Dynamics of male pelvic floor muscle contraction observed with transperineal ultrasound imaging differ between voluntary and evoked coughs

J Appl Physiol (1985). 2014 Feb 13. [Epub ahead of print]

Dynamics of male pelvic floor muscle contraction observed with transperineal ultrasound imaging differ between voluntary and evoked coughs

Ryan E. Stafford[1]; Stuart Mazzone[2]; James A. Ashton-Miller[3]; Christos Constantinou[4]; Paul W. Hodges[1]

[1]Centre for Clinical Research Excellence – Spinal Pain, Injury and Health, School of Health and Rehabilitation Sciences, The University of Queensland, Brisbane, Australia

[2]School of Biomedical Sciences, The University of Queensland, Brisbane, Australia

[3]Biomedical Engineering, Department of Obstetrics and Gynecology, University of Michigan, Ann Arbor, USA

[4]Department of Urology, School of Medicine, Stanford University, Palo Alto, USA

Running head:
Imaging of male pelvic floor muscle contraction during cough

Address for correspondence:

Paul W. Hodges

Centre for Clinical Research Excellence in Spinal Pain, Injury and Health, School of Health and Rehabilitation Sciences
University of Queensland
St. Lucia, Queensland
Australia 4072
Telephone: (07) 3365 4567; FAX: (07) 3365 4567
Email: p.hodges@uq.edu.au

Abstract

Coughing provokes stress urinary incontinence and voluntary coughs are employed clinically to assess pelvic floor dysfunction. Understanding of urethral dynamics during coughing in men is limited and it is unclear if voluntary coughs are an appropriate surrogate for spontaneous coughs. We aimed to investigate the dynamics of urethral motion in continent men during voluntary and evoked coughs. Thirteen men (28-42 years) with no history of urological disorders volunteered to participate. Transperineal ultrasound (US) images were recorded and synchronised with measures of intra-abdominal pressure (IAP), airflow and abdominal/chest wall electromyography during voluntary coughs and coughs evoked by inhalation of nebulised capsaicin. Temporal and spatial aspects of urethral movement induced by contraction of the striated urethral sphincter (SUS), levator ani (LA) and bulbocavernosus (BC) muscles and mechanical aspects of cough generation were investigated. Results showed coughing involved complex urethral dynamics. Urethral motion implied SUS and BC shortening and LA lengthening during preparatory and expulsion phases. Evoked coughs resulted in greater IAP, greater bladder base descent (LA lengthening), and greater mid-urethral displacement (SUS shortening). The preparatory inspiration cough phase was shorter during evoked coughs as was the latency between onset of mid-urethral displacement and expulsion. Maximum mid-urethral displacement coincided with maximal bladder base descent during voluntary cough, but followed it during evoked cough. The data revealed complex interaction between muscles involved in continence in men. Spatial and temporal differences in urethral dynamics and cough mechanics between cough types suggest voluntary coughing may not adequately assess capacity of the continence mechanism.

1. Introduction

Stress urinary incontinence (SUI), defined as unwanted urine leakage during events which increase intra-abdominal pressure (IAP) (1), is common in men after prostatectomy (6) and is provoked by coughing (27). However, the mechanisms are surprisingly poorly understood (27), given the limited investigation of the mechanics of continence control in men. Few studies have investigated the control of continence during coughing in men and most relate to voluntary coughing (e.g. (16)), which may not reflect the continence strategy used during the spontaneous or evoked coughing. Spontaneous coughing is more likely to be associated with SUI because the time-critical nature of involuntary coughs allows little time for volitional preparation.

The requirements for maintenance of urinary continence during dynamic events (such as coughing) are straightforward; urethral pressure must exceed bladder pressure in order to prevent leakage of urine. However, the temporal and spatial mechanics of continence control are complex and include coordinated input from different mechanisms (including smooth and striated [levator ani - LA; striated urethral sphincter – SUS] muscle activation) to control urethral pressure. Voluntary coughing is routinely used to investigate pelvic floor muscle function, particularly in females with SUI (14, 19, 35, 37). Spontaneous coughing is typically evoked by airway irritation, which requires contraction of the muscles of the chest wall and abdomen to rapidly elevate IAP and intra-thoracic pressure (ITP) to forcefully expel air and irritants from the respiratory system (3, 12, 26, 36). Pelvic floor muscle activation is necessary to resist the downward displacement that would be caused by the increase in IAP, as well as to maintain continence against elevated bladder pressure (2, 30). Ultrasound imaging (US) measures of the bladder base (urethrovesical junction - UVJ) movement show greater caudal displacement of this structure in females with SUI during coughing as a result of decreased support by the LA muscle (14, 19, 35, 37). Reduced SUS function is also implicated in SUI (5, 9, 11) because maximal urethral closure pressure is reduced and this depends on both the LA and SUS muscles (8).

In men, simultaneous cranial displacement of the UVJ, dorsal displacement of the mid-urethra (MU) distal to the prostate, and compression of the bulb of the penis, are clearly visualised with transperineal US imaging during voluntary pelvic floor muscle contractions (28, 29, 32). Based on the anatomy of the muscles of the pelvic floor in men these movements are best explained by contraction of the LA, SUS, and bulbocavernosus (BC) muscles, respectively, although other muscles could be involved. The LA muscle (which includes a group of muscles defined by different researchers as puborectalis, iliococcygeus, pubococcygeus, pubovisceralis) elevate the bladder base (UVJ) and support the floor of the abdominal cavity (18). This muscle group, particularly puborectalis which forms a loop behind the rectum, also moves the anorectal junction (ARJ) in a ventral direction. Tonic activity of puborectalis produces the ventral curvature in the rectum. Dorsal movement of the mid-urethra is best explained by activation of the SUS because this is the only muscle with the appropriate anatomical location; origin and insertion from and into the perineal body, forming an omega-shaped loop around the anterior and lateral aspects of the mid urethra (33). No muscles other than BC have the appropriate anatomical orientation to directly compress the penile bulb, although this region could be distorted by movement of other pelvic structures.

Such imaging highlights complex dynamics (29) yet coordination of the LA, SUS and BC muscles has not been studied during dynamic tasks. Previous investigations of dynamic events have been limited to either the temporal or spatial contributions from individual muscles. Hodges et al. (13) reported increased anal electromyography (EMG) before increased IAP associated with voluntary limb movements, in agreement with data of SUS EMG (31). This provides evidence of preparatory contribution of the pelvic floor muscles with predictable elevation of IAP. However, activation in voluntary efforts may not reflect that in spontaneous coughing. Recent fMRI studies highlight different supraspinal control of voluntary and evoked coughs (20). In comparison with voluntary coughing, evoked coughs involve shorter duration (or absence) of inspiration prior to air expulsion (2, 3, 12, 34), earlier onset of abdominal muscle activity (17), and greater peak IAP (2). Each of these factors will influence the demand on the pelvic floor muscles. Perhaps most critically, voluntary coughs enable preparation and recruitment of the pelvic floor in a manner that may not be representative of spontaneous coughing.

