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Respiratory muscle recruitment and their correlates with pulmonary volumes and flute musical tasks

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In order to produce sound on a wind instrument, the respiratory system and muscles contract or relax to create the required pressure, flow and velocity for each instrument (1, 2). In the case of low pressure instruments, researchers agree that some inspiratory muscles are recruited as antagonists during the expiratory phase (1, 3). Only few studies actually measured the respiratory muscle recruitment during wind instrument playing (4, 5, 6). The authors' study (6) reported that flute 'breath support', which is associated with high quality playing, entails antagonistic contraction of non-diaphragmatic inspiratory muscles. The rib cage is held at higher lung volume during long legato phrase playing. Relieved from the task of producing the right mouth pressure, especially at lower lung volume, the expiratory muscles contribute more to the finer control of mouth pressure modulations. Furthermore, during 'support', the lung volume at which playing a phrase ends is usually above Functional Residual Capacity (FRC) and rarely far below it. The strong expiratory muscle pressures required to play the flute at low lung volumes are generally avoided, while advantage is taken of the high relaxation pressures at high lung volumes. For this study, we compared the respiratory patterns and muscle recruitment above and under FRC while four standing young professional flautists' were performing melodies and long tones with and without 'breath support' at different intensities. These musical tasks required the performers to use most of their vital capacity during loud playing. Recordings included optoelectronic plethysmographic measurements of the chest wall volume and its compartments, surface electromyography of the respiratory muscles (scalene, lateral abdominal, rectus abdominus, and sternocleidomastoid), mouth pressure, and sound. Preliminary analysis suggests that volume (rather than time only), condition (with/without support), as well as intensity (*forte/piano*) are all determinants of muscle activation.

1 Introduction

It takes a few weeks to train a flute player to produce a flute sound, a few years to control the whole compass of the instrument and at least 10 years to play with a sound quality recognized as professional (7). One important topic in the training towards professional level is the idea of "breath support" (BS). This "support" is difficult to describe accurately, probably because of its complex nature and the fact that it involves muscles that are difficult to feel directly.

Respiration depends on both passive and active forces applied to the components of the respiratory system. Because of their own intrinsic physical properties, the components behave differently individually or as part of the system. The passive forces acting on the respiratory system are due to gravity and the physical properties (elastance, compliance and surface tension) of the tissues. These passive forces, often called elastic recoil of the respiratory system, result from the different lung and chest wall resting states. The active forces result from muscle contractions.

Through practice, the flautist learns to control both the passive and active forces to control the required air to produce the sound while playing.

It is agreed that during playing a low-pressure wind instrument like the flute (2), inspiratory muscles are recruited as antagonists to the expiratory act of playing (1, 3, 6, 8, 9, 10). At high lung volume, the elastic recoil of the respiratory system provides a pressure (approximately 40 cmH_2O) that is too high for most of the notes produced on the flute (10). Previous studies (5, 10) showed that different professional flautists use different muscle recruitment patterns while playing at similar frequencies and intensities. The diaphragm was generally non-activated but was recruited during specific manoeuvres like staccato, octaves and one flautist showed some diaphragmatic activity during vibrati.

According to Cossette et al. (6), flute breath support entails antagonistic contraction of non-diaphragmatic inspiratory muscles that tend to hold the rib cage at a higher lung volume. This allows relaxation pressures to provide expiratory pressures over a longer period of the phrase being played. Inspiratory muscle activation may require some expiratory muscle activation increase to counteract the antagonistic inspiratory action (6). Nevertheless, the lung volume at which a phrase ends is usually above functional residual capacity (FRC) and rarely far below it during high quality playing. Thus, the strong expiratory muscle pressures required to play the flute at low lung volumes are generally avoided, while advantage is taken of the high relaxation pressures at high lung volumes. During BS playing, scalene (neck) inspiratory contraction was increased; playing was done at a higher lung volume, mostly over FRC; and lateral abdominals were contracted at a higher lung volume than during without breath support (NBS) playing.

A subsequent study (11) further suggested that specific muscle activations may control specific parameters that are linked to specific musical tasks playing. The flautist's playing strategy was summarized as follows: playing occurs over FRC whenever possible; sternocleidomastoidians (neck) are contracted through the phrases; scalenes inspiratory contraction is always present at the beginning of playing and relaxes slowly until FRC is reached; lateral abdominals start contracting when scalenes are close to their relaxation state (scalenes and laterals seem to be synchronised and opposite); rectus abdominus muscles seem to produce specific pressure changes to compensate or complete contraction of other muscles.

