp Brain Res* 144: 293-302, 2002.
23. **Hodges PW, Heijnen I, Gandevia SC**. Postural activity of the diaphragm is reduced in humans when respiratory demand increases. *J Physiol* 537: 999-1008, 2001.
24. **Hodges PW, Richardson CA**. Delayed postural contraction of transversus abdominis in low back pain associated with movement of the lower limb. *J Spinal Disord* 11: 46-56, 1998.
25. **Hodges PW, Sapsford R, Pengel LH**. Postural and respiratory functions of the pelvic floor muscles. *Neurourol Urodyn* 26: 362-371, 2007.
26. **Hudson AL, Butler JE, Gandevia SC, De Troyer A**. Interplay between the inspiratory and postural functions of the human parasternal intercostal muscles. *J Neurophysiol* 103: 1622-1629, 2010.

27. **Janssens L, Brumagne S, Polspoel K, Troosters T, McConnell A**. The effect of inspiratory muscles fatigue on postural control in people with and without recurrent low back pain. *Spine (Phila Pa 1976)* 35: 1088-1094, 2010.
28. **Koenig LL, Lucero JC, Perlman E**. Speech production variability in fricatives of children and adults: Results of functional data analysis. *Journal of Accoustical Society of America* 124: 3158-3170, 2008.
29. **Kuczyński M, Wieloch M**. Effects of Accelerated Breathing On Postural Stability. *Human Movement* 9: 107-110, 2008.
30. **Ladefoged P, Maddieson I**. *The Sounds of the World's Languages*. Oxford, UK & Cambridge, USA: Blackwell, 1996.
31. **Lamberg EM, Hagins M**. Evidence supporting the role of breath control in postural stabilization. In: *APTA CSM 2009*. Las Vegas, NV: 2009.
32. **Lavender SA, Marras WS, Miller RA**. The development of response strategies in preparation for sudden loading to the torso. *Spine (Phila Pa 1976)* 18: 2097-2105, 1993.
33. **Massery M**. Breathing and Upright Posture: Simultaneous Needs. In: *26th International Seating Symposium*. Vancouver, BC: Sunny Hill Health Centre for Children, 2010, p. 25-28.
34. **Massery M**. Multisystem Consequences of Impaired Breathing Mechanics and/or Postural Control. In: *Cardiovascular and Pulmonary Physical Therapy Evidence and Practice, ed. 4.*, edited by Frownfelter D, and Dean E. St. Louis, MO.: Elsevier Health Sciences, 2006, p. 695-717.
35. **Narloch JA, Brandstater ME**. Influence of breathing technique on arterial blood pressure during heavy weight lifting. *Arch Phys Med Rehabil* 76: 457-462, 1995.
36. **Nava S, Ambrosino N, Crotti P, Fracchia C, Rampulla C**. Recruitment of some respiratory muscles during three maximal inspiratory manoeuvres. *Thorax* 48: 702-707, 1993.
37. **O'Sullivan PB, Beales DJ**. Changes in pelvic floor and diaphragm kinematics and respiratory patterns in subjects with sacroiliac joint pain following a motor learning intervention: a case series. *Man Ther* 12: 209-218, 2007.
38. **Orlikoff RF**. Voice production during a weightlifting and support task. *Folia Phoniatr Logop* 60: 188-194, 2008.
39. **Saunders SW, Rath D, Hodges PW**. Postural and respiratory activation of the trunk muscles changes with mode and speed of locomotion. *Gait Posture* 20: 280-290, 2004.
40. **Shirley D, Hodges PW, Eriksson AE, Gandevia SC**. Spinal stiffness changes throughout the respiratory cycle. *J Appl Physiol* 95: 1467-1475, 2003.
41. **Smith M, Coppieters MW, Hodges PW**. Effect of experimentally induced low back pain on postural sway with breathing. *Exp Brain Res* 2005.

42. **Smith MD, Coppieters MW, Hodges PW**. Postural response of the pelvic floor and abdominal muscles in women with and without incontinence. *Neurourol Urodyn* 26: 377-385, 2007.
43. **Uga M, Niwa M, Ochiai N, Sasaki S**. Activity patterns of the diaphragm during voluntary movements in awake cats. *J Physiol Sci* 60: 173-180, 2010.
44. **Villars PS, Kanusky JT, Levitzky MG**. Functional residual capacity: the human windbag. *AANA J* 70: 399-407, 2002.