Assessment of function of the pelvic floor muscles in men after prostatectomy is important to understand incontinence, particularly with respect to SUS which may be injured or denervated during prostatectomy (33). A first step is to understand healthy function during natural behaviours, particularly those related to patient symptoms, such as coughing. However, this is not trivial as it remains unclear whether voluntary coughing is an adequate surrogate for spontaneous coughing. This study aimed to investigate the kinematics of urethral displacement in men during voluntary coughs, and compare these with corresponding data obtained during evoked coughs. On the basis of data from females, predictions from anatomy and our previous data of voluntary contractions we hypothesized that the dynamics of the urethra would differ between regions during coughing, involving some descent of the UVJ as IAP rises (as in women), but with dorsal displacement of the MU, consistent with shortening of SUS, to maintain continence. Further, we hypothesised that the amount of preparation would be reduced with evoked coughs and this would affect spatial and temporal aspects of urethral dynamics.

2. Materials and Methods

2.1 Subjects

Thirteen men aged between 28-42 years with no history of urological or neurological disease volunteered to participate in this study. Participants provided informed written consent and the institutional Medical Research Ethics Committee approved the study protocol.

2.2 Equipment

Urethral position/displacement was recorded using real-time US in video format (frame rate = 10 Hz) with a transducer placed on the perineum in the mid-sagittal plane (28) (frequency: 7.0 MHz [M7C]; Logiq9 ultrasound, GE Healthcare, Australia). A nasogastric pressure transducer (CTG-2, Gaeltec Ltd, UK) quantified ITP (estimated from oesophageal pressure) and IAP (estimated from gastric pressure) via two sensors separated by 20 cm and a pneumotachometer (3813, Hans Rudolph Inc., USA) fitted with a one-way valve (2600 Hans Rudolph Inc., USA) and facemask was used to record onset and amplitude of expiratory airflow. Unilateral (right-side) EMG recordings were made from obliquus externus and internus abdominis, and rectus abdominis muscles using surface electrodes (Noraxon Inc, USA) with a reference electrode (9160F, 3M Ltd, Australia) placed over the iliac crest. An electrode pair placed along a vertical line over the 7th and 8th intercostal spaces was used to record from the chest wall muscles including the diaphragm. EMG was bandpass filtered (10 - 1000 Hz), amplified 2,000 times, and sampled at 2 kHz (Digitimer Ltd, UK). IAP, EMG and airflow recordings were digitised using a Power 1401 data acquisition system and Spike2 software (Cambridge Electronic Design, UK) and synchronised with the US data via triggers made by depression of a footswitch which triggered the capture of US images and was recorded as a pulse with the EMG data.

2.3 Experimental protocol

Participants emptied their bladder and then consumed a standardised volume of water (300 ml), which was also used to facilitate insertion of the nasogastric tube (see above).

Participants sat on a plinth with the trunk resting against a back rest inclined at approximately 70° from the horizontal and the knees extended. Three voluntary coughs were performed to strong effort followed by 3 coughs evoked using an established protocol. For the voluntary coughs, our investigation aims to study the strategy used during a strong voluntary cough performed in a manner that was natural to the participants. To standardise this participants were instructed to inhale deeply and perform a strong voluntary cough with an effort equivalent to 8 out of 10 on a visual analogue scale with “10” representing maximal effort and to perform this as a single effort. As with any voluntary cough, this was performed in the absence of an urge to cough. For the evoked coughs, participants were instructed to inhale deeply but coughing was stimulated by inhalation of nebulised capsaicin dissolved in saline as per the protocol described by Mazzone et al. (20). The concentration of capsaicin solution (1.95-62.5 µM) that elicited 2 or more involuntary coughs (C2 response) was determined for each participant prior to onset of the experimental protocol.

2.4 Data analysis

Coughs were analysed with respect to three phases as described in previous investigations (12, 36) (Fig. 1A). The “inspiration” phase is initiated by activation of the inspiratory muscles (not recorded here) to fill the thoracic cavity and was identified from the onset of the slow rise in IAP that was coupled with reduction in ITP and without abdominal muscle activation, to the onset of the phase of rapid rise in IAP accompanied by abdominal muscle activation (these events could not be identified from inspiratory flow as a one-way valve was used to allow inhalation of capsaicin via an inspiratory inlet for the evoked cough trials). The “pressurisation” phase involves forceful contraction of the abdominal, intercostal and other trunk muscles (17) to increase IAP/ITP against a closed glottis and was identified from the end of the inspiratory phase to the onset of expiratory airflow. The “expulsion” phase involves rapid glottis opening to expel air as IAP displaces the diaphragm superiorly (2, 12) and was identified from the onset to end of expiratory airflow.

The mechanical variables of IAP and flow used to characterise the cough were: (i) time of onset of IAP increase; (ii) time of onset of expiratory airflow; (iii) time and amplitude of peak expiratory air flow; and (iv) time and amplitude of peak IAP (Fig. 1A). Variables were identified using Spike2 software (Cambridge Electronic Design, UK) and used to calculate the duration of each phase of cough. Temporal variables were expressed relative to onset of expiratory airflow and averaged over three repetitions.

Ultrasound video data were exported to single frame images and analysed frame-by-frame using a method described previously (28) to calculate urethral displacements associated with activation of SUS (MU motion), LA (dorsal [dUVJ] and ventral [vUVJ] aspects of the urethrovesical junction, and anorectal junction [ARJ] motion) and BC (compression of the bulb of penis [BP]) muscles (Fig. 1B). In brief, this method includes a graphical user interface written in Matlab (r2011b, The Mathworks, USA) which enables the user to identify pelvic structure borders. Points of interest are identified in a semi-automated manner based on established criteria. Two-dimensional coordinates are referenced to an axis system referenced to a bony landmark (pubic symphysis). The orientation of each image is checked and corrected with respect to this axis system and is thus, independent of pelvic motion. Repeatability of this method has been confirmed during voluntary contractions of the pelvic floor muscles (28).

On the basis of preliminary analysis seven key elements of motion of the different urethral components were identified for comparison. These were the amplitudes of: (i) initial ventral to dorsal motion of the MU; (ii) initial caudal movement of vUJV followed by; (iii) cranial movement of vUVJ; (iv) initial caudal movement of dUJV followed by; (v) cranial movement of dUVJ; (vi) initial ventral movement of ARJ and (vii) initial ventral movement of BP.

For the evoked cough trials, only the first cough from each of the three stimulated cough events (which could involve multiple coughs) was analysed. Voluntary and evoked cough data were averaged over the three repetitions. Timing (s) and amplitude (mm) of urethral displacements associated with SUS, LA and BC contraction were identified using Matlab (r2011b, The Mathworks, USA). Temporal measures could be quantified to the nearest 100-ms based on the sampling frequency of the US images.

2.5 Statistical analysis

The times of onset and amplitudes of displacement of the urethral measures were compared between measures and between cough types with a repeated measures ANOVA (repeated measures – Cough type [voluntary vs. evoked] and Measure of urethral dynamics [seven standardised measures of motion of MU, vUVJ, dUVJ, ARJ and BP]). Pearson's R^2 correlation coefficient was calculated to explore the relationship between the duration of the pressurisation phase and each of the measures of displacement of the urethra. Paired, two-sided, students t-tests were used ($P<0.05$) to compare phase duration, IAP amplitude and flow variables between cough types. Data are presented as mean ± standard deviation throughout the text and figures.