In brief, the sternocleidomastoidians seem to act as fixators, the scalenes antagonize the elastic recoil of the respiratory system (over FRC), and work jointly with the laterals which also eventually antagonize the elastic recoil of the respiratory system (under FRC). In addition, the laterals act as the prime mover of air in opposition to the inspiratory muscles. The rectus abdominus seem to be mostly used as agonists for specific large pressure requirements. This respiratory strategy does not occur during quiet breathing and is the result of many years of training for the player.

By correlating the respiratory muscle activation with pulmonary volumes, conditions (BS/NBS) and dynamics (*f/p*), we will determine which of those parameters impact the most on muscle recruitment during flute playing.

2 Methods

2.1. The players and the protocol

We measured chest wall displacements, surface electromyography (SEMG) of the respiratory muscles, mouth pressure, and recorded sound during professional flute playing with 'breath support' (BS) and without 'breath support' (NBS). Four young professional flautists (3 males, 1 female, 29 to 34 years old) were recruited at La Scala di Milano or amongst the finishing students of schools associated with La Scala and from Canadian institutions of similar level.

The same flute was used by all subjects (Sankyo, Etude model). The subjects were asked to play melodies and long tones (D4, E5/A5, D6, A6/C7) with BS and NBS at different intensities, *piano (p)* and *forte (f)*. The melody, taken from a standard practice book (Trevor Wye), consisted of 14 legato tones in E minor (flute low register between E4 and C5). The flautists played the melody in one breath but were not given any definition of support as we wanted them to play as naturally as possible what they considered to be support (BS) and no support (NBS). They were also asked to play without vibrato. Musicians train themselves to play with vibrato. As a result, vibrato was seen on some of the sound tracings in both conditions (BS and NBS), though at different amplitudes. For the analysis, we separated each of the 14 notes of the melody so we could compare similar events between subjects. That allowed us to compute the average value of the recorded quantities within each note and each musical phrase.

2.2. Setup

Recordings include measurements of chest wall volumes (V_{cw}), surface electromyography of the respiratory muscles, mouth pressure and sound. The chest wall volumes are measured by **O**pto**E**lectronic **P**lethysmography (OEP, Smart System, BTS, Milan, Italy) and encompass three compartments: i.e. the lung, the diaphragm-apposed parts of the rib cage ($V_{rc,p}$ and $V_{rc,a}$, respectively) and the abdomen (V_{ab}). The respiratory muscles include: scalene, sternocleidomastoidian, rectus abdominus and lateral abdominal muscles , i.e., internal and external obliques and transversus combined. The instantaneous flow is calculated by differentiation of the volume signals obtained by OEP. The subject 4 measurements were acquired during two different sessions. The first experiment (referred to as 4a) includes OEP measurements of chest wall volumes and flow, mouth pressure (Pm) and sound recording. Electromyography of the respiratory muscles and sound recording were acquired during the second experiment (4b).

The OEP consists of 7 infrared video cameras (5 in front and 2 behind the subject at a distance of approximately 2 m) tracking 89 hemispherical 10 mm diameter reflective markers (Figure 1). These were applied to the area of the chest wall, front and back in seven rows between the clavicle and the iliac crest (12). The three chest wall volumes are derived from the 3D coordinates of the 89 markers and the fitting of an appropriate mesh. The volume variations are calculated using Gauss' theorem (13). The OEP data was sampled at 50 Hz during flute playing and at 25 Hz during respiratory manoeuvres.

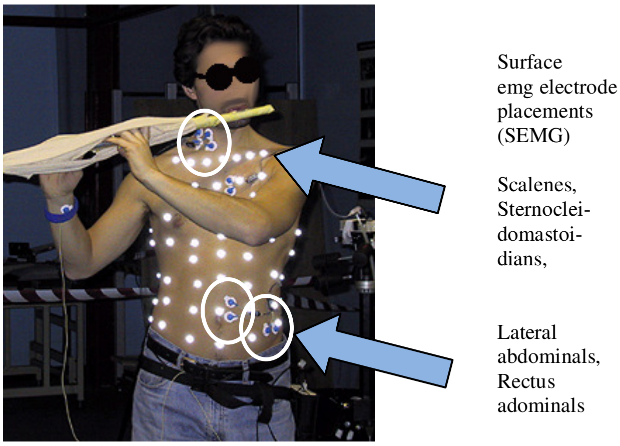

Figure 1: 89 reflective markers of the OEP system. Circles indicate the placement of the emg surface electrodes. The flute is covered by material to avoid reflectance.