FIGURES

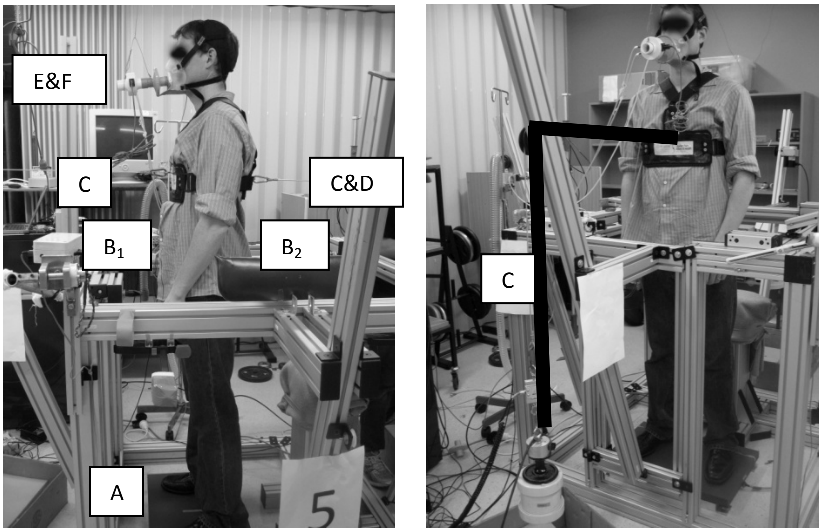

Fig. 1. Procedural set up

A) *Force plate*: recorded ground reaction forces to determine center of pressure (CoP).

B) *Surface Electromyography (EMG):* recorded trunk muscle activity.
   1. right obliquus externus abdominis (OE)
   2. erector spinae (ES) muscles

C) *Chest harness, anterior-posterior cables and electro-magnetic weights*: created the perturbation. Cable line thickness was enhanced in right picture for easier viewing of the anterior cable's position to the chest harness, over the pulley and down to the electromagnetic weight. A similar cable and weight was set up posteriorly.

D) *Linear potentiometer*: attached posteriorly to chest harness. Recorded horizontal thoracic displacement response to the perturbation.

E) *Pneumotachometer*: attached to facemask. Confirmed airflow during breathing tasks.

F) *Nasogastric (NG) tube with pressure transducer*: gastric pressure transducer recorded intra-abdominal pressure (IAP) in 4 of 11 participants.

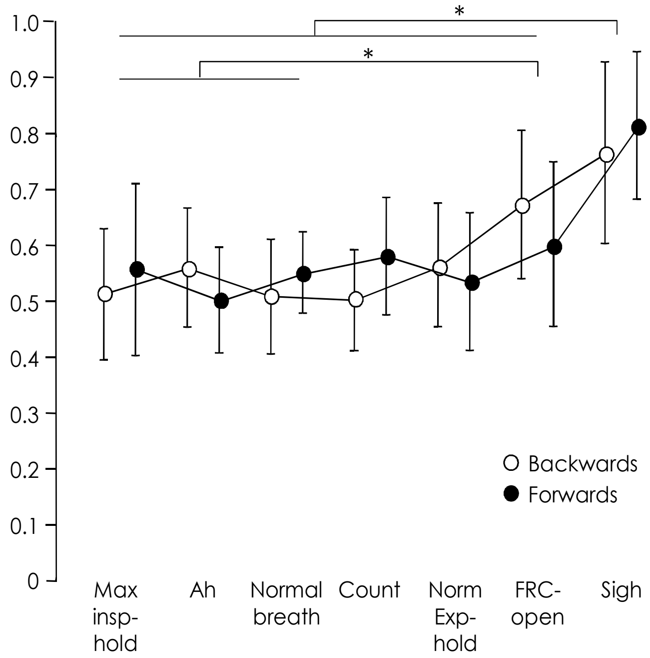

Fig. 2. Peak horizontal linear displacement of the thorax during perturbation trials. Absolute thoracic displacement normalized to peak across conditions. The largest displacement value across all trials for each participant was converted to 1.0 value (normalized data) and the rest of the displacement values were converted to a percentage of 1.0. This reduced inter-subject variability for a more accurate comparison of thoracic horizontal movement. There was no effect (*P* = 0.87) for the direction of the perturbation on the thoracic displacement, thus forward and backward displacement values were converted to positive numbers and pooled together for the analysis of condition. Breathing condition abbreviations listed on Table 1.