3. Results

Urethral kinematics during voluntary coughing

During the voluntary cough, IAP increased gradually without abdominal muscle activation as the participant breathed in during the "inspiration" phase. During the "pressurisation" phase IAP increased synchronously with abdominal muscle activation. Displacement of the urethral structures was complex during these initial preparatory phases of the cough. Dorsal displacement of the MU (consistent with predicted action of SUS) began 400±200 ms before the onset of the “expulsion” phase in all participants. In ten participants this was associated with downward/caudal motion of the ARJ and vUVJ/dUVJ (indicating lengthening of the LA) at a similar time before the onset of the “expulsion” phase (ARJ = 400±300 ms; vUVJ/dUVJ = 400±400 ms; Interaction – Measure vs. Cough: $P<0.001$; Post hoc MU vs. dUVJ $P=0.22$; MU vs. vUVJ $P=0.25$; MU vs. ARJ $P=0.21$) and associated with no motion in two participants. During the pressurisation phase, penile bulb compression (contraction of BC) was initiated 100±100 ms before the onset of the “expulsion” phase, thereby following the onset of motion of the other measures of urethral displacement (all $P<0.001$). The duration of the pressurisation phase varied between participants and had a coefficient of variation (0.67) that was 4.9 and 2.5 times that recorded for the inspiration and expulsion phases (see Fig. 1 for an example of a longer pressurisation phase and Fig. 2 for an example of a shorter pressurisation phase). The duration of the pressurisation phase was not related to the amplitude of displacement of any measure of urethral displacement (all measures: $R^2 < 0.012$).

During the “expulsion” phase, IAP reached a maximum of 163±40 $\mathrm{cmH_2O}$ at 125±63 ms after the onset of expiratory airflow and after the time of peak airflow. The latter occurred at 31±6 ms after the onset of expulsion. At the onset of expulsion, dynamics of urethral motion implied further shortening of the SUS and BC and lengthening of the LA as IAP increased towards maximum amplitude. Further dorso-caudal displacement of ventral and dorsal UVJ was observed in most men (n=10) (consistent with lengthening of the LA as observed in females (15)) and reached a maximum of 3.6±2.6 mm (Fig. 2) at 300±100 ms after the onset of expulsion (after peak IAP and peak airflow) at which time it began to move in the ventral-cranial direction. Maximum dorsal displacement of the MU (4.5±1.6 mm) occurred at a similar time to maximum vUVJ/dUVJ descent, 300±100 ms after the onset of the expulsion and ~175 ms after the time of peak IAP (Post hoc: P=0.243). Onset of dorsal motion of the MU (shortening of the SUS) preceded cranial motion of vUVJ/dUVJ and ventral motion of ARJ (shortening of LA) and ventral compression of BP (shortening of BC) (Post hoc all: P<0.001). Urethral motions at vUVJ/dUVJ, ARJ, BC and SUS were consistent with muscle shortening only after the time of peak IAP. Peak ventro-cranial motion (ascent) of vUVJ of 6.9±2.6 mm was reached either during the expulsion phase or after its completion at an average of 800±200 (range: 500-1000) ms after the onset of expulsion. Peak compression of the penile bulb and ventral motion of ARJ were reached 600±200 ms and 700±300 ms, respectively, after the onset of the expulsion phase. During this period and following its peak displacement, the mid urethra position returned to its initial location at 1200±200 ms after the onset of expulsion.

Urethral kinematics during evoked coughing

Evoked coughs involved the same phases as described for the voluntary cough but differed in several respects. The inspiration phase was longer during voluntary (2095±287 ms) than evoked (1272±337 ms) coughs (Interaction - Phase vs. Cough - P<0.001; Post hoc voluntary vs. evoked – P<0.001). The duration of the pressurisation (voluntary: 225±150 ms, evoked: 156±36 ms, Post hoc - P=0.37) and expulsion (voluntary: 477±129 ms, evoked: 415±121 ms, Post hoc – P=0.47) phases did not differ between cough types. The latency between the onset of expiration and key mechanical events of the cough also differed between tasks (Table 1). The latency from onset of expiration to peak airflow was longer in voluntary (43±9 ms) than evoked (31±6 ms, t-test; P=0.001) coughs, but the time to peak IAP was later relative to the onset of expulsion phase during evoked coughs (voluntary: 125±63 ms; evoked: 157±43 ms, t-test; P=0.021). Peak IAP amplitude was greater during evoked coughs (voluntary: 163±35 cmH_2O, evoked: 209±39 cmH_2O, t-test; P=0.001), and there was a concomitant increase in airflow in the evoked cough (voluntary: 4.1±1.1 L/s, evoked: 4.5±1.0 L/s, t-test; P=0.003) (Table 1).

Temporal relationships between aspects of urethral motion and key cough variables differed between cough types (Fig. 3). MU displacement was initiated either during the inspiration or pressurisation phase of evoked cough but with a shorter latency before onset of the expulsion phase for the evoked (200±100 ms) than voluntary (400±100 ms) coughs (Interaction – Cough x Measure: P=0.001; Post hoc: P=0.001). Similar to the voluntary cough, peak MU displacement occurred after peak IAP in the expulsion phase but at a longer latency after the onset of expiration (400±100 ms) than for voluntary (300±100 ms) coughs (Interaction – Measure vs. Cough: P=0.001; Post hoc SUS: P=0.038). Unlike the voluntary cough, maximal vUVJ/dUVJ descent preceded (300±100 ms) peak MU displacement (Interaction – Measure vs. Cough: P=0.001; Post hoc: P<0.05). Peak MU displacement consistently preceded time of peak cranial motion of UVJ (voluntary: 800±200 ms, evoked: 900±300 ms) during both cough types (peak dUVJ/vUVJ vs. peak SUS in both coughs - Post hoc: P<0.001). Spatial features of urethral kinematics also differed between cough types (Fig. 3C). Dorsal displacement of the MU, caudal motion of the dUVJ and vUVJ, and ventral motion of ARJ were greater during evoked coughs (Interaction – Measure vs. Cough: P=0.001; Post hoc: MU, vUVJ, dUVJ, ARJ: P<0.05), but dorsal motion of ARJ was less (Post hoc: P=0.019). There was no difference in the amplitude of the later vUVJ cranial motion or BP compression (Post hoc: UVJ, BP: P>0.05). The later cranial motion of dUVJ was less in the evoked cough (Post hoc: P=0.028).

4. Discussion

These data of coughing in healthy men show complex patterns of urethral movement that can be attributed to shortening and lengthening of different muscles of the pelvic floor.