Because of movement artefacts due to the position, some markers were occasionally hidden. When too many markers were missing for volume reconstruction, the data was rejected.

Prior to flute playing, the subject breathed quietly (qb) and performed two vital capacity (VC) manœuvres used as references for the analysis. During qb and VC, flow was measured with a pneumotachometer (HR 4700-A; Hans Rudolph Inc.) at the mouth connected to a pressure transducer (Celesco, ± 5 cmH_2O) and to an analog-to-digital converter (RTI 800; Analog Devices; Norwood). Since the elastic recoil of the respiratory system decreases continually during playing, we took our measurements as a function of lung volume and estimated FRC by averaging the end expiratory volumes during quiet breathing.

Flow was obtained by dividing ΔVcw by the time to complete the phrase. Vcw and average flow per phrase were compared among the different conditions (BS/NBS) and dynamics (*f/p*) for all notes both during long tone and melody playing. Statistical paired t-tests were performed between the different playing conditions and dynamics. P-values of the tests < 0.05 were considered significant.

Mouth pressure (P_m) was measured with a catheter inserted at the corner of the mouth during playing and connected to a pressure transducer (SCX01; Sensym, ± 100

cmH_2O). All analog data (P_m, emg and low frequency sound) were stored on a PC via the OEP System at a sample frequency of 1000 Hz.

Surface electromyograms were recorded using a telemetric 8-channel system (BTS). Movements were done to verify for the appropriate placement of the electrodes (6). During the analysis, the signals were filtered with a cross correlation technique for ECG removal (6, 14) and then rectified and low pass filtered (2Hz, Butterworth window). The length of each phrase, generally different between the 2 conditions, was normalised to 100%. Comparisons of the average activation between BS and NBS were performed for every 10% section of the total length of each phrase. The data was then ensemble averaged over the different phrases within each subject and over all the phrases for all the subjects. The EMG activations were plotted against time and over V_{cw} relative to FRC as a function of the maximal activation during the BS playing (% max BS).

During playing, sound was recorded at 44 100Hz (Sony Tape recorder, TC-D5, Sennheiser Microphone (Phantom Power) MKH-416T) and simultaneously through the OEP at 960 Hz for synchronization. The microphone was placed at a fixed position about 1 meter from the opening of the flute. The sound was analysed by quantifying the frequency and amplitude variations between condition (BS/NBS) and dynamic (*f/p*) variantions. The sound was then rectified and a linear interpolation function was used to get the envelope of the sound. The mean of this function within each note gave us the averaged intensity for that note.

3 Results

3.1. Melody

3.1.1. Flow

The intensity varied according to what had been asked to the performers. *f* playing was significantly (p-value < 0.05) louder than *p* playing in all melodies.

Table 1 shows each subject's averaged flows during melody playing and the associated paired t-test results for each combination of conditions and dynamics. For subjects 1 and 2, the flow was significantly higher (p-value < 0.05) during *f* than during *p*, both during BS and NBS conditions. As subject 4a did not play the *f* excerpt, the comparison was not possible.

Flow ml/s	**S1**	**S2**	**S4**
f BS	300 ml/s	256 ml/s	----
f NBS	383 ml/s	308 ml/s	----
p BS	171 ml/s	174 ml/s	127 ml/s
p NBS	177 ml/s	198 ml/s	308 ml/s
T-test p values	**S1**	**S2**	**S4**
fBS-fNBS	**0.044**	0.093	----
pBS-pNBS	0.83	0.671	**0.041**
fBS-pBS	**0.001**	**0.034**	----
fNBS-pNBS	**0.00**	**0.045**	----

Table 1. Subjects 1, 2 and 4 flows (ml/s) during melody playing for the 2 conditions (BS/S) and dynamics (*f/p*). Paired t-tests p-values < 0.05 are significantly different.

When comparing the flow at the same loudness, we did not note any significant change between BS and NBS except for *f* and *p* playing respectively for subject 1 and 4a, for which the flow was significantly smaller in BS playing.