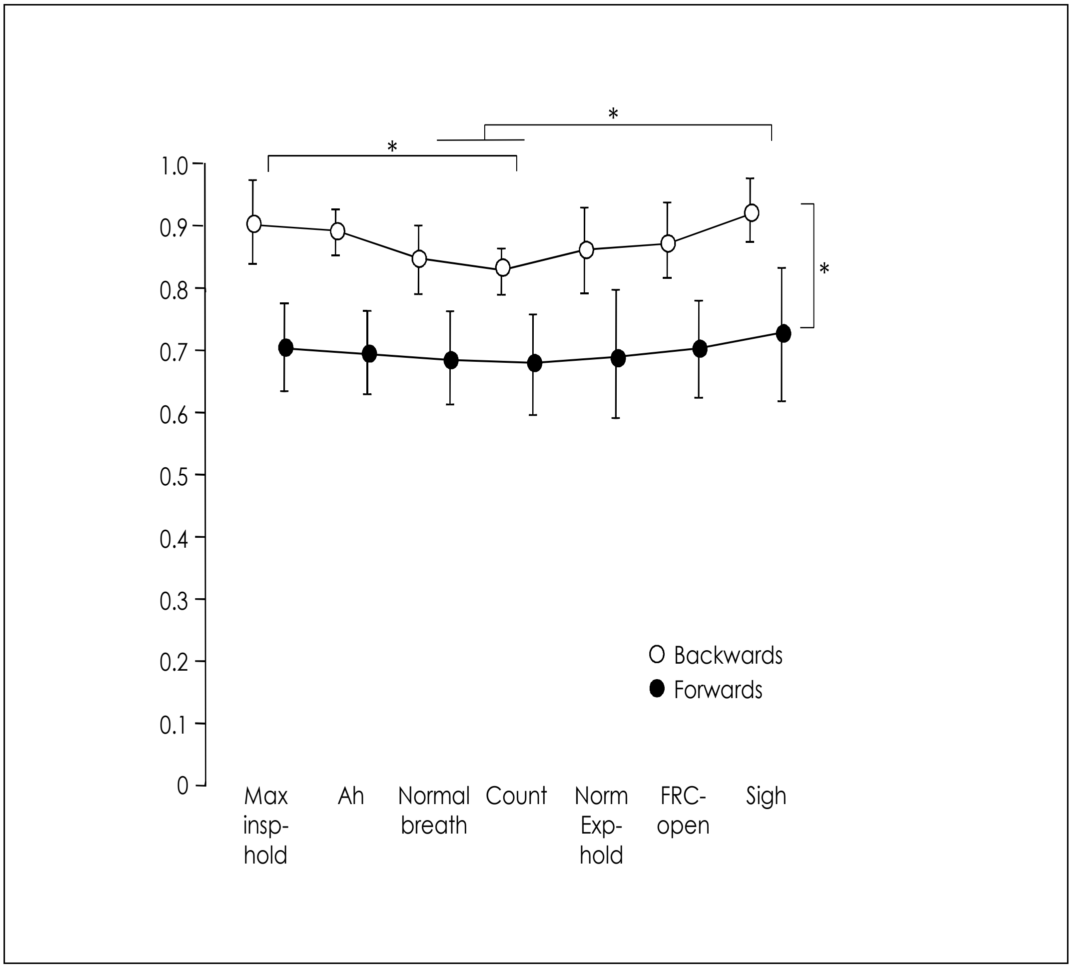

Fig. 3. Peak Center of Pressure (CoP) displacement of the body during perturbation trials. Absolute CoP displacement normalized to peak across all conditions The largest displacement value across all trials for each participant was converted to 1.0 value (normalized data) and the rest of the displacement values were converted to a percentage of 1.0. There was an effect (P= 0.001) for the direction of the perturbation on CoP displacement, thus forward and backward displacement values were analyzed separately for effect of condition. Breathing condition abbreviations listed on Table 1.