Urethral movement was consistent with shortening of the SUS and lengthening of the LA during the pressurisation and expulsion phases of cough, in association with elevation of IAP. An important observation was that spatial and temporal aspects of urethral kinematics differed between voluntary and evoked coughs in several regards. First, evoked coughs involved greater elevation of IAP, and this was associated with greater caudo-dorsal displacement of the vUVJ/dUVJ and greater dorsal displacement of the MU. Second, the durations of the inspiratory and pressurisation phases were shorter during evoked coughing with a shorter latency between onset of dorsal MU displacement (SUS shortening) and expulsion. Consequently, peak dorsal MU displacement followed maximum UVJ descent (LA lengthening), unlike voluntary coughs, in which these events occurred almost simultaneously. These spatial and temporal differences between cough types provide evidence that the challenge to maintain continence during evoked coughs is likely to be greater, and this may present a greater probability for identification of incompetence of the system in men with dysfunction. Thus, assessment of pelvic floor function with voluntary coughing may not be an optimal method to investigate and characterise dysfunction in some men.

Urethral dynamics during voluntary coughing and implications for continence control in men

Previous investigations of urethral dynamics during coughing have been limited to the study of movement of UVJ and ARJ in females during voluntary coughs. Similar to our data for continent men, Lovegrove-Jones et al. (19) and Howard et al. (15) reported an initial phase of bladder base (dUVJ) descent (LA lengthening) in continent women (9.2±2.8 mm(19) and 8.2±4.1 mm(15)). The greater magnitude of dUVJ descent in women than our data for men during the voluntary (3.6±2.5 mm) and evoked (4.9±2.5 mm) coughs might be explained by differences in passive support for pelvic organs between genders (5). Despite the muscle lengthening, participants maintained continence, which implies that shortening of LA (observed on US) is not necessary for maintenance of continence. EMG data in men (30) and women (13) show activity of some pelvic floor muscles is related to IAP amplitude. Taken together this suggests that movements attributed to lengthening of LA probably reflect eccentric contraction.

Additional features of urethral dynamics observable in men with transperineal US were the dorsal movement of the MU (SUS shortening) and compression of the BP (BC shortening) during both voluntary and evoked coughs. Although the latter aspect is obviously specific to men, some dorsal motion of MU may be expected in females given the anatomical orientation of the urethrovaginal and striated urogenital sphincter muscles, which compress the urethra towards the perineal body (5) and are active during voluntary contractions (7). Although displacement of the entire urethra is visualised with US in women, this aspect of MU displacement has not been comprehensively studied. There is some evidence of downward motion of this region during coughing (attributed to “deep perineal muscles”) (23) and support of this region of the urethra has been argued to be important for success of surgical management of SUI in women (24). In men, dorsal MU motion has been described caudal to the prostate (location of SUS (32)) during voluntary contractions and is inversely related to cranial motion of UVJ (activation of LA) (29).

The present study provides new data of MU dynamics during cough attributed to shortening of the SUS. In contrast to the caudal displacement of dUVJ and vUVJ (lengthening of LA), dorsal displacement of the MU (SUS shortening) occurred throughout the pressurisation and expulsion phases of voluntary cough. Thus, although both SUS and LA are likely to be active throughout the cough (as has been reported for women (7)), they undergo opposite length changes and this combined displacement was clearly sufficient to maintain continence. BC is generally regarded to aid ejaculation and clear the urethra at the completion of micturition (38). Although not considered for maintenance of continence, BC activation would add pressure to the urethra and artificial sphincter mechanisms placed in a similar location to BC have been used to treat post-prostatectomy incontinence with high rates of cure (25). In the present study onset of BP compression preceded the expulsion phase of the voluntary cough and peak IAP. Pressure applied to the urethra at this time would be positive for maintenance of continence. Although it may be expected that the time of peak urethral pressure would coincide with the time of peak IAP, peak SUS shortening followed peak IAP amplitude and peak flow. This highlights that although motion may reflect activation, it is only one determinant of urethral pressure and future work should study the relationship between these parameters in conjunction with other measures.

Differences in urethral dynamics between voluntary and evoked coughs

Although voluntary and evoked coughs shared key features such as the basic coordination of phases of pressurisation and expulsion, they differed in several regards. Inhalation of a chemical stimulant has previously been reported to evoke stronger, more rapid coughs than voluntarily produced coughs (2). This difference in mechanical demand was also observed in the present study and not surprisingly was associated with differences in urethral kinematics.

Greater peak IAP was accompanied with greater dorsal displacement of the MU during the stronger evoked coughs, which implies greater activation of SUS. Previous work has shown a relationship between IAP and pelvic floor muscle activation; IAP amplitude is linearly related to SUS activation during repetitive arm movements performed with increasing acceleration (i.e. increasing reactive movement on the trunk) (31), anal EMG increases with coughing intensity (4), and anal and vaginal EMG increase with arm movements at greater speed (13). In contrast to SUS, lengthening of LA was greater with higher IAP. The lesser LA length change with voluntary cough may be the result of enhanced preparatory contraction of the pelvic floor muscles in this predictable task. This would concur with reduced bladder base descent during coughing with preparatory contraction in females (21). If true, investigation of voluntary coughing may overestimate the integrity of the continence mechanism.

The shorter inspiratory phase during evoked coughs affected the temporal relationship between MU displacement and bladder base descent. During evoked coughing, peak MU displacement followed maximal vUVJ/dUVJ descent in contrast to coincident timing of these events during voluntary coughing. The spatial and temporal relationship between MU displacement and UVJ descent may be an important feature of continence function. As UVJ descent increases with greater IAP, enhanced contribution from SUS may be required to maintain continence, and this may be reflected by the later peak.

Clinical implications

Previous studies of females with SUI have shown a range of changes in PFM function. For instance caudal displacement of the UVJ is greater in women with SUI (20.0±7.1 mm(19) and 13.8±5.4 mm(15)) than continent control participants. Maximal urethral closure pressure is also lower in females with SUI (11), as is resting urethral pressure (10). In females, Dietz and Clarke (11) reported that urethral hypermobility (UVJ descent) was not associated with SUI. The authors hypothesized that their findings were indicative of SUS dysfunction but US limitations prevented quantification of SUS thickness (as a measure of function). In men, elevation of the bladder base (measured with transabdominal US) after prostatectomy is less during voluntary contraction in those with incontinence than those who are continent (22). Although no studies have investigated MU displacement in men with SUI after prostatectomy using transperineal US, Strasser et al (32) reported atrophy and scarring of SUS using a transurethral technique. Changes to SUS function may be critical for this group as SUS is more likely to be affected by the surgery than the LA muscle. The new measure of MU displacement in the present study allows quantification of temporal and spatial features attributed to SUS activation. Delayed and/or reduced shortening of the SUS, coupled with more rapid and/or increased lengthening of LA, would likely compromise continence control and may be features of SUI. This requires investigation. Although the duration of the pressurisation phase was not related to urethral dynamics in this study, the period of time available for preparation may have significance for men with incontinence and is worthy of further investigation.

Limitations

Several methodological issues require consideration. Data were analysed by a single experienced investigator and further investigation is required to test the reliability of the measures between investigators. Although the sample size was modest, most features of urethral motion and cough generation were consistent between participants. Participants were not blinded to the inhalation of capsaicin solution therefore it is possible that some aspects of the pelvic floor muscle activity were initiated voluntarily during the evoked coughs. The temporal resolution of the US was limited to 100 ms, but was sufficient to detect differences between cough types. A temporal resolution that is an order of magnitude better would ensure that peak motions are not underestimated. An important issue for further investigation is to validate the interpretation of the relationship between urethral movements observed on US and activation of individual muscles. The current interpretation is based on anatomical descriptions of the muscles and pilot research using simultaneous recording of urethral motion and muscle activation. Although the length of preparatory phases of cough likely account for many of the differences in urethral dynamics observed between cough types and this is likely to be independent of differences in cough intensity, we cannot be certain the differences are independent of cough strength. One feature that implies that cough strength does not account for the observed differences is that individuals with greater cough strength did not have later onset of MU motion relative to onset of expulsion (R^2=0.03) or greater vUVJ descent (R^2=0.003). Further investigation that includes analysis of coughs of different type but with matched cough intensity is required to confirm the observation of this study. A further consideration is the pelvic support mechanisms is likely to be affected by gravitational load and further work is required in upright positions to determine whether this changes dynamics of urethral motion with coughing.

Conclusion

This study revealed complex interaction between multiple muscles involved in maintenance of continence in men during coughing. Spatial and temporal differences in urethral dynamics and cough mechanics differed between cough types. This suggests voluntary coughing may not be an adequate surrogate for assessment of competence of continence mechanisms.

References

1. Abrams P, Cardozo L, Fall M, Griffiths D, Rosier P, Ulmsten U, et al. The standardisation of terminology in lower urinary tract function: report from the standardisation sub-committee of the International Continence Society. Urology. 2003 Jan;61(1):37-49. PubMed PMID: 12559262. Epub 2003/02/01. eng.
2. Addington WR, Stephens RE, Phelipa MM, Widdicombe JG, Ockey RR. Intra-abdominal pressures during voluntary and reflex cough. Cough. 2008;4:2. PubMed PMID: 18447952. Pubmed Central PMCID: 2427048. Epub 2008/05/02. eng.
3. Addington WR, Stephens RE, Widdicombe JG, Ockey RR, Anderson JW, Miller SP. Electrophysiologic latency to the external obliques of the laryngeal cough expiration reflex in humans. Am J Phys Med Rehabil. 2003 May;82(5):370-3. PubMed PMID: 12704276. Epub 2003/04/22. eng.
4. Amarenco G, Ismael SS, Lagauche D, Raibaut P, Rene-Corail P, Wolff N, et al. Cough anal reflex: strict relationship between intravesical pressure and pelvic floor muscle electromyographic activity during cough. Urodynamic and electrophysiological study. The Journal of urology. 2005 Jan;173(1):149-52. PubMed PMID: 15592060. Epub 2004/12/14. eng.
5. Ashton-Miller JA, DeLancey JO. Functional anatomy of the female pelvic floor. Ann N Y Acad Sci. 2007 Apr;1101:266-96. PubMed PMID: 17416924.
6. Bauer RM, Bastian PJ, Gozzi C, Stief CG. Postprostatectomy incontinence: all about diagnosis and management. European urology. 2009 Feb;55(2):322-33. PubMed PMID: 18963418. Epub 2008/10/31. eng.
7. Bo K, Stien R. Needle EMG registration of striated urethral wall and pelvic floor muscle activity patterns during cough, Valsalva, abdominal, hip adductor, and gluteal muscle contractions in nulliparous healthy females. Neurourol Urodyn. 1994;13(1):35-41. PubMed PMID: 8156073.
8. DeLancey JO. Structural support of the urethra as it relates to stress urinary incontinence: the hammock hypothesis. Am J Obstet Gynecol. 1994 Jun;170(6):1713-20; discussion 20-3. PubMed PMID: 8203431. Epub 1994/06/01. eng.

9. Delancey JO, Ashton-Miller JA. Pathophysiology of adult urinary incontinence. Gastroenterology. 2004 Jan;126(1 Suppl 1):S23-32. PubMed PMID: 14978635. Epub 2004/02/24. eng.

10. DeLancey JO, Trowbridge ER, Miller JM, Morgan DM, Guire K, Fenner DE, et al. Stress urinary incontinence: relative importance of urethral support and urethral closure pressure. J Urol. 2008 Jun;179(6):2286-90; discussion 90. PubMed PMID: 18423707. Pubmed Central PMCID: 2673985. Epub 2008/04/22. eng.

11. Dietz HP, Clarke B. The urethral pressure profile and ultrasound imaging of the lower urinary tract. Int Urogynecol J Pelvic Floor Dysfunct. 2001;12(1):38-41. PubMed PMID: 11294530.

12. Fontana GA. Before we get started: What is a cough? Lung. 2008;186:S3-S6. PubMed PMID: WOS:000254284700002. English.

13. Hodges PW, Sapsford R, Pengel LH. Postural and respiratory functions of the pelvic floor muscles. Neurourol Urodyn. 2007;26(3):362-71. PubMed PMID: 17304528.

14. Howard D, Miller JM, Delancey JO, Ashton-Miller JA. Differential effects of cough, valsalva, and continence status on vesical neck movement. Obstet Gynecol. 2000 Apr;95(4):535-40. PubMed PMID: 10725485. Pubmed Central PMCID: 1226414.

15. Howard D, Miller JM, Delancey JOL, Ashton-Miller JA. Differential effects of cough, Valsalva, and continence status on vesical neck movement. Obstetrics and Gynecology. 2000 Apr;95(4):535-40. PubMed PMID: WOS:000086031000011. English.

16. Koraitim MM, Atta MA, Fattah GA, Ismail HR. Mechanism of continence after repair of post-traumatic posterior urethral strictures. Urology. 2003 Feb;61(2):287-90. PubMed PMID: 12597932.

17. Lasserson D, Mills K, Arunachalam R, Polkey M, Moxham J, Kalra L. Differences in motor activation of voluntary and reflex cough in humans. Thorax. 2006 Aug;61(8):699-705. PubMed PMID: 16601089. Pubmed Central PMCID: 2104707. Epub 2006/04/08. eng.

18. Lawson J. Anatomy of the pelvic floor muscles. Annals of the Royal College of Surgeons of England. 1974;54(5):244-52. PubMed PMID: WOS:A1974S942300004. English.

19. Lovegrove Jones RC, Peng Q, Stokes M, Humphrey VF, Payne C, Constantinou CE. Mechanisms of pelvic floor muscle function and the effect on the urethra during a cough. European Urology. 2010

Jun;57(6):1101-10. PubMed PMID: 19560261. Pubmed Central PMCID: 2889228. Epub 2009/06/30. eng.

20. Mazzone SB, McLennan L, McGovern AE, Egan GF, Farrell MJ. Representation of capsaicin-evoked urge-to-cough in the human brain using functional magnetic resonance imaging. Am J Resp Crit Care. 2007 Aug 15;176(4):327-32. PubMed PMID: ISI:000248682100005. English.

21. Miller JM, Perucchini D, Carchidi LT, DeLancey JO, Ashton-Miller J. Pelvic floor muscle contraction during a cough and decreased vesical neck mobility. Obstetrics and gynecology. 2001 Feb;97(2):255-60. PubMed PMID: 11165591. Pubmed Central PMCID: 1226460. Epub 2001/02/13. eng.