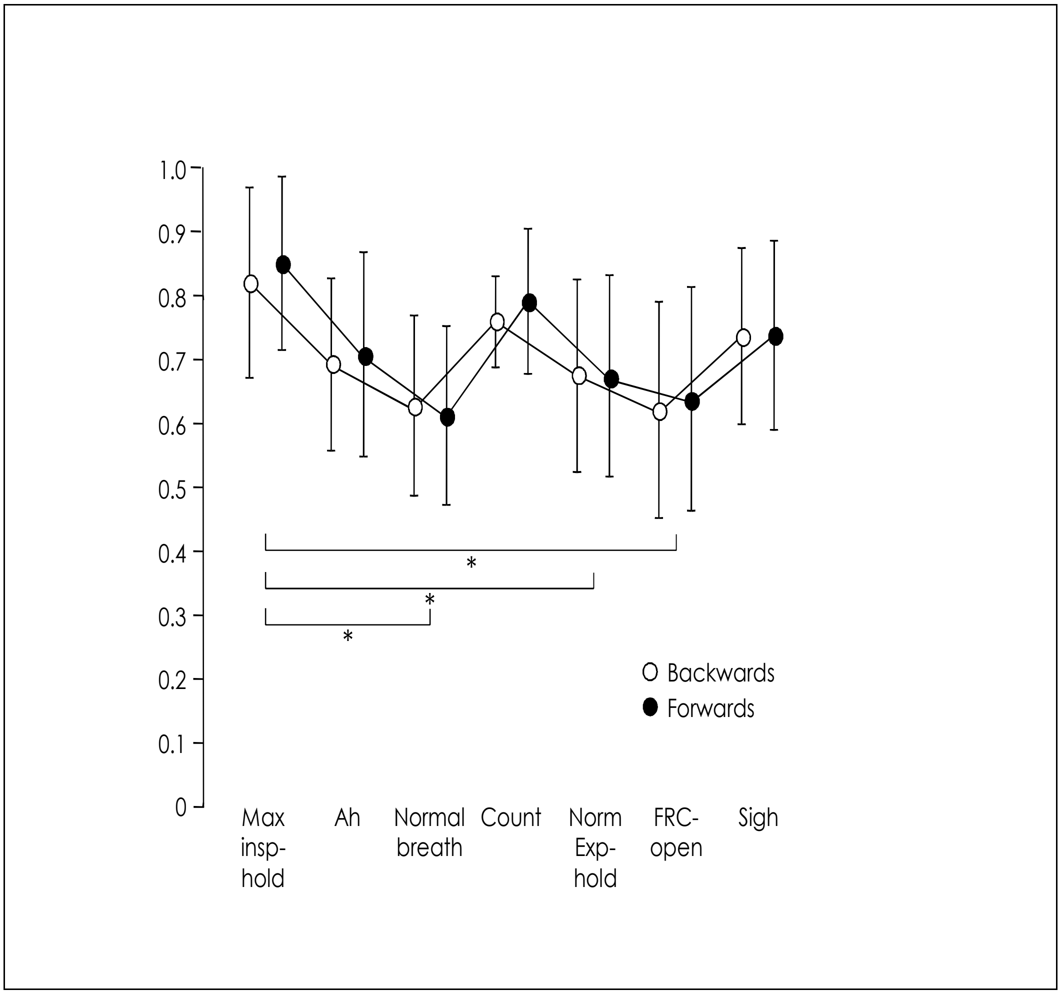

Fig. 4. OE EMG activity just prior to loading, normalized to peak across all conditions. The largest displacement value across all trials for each participant was converted to 1.0 value (normalized data) and the rest of the displacement values were converted to a percentage of 1.0. There was an effect for condition (*P* = 0.035), but not direction. Breathing condition abbreviations listed on Table 1.

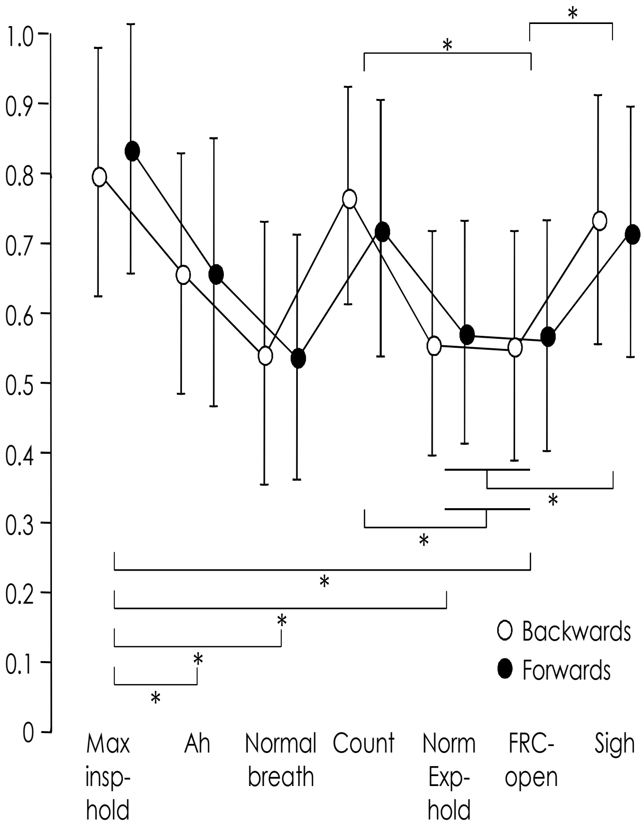

Fig. 5. ES EMG activity just prior to loading, normalized to peak across all conditions The largest displacement value across all trials for each participant was converted to 1.0 value (normalized data) and the rest of the displacement values were converted to a percentage of 1.0. There was no effect for direction. There was an effect for condition (*P* = 0.0002), but not direction. Breathing condition abbreviations listed on Table 1.