22. Nahon I, Waddington G, Adams R, Dorey G. Assessing muscle function of the male pelvic floor using real time ultrasound. Neurourology and Urodynamics. 2011 May 11. PubMed PMID: 21563212. Epub 2011/05/13. Eng.

23. Petros PE, Ulmsten U. Role of the pelvic floor in bladder neck opening and closure I: muscle forces. Int Urogynecol J Pel. 1997;8(2):74-80. PubMed PMID: 9297595. Epub 1997/01/01. eng.

24. Petros PP, Von KB. Anchoring the midurethra restores bladder-neck anatomy and continence. Lancet. 1999 Sep 18;354(9183):997-8. PubMed PMID: 10501364. Epub 1999/09/29. eng.

25. Schaeffer AJ, Clemens JQ, Ferrari M, Stamey TA. The male bulbourethral sling procedure for post-radical prostatectomy incontinence. J Urology. 1998 May;159(5):1510-5. PubMed PMID: WOS:000073045200025. English.

26. Shannon R, Baekey DM, Morris KF, Lindsey BG. Ventrolateral medullary respiratory network and a model of cough motor pattern generation. Journal of applied physiology. 1998 Jun;84(6):2020-35. PubMed PMID: 9609797.

27. Silva LA, Andriolo RB, Atallah AN, da Silva EMK. Surgery for stress urinary incontinence due to presumed sphincter deficiency after prostate surgery. Cochrane Database of Systematic Reviews. 2011 (4). PubMed PMID: WOS:000289490200015. English.

28. Stafford RE, Ashton-Miller JA, Constantinou CE, Hodges PW. A New Method to Quantify Male Pelvic Floor Displacement From 2D Transperineal Ultrasound Images. Urology. 2013 Mar;81(3):685-9. PubMed PMID: 23332998. Epub 2013/01/22. eng.

29. Stafford RE, Ashton-Miller JA, Constantinou CE, Hodges PW. Novel insight into the dynamics of male pelvic floor contractions through transperineal ultrasound imaging. J Urol. 2012 Oct;188(4):1224-30. PubMed PMID: 22902016.

30. Stafford RE, Ashton-Miller JA, Sapsford R, Hodges PW. Activation of the striated urethral sphincter to maintain continence during dynamic tasks in healthy men. Neurourol Urodyn. 2012 Jan;31(1):36-43. PubMed PMID: 21780175. Epub 2011/07/23. eng.

31. Stafford RE, Ashton-Miller JA, Sapsford R, Hodges PW. Activation of the Striated Urethral Sphincter to Maintain Continence During Dynamic Tasks in Healthy Men. Neurourol Urodyn. 2011.

32. Strasser H, Frauscher F, Helweg G, Colleselli K, Reissigl A, Bartsch G. Transurethral ultrasound: evaluation of anatomy and function of the rhabdosphincter of the male urethra. J Urol. 1998 Jan;159(1):100-4; discussion 4-5. PubMed PMID: 9400446. Epub 1997/12/24. eng.

33. Strasser H, Klima G, Poisel S, Horninger W, Bartsch G. Anatomy and innervation of the rhabdosphincter of the male urethra. Prostate. 1996 Jan;28(1):24-31. PubMed PMID: 8545278. Epub 1996/01/01. eng.

34. Vovk A, Bolser DC, Hey JA, Danzig M, Vickroy T, Berry R, et al. Capsaicin exposure elicits complex airway defensive motor patterns in normal humans in a concentration-dependent manner. Pulm Pharmacol Ther. 2007;20(4):423-32. PubMed PMID: 17236796. Pubmed Central PMCID: 3121193. Epub 2007/01/24. eng.

35. Weil EH, van Waalwijk van Doorn ES, Heesakkers JP, Meguid T, Janknegt RA. Transvaginal ultrasonography: a study with healthy volunteers and women with genuine stress incontinence. Eur Urol. 1993;24(2):226-30. PubMed PMID: 8375444.

36. Widdicombe JG. Neurophysiology of the cough reflex. Eur Respir J. 1995 Jul;8(7):1193-202. PubMed PMID: 7589405. Epub 1995/07/01. eng.

37. Wijma J, Tinga DJ, Visser GH. Perineal ultrasonography in women with stress incontinence and controls: the role of the pelvic floor muscles. Gynecologic and obstetric investigation. 1991;32(3):176-9. PubMed PMID: 1756999.

38. Yang CC, Bradley WE. Somatic innervation of the human bulbocavernosus muscle. Clinical Neurophysiology. 1999 3/1/;110(3):412-8.

Figure legends

Fig. 1 Method for identification of phases of the cough (A) and quantification of urethral displacement (B). Definition of cough phases: Inspiratory phase – onset of initial rise in IAP (coupled with a decrease in ITP) (I_o) to onset of rapid rise in IAP (P_o); Pressurisation phase - P_o to onset of expiratory flow (E_o); Expulsion phase - E_o to steady state of pre-cough level. (B) Points used for analysis of urethral displacement. Dark circles indicate landmarks used to quantify movement of mid-urethra (MU), ventral (vUVJ) and dorsal (dUVJ) aspects of the urethrovesicle junction, ano-rectal junction (ARJ) and the bulb of the penis (BP). Arrows indicate direction of movement attributed to muscle shortening.

Fig. 2 Raw data from a representative participant with a short pressurisation phase. Data are shown for a (A) voluntary and (B) evoked cough. Onset of MU displacement occurs in the inspiration phase during voluntary cough but in the later pressurisation phase during evoked cough. Peak MU displacement occurs at a similar time to maximum vUVJ/dUVJ descent during voluntary, but after during evoked cough. IAP – intra-abdominal pressure; EMG – electromyography; RA – rectus abdominis; OI – internus obliquus abdominis; OE – external obliquus abdominis; MU – mid-urethra; vUVJ – ventral urethrovesical junction; dUVJ – dorsal urethrovesical junction; ARJ – ano-rectal junction; BP – bulb of penis. Arrow length equal to 2 mm.

Fig. 3 Group data for comparison of temporal and spatial features of urethral displacement between voluntary and evoked coughs. (A) Time of onset of displacement, (B) time of peak displacement and (C) amplitude of peak displacement are shown for each cough type. Means and SD are shown. * - $P<0.05$ for comparison between cough types. MU – mid-urethra;

vUVJ – ventral urethrovesical junction; dUVJ – dorsal urethrovesical junction; ARJ – ano-rectal junction; BP – bulb of penis.

Figure 1

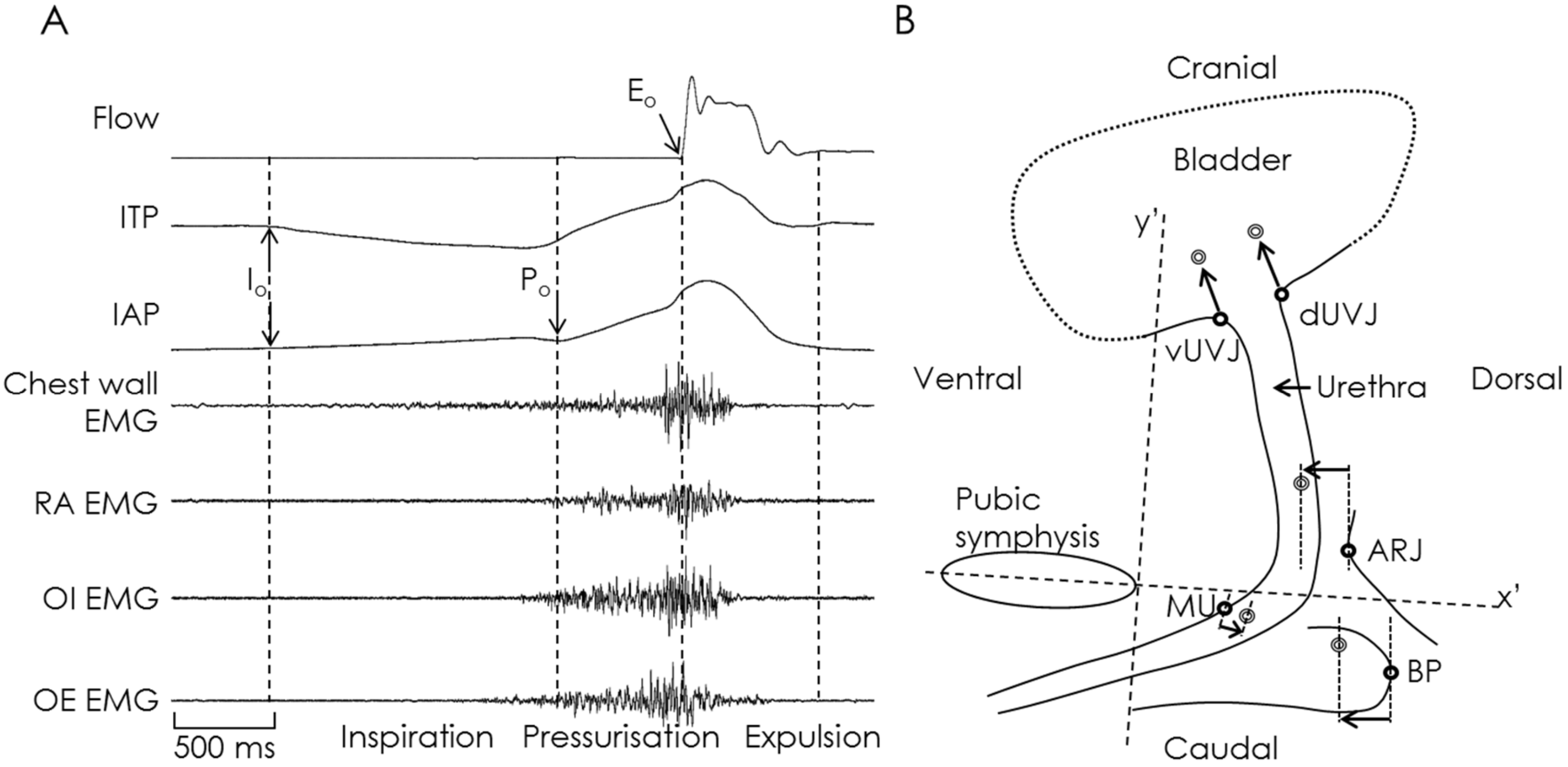
A
Flow
E$_o$
ITP
I$_o$
P$_o$
IAP
Chest wall EMG
RA EMG
OI EMG
OE EMG
500 ms
Inspiration
Pressurisation
Expulsion
B
Cranial
Bladder
y'
dUVJ
vUVJ
Ventral
Urethra
Dorsal
Pubic symphysis
ARJ
x'
MU
BP
Caudal

Figure 2

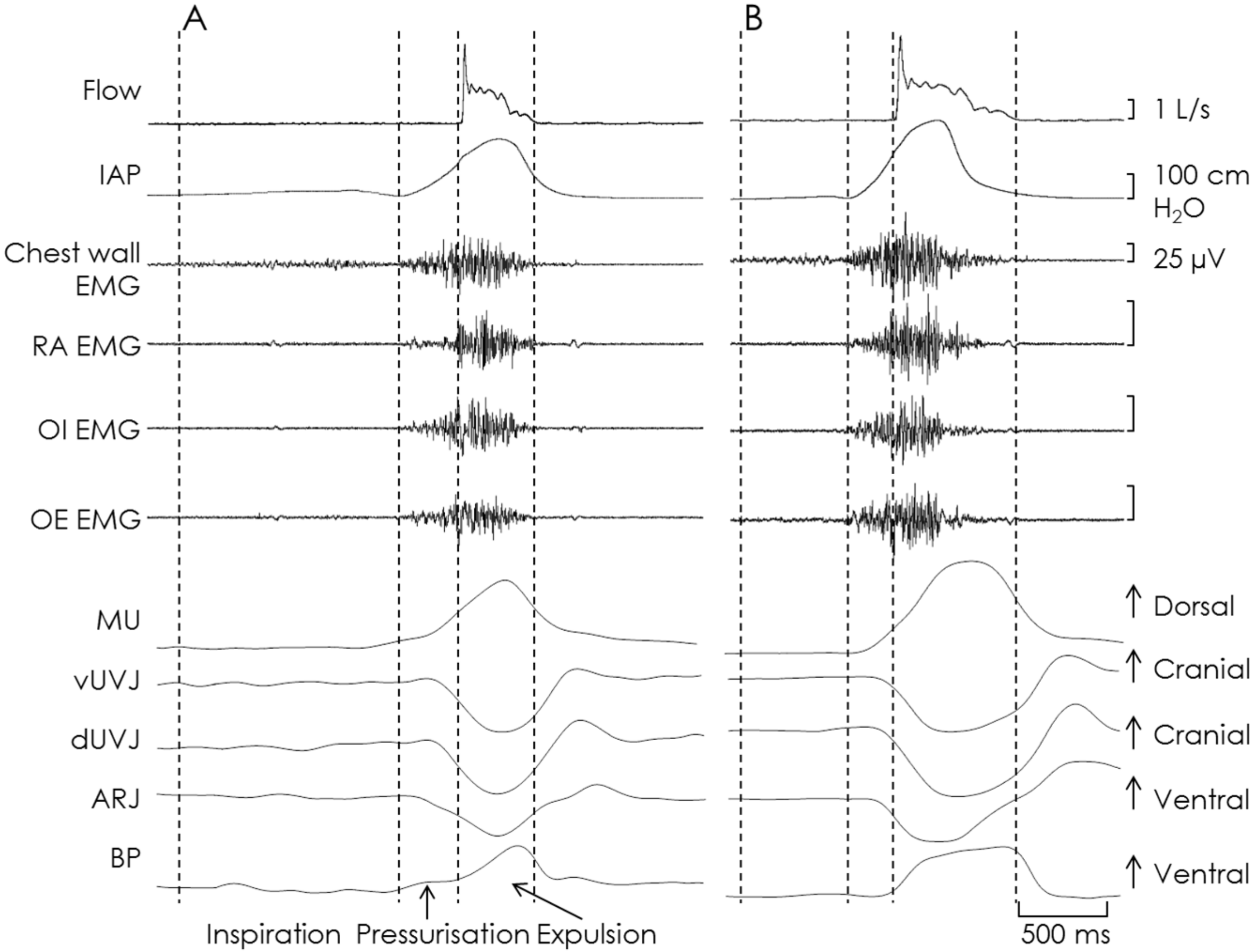
A
B
Flow
IAP
Chest wall EMG
RA EMG
OI EMG
OE EMG
MU
vUVJ
dUVJ
ARJ
BP
1 L/s
100 cm H_2O
25 μV
↑ Dorsal
↑ Cranial
↑ Cranial
↑ Ventral
↑ Ventral
Inspiration
Pressurisation
Expulsion
500 ms