TABLES

Table 1. *Independent Variables:7 breathing/voicing conditions during perturbation trials.*

	Seven breathing conditions	**Abbreviation for graphs and text**	**Airflow through the glottis just prior to the perturbation?**	**Glottis during perturbation: closed, open, or partially opened**	**Instruction to participants***
1	Maximal inhalation, then breath-hold	Max insp-hold	No	Closed	"Take in the biggest breath you can. Then hold your breath until the weight drops."
2	/Ah/ voicing	Ah	Yes	Partially open†	"In a normal, full speaking voice, say "ah" for as long as you can until the weight drops."
3	Natural Breathing	Normal breath	Yes	Open	"Breathe normally. Do not take deep breaths. Do not take shallow breaths. Don't hold your breath. Just breathe normally until the weight drops."
4	Counting out loud	Count	Yes	Partially open†	"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."
5	Normal exhalation, then breath-hold	Norm exp-hold	No	Closed	"Take an easy breath in. Exhale normally. Then hold your breath until the weight drops."
6	Normal exhalation, then airway left open (no breath hold)	FRC-open‡	No	Open	"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."
7	Sigh (/H/ sound)	Sigh	Yes	Open	"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."

* General instructions to all participants prior to starting the testing: "Stand up straight. The weight in front or behind you will randomly fall. You will feel a quick pull forward or backward, similar to being bumped in a crowd. Try to regain your straight posture as quickly as possible. If you feel like you might fall, grab the bar in front of you or sit down on the stool behind you. You should stand relaxed between the trials. If you get tired, let us know and you can rest."

† In order to produce sound, the vocal folds actively constrict the airway, thus the glottis is only partially open.

‡ Functional residual capacity (FRC): The resting point at the end of normal passive exhalation (the opposing forces of the lungs and chest wall are equal and opposite).

Table 2. *Correlation coefficients (R^2 values) for relationship between EMG parameters immediately prior to perturbation and the amplitude of perturbation (thoracic displacement 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

There was no correlation between peak thoracic or CoP displacement and OE and ES EMG parameters immediately prior to the perturbation (All $P > 0.05$).

APPENDIX.

Reasons for including each breathing condition in this study.

	Breathing / voicing conditions	**Reasons for including each of the 7 breathing/voicing conditions**
1	Maximal inhalation, breath hold	Breath holding is a natural form of trunk stabilization (12, 14). Hagins (13) showed healthy people naturally take in a deeper breath prior to lifting a heavier load compared to a lighter load, and that having a greater lung volume while breath-holding resulted in greater IAP. We hypothesized that this would be the most posturally stable static condition.
2	/Ah/ voicing	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), thus providing mid range control of the glottis. The partially opened glottis condition results in markedly longer exhalation phase than a completely open airway exhalation like a sigh. We hypothesized that the vocal fold engagement for voicing would increase dynamic postural stability as opposed to static stability (breath holding, condition #1) because it would afford mid range control of the airway similarly to mid range control of the trunk.
3	Natural Breathing	Natural breathing uses a passive open airway, no conscious effort. It was included to observe a natural rather than contrived response to a perturbation during an open airway condition as opposed to a forced open-glottal condition like conditions #6 & 7.
4	Counting out loud	As during /ah/ voicing condition, counting will partially obstruct the airway (38). However, unlike /ah/, counting is a natural use of voicing rather than contrived. We were uncertain as to whether any voicing or the type of voicing would provide different balance responses.
5	Normal exhalation, then breath hold	Functional residual capacity (FRC), the end of a natural breath, is the natural end resting position of the chest (44). 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 (44). Closing the airway at FRC will trap approximately half the volume of air in the lungs compared to condition #1 where the participants inhaled a maximal effort. Based on Hagins (14), we hypothesized that this condition would likely produce less trunk stability than condition #1 because the smaller lung volume to minimize the participant's ability regulate thoracic pressures in spite of the closed glottis.

6	Normal exhalation, airway left open (no breath hold)	Like condition #5, 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. We hypothesized that without glottal constriction, even at this lower lung volume condition, the trunk would be less stable, therefore it would be less stable than in condition #5.
7	Sigh (/H/ sound)	/H/ is an unvoiced sound (28, 30). 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. We hypothesized that this would be the least posturally stable condition.