Figure 3

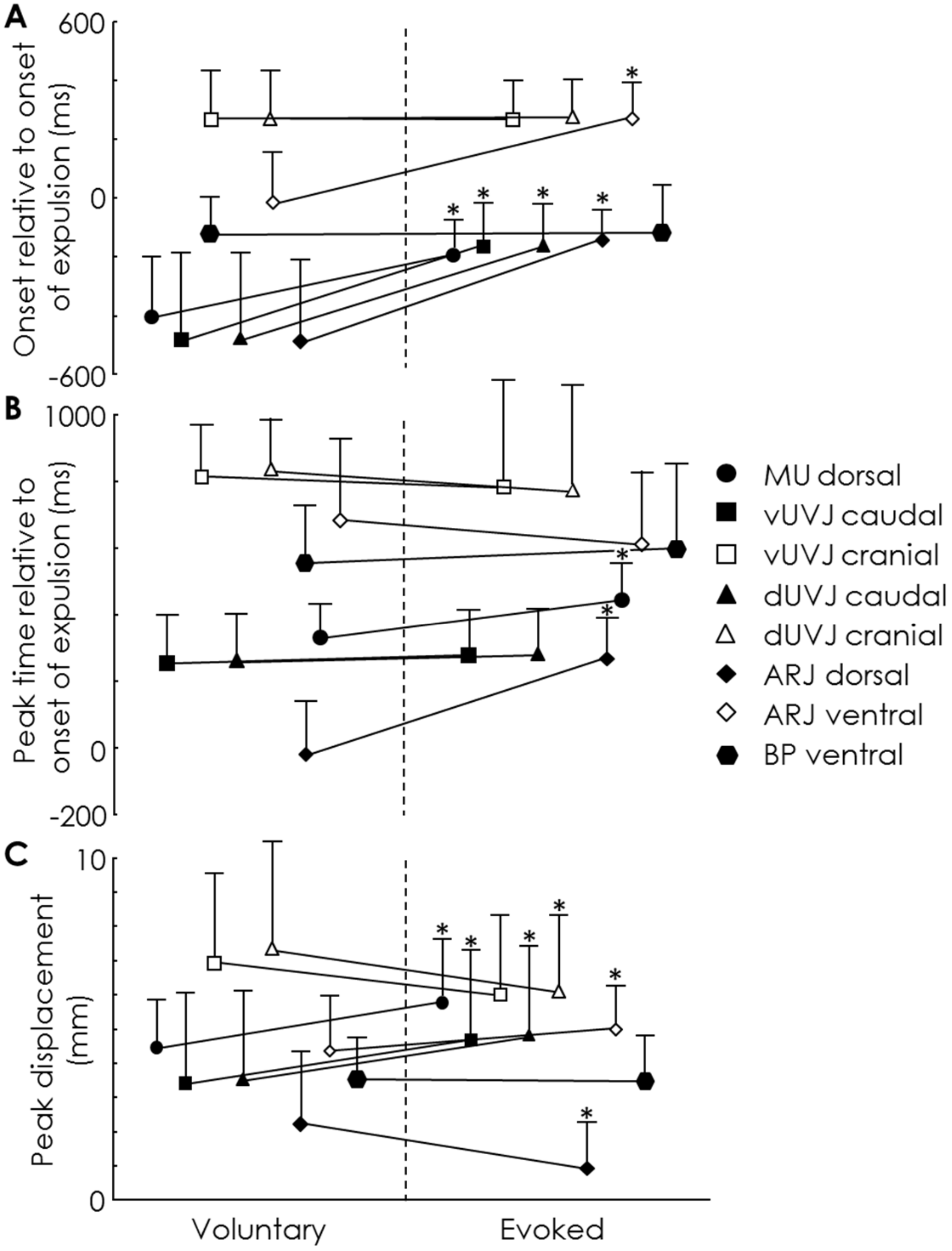
A
600
0
-600
Onset relative to onset of expulsion (ms)
B
1000
0
-200
Peak time relative to onset of expulsion (ms)
C
10
0
Peak displacement (mm)
Voluntary
Evoked
*
● MU dorsal
■ vUVJ caudal
□ vUVJ cranial
▲ dUVJ caudal
△ dUVJ cranial
◆ ARJ dorsal
◇ ARJ ventral
⬢ BP ventral

Table 1: The timing and amplitude of mechanical events for voluntary and evoked coughs

	Time to peak air flow (s)		Time to peak IAP (s)		Flow (L/s)		IAP AMP (cm H_2O)		ITP AMP (cm H_2O)	
Subject	Vol	Evoked	Vol	Evoked	Vol	Evoked	Vol	Evoked	Vol	Evoked
1	0.042	0.039	0.119	0.122	3.8	5.3	169	186	133	158
2	0.041	0.037	0.095	0.142	3.9	4.2	135	179	95	179
3	0.036	0.025	0.032	0.181	2.6	3.5	103	193	88	199
4	0.064	0.035	0.096	0.190	1.6	2.0	147	205	99	172
5	0.044	0.041	0.265	0.226	4.5	4.7	196	198	135	129
6	0.036	0.026	0.080	0.109	3.2	3.4	211	210	182	183
7	0.030	0.026	0.102	0.117	4.0	4.2	153	214	113	194
8	0.036	0.023	0.195	0.205	5.3	5.5	161	212	124	174
9	0.050	0.029	0.058	0.098	4.9	5.2	162	227	132	154
10	0.036	0.029	0.169	0.129	4.9	5.2	165	183	118	125
11	0.052	0.030	0.143	0.170	4.9	5.0	145	232	117	198
12	0.037	0.027	0.179	0.211	4.6	4.9	255	310	227	287
13	0.051	0.035	0.098	0.138	4.9	5.1	118	167	93	128
Mean(SD)	0.043(0.009)	0.031(0.006)	0.125(0.063)	0.157(0.043)	4.1(1.1)	4.5(1.0)	163(40)	209(36)	127(38)	175(42)
p-value	<0.001		0.042		0.003		<0.001		<0.001	

Temporal data are listed as relative to onset of expiration. P-values relate to the comparison between voluntary and evoked coughs. IAP – intra-abdominal pressure, ITP – intra-thoracic pressure, Vol – voluntary.