3.1.2. Muscle activation and volumes

Figure 2 shows the averaged respiratory muscle activation over time for subjects 1, 2, and 4 during melody playing. The melody was separated in 10 sections (dots). Inspiratory neck muscles (scalenes and sternocleidomastoidians) are more recruited during BS playing and more so during *p* BS playing. The expiratory muscles are more activated at the beginning of the BS melody and more at the end of the NBS melody.

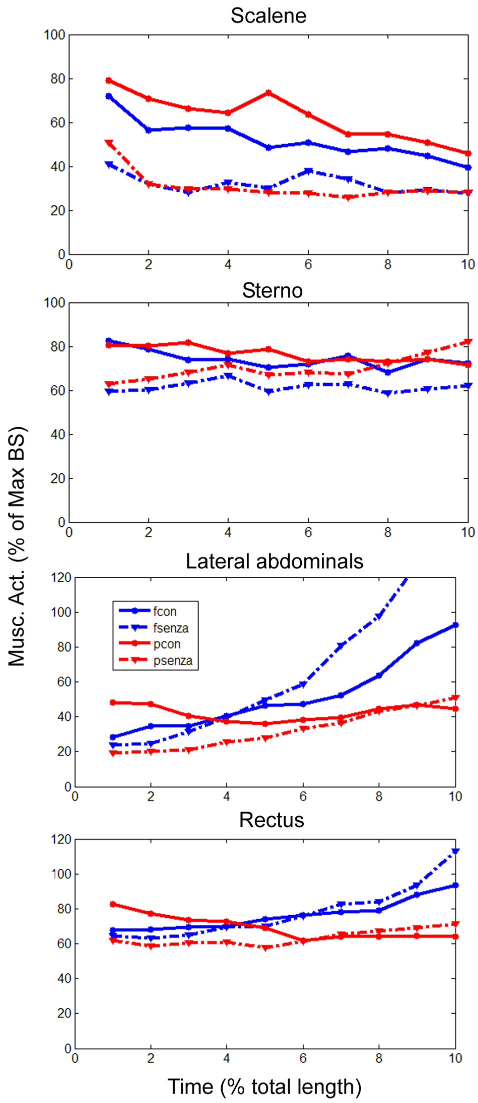

Figure 2. Subjects 1, 2, and 4 respiratory muscle activation (% of maximal activation during BS) during melody playing in relation to % time. Solid lines indicate BS, dashed lines indicate NBS. Blue lines: *f* ; red lines: *p*.

Looking at each subject individually (not shown here), we note that subjects 1 and 4 recruit the inspiratory muscles much more during BS *p* playing and that subject 2 recruits them more during BS *f* playing.

t-test S1	Scal.	Stern.	Lat.	Rect.
fBS-fNBS	0.000	0.000	0.029	**0.648**
pBS-pNBS	0.000	0.000	0.000	0.000
fBS-pBS	0.000	0.000	**0.084**	**0.269**
fNBS-pNBS	**0.852**	**0.943**	0.005	0.000
t-test S2	Scal.	Stern.	Lat.	Rect.
fBS-fNBS	0.000	0.000	0.000	**0.120**
pBS-pNBS	0.002	**0.285**	0.000	**0.977**
fBS-pBS	0.000	0.000	0.000	0.004
fNBS-pNBS	0.006	**0.799**	0.000	0.001
t-test S4	Scal.	Stern.	Lat.	Rect.
fBS-fNBS	0.000	0.000	**0.233**	**0.152**
pBS-pNBS	0.000	0.000	0.000	**0.256**
fBS-pBS	0.000	0.000	0.000	0.000
fNBS-pNBS	0.005	0.000	0.004	0.000

Table 2. Comparison (paired t-tests) between different combinations of conditions and dynamics for averaged muscle recruitment during melody playing for subjects 1, 2 and 4; p-values < 0.05 are significantly different. Non-significant values are in bold.

Each note of the melody was compared for the 2 conditions and dynamics (Table 2). Inspiratory muscle activation was significantly different in most comparisons. The non-significant ones (bold) suggest that these condition or dynamic changes did not influence muscle activation.

Figure 3 shows that BS starts at a higher lung volume than when playing with NSB in both *f* and *p* dynamics, and that *f* requires a larger proportion of the vital capacity than when playing *p*. The proportion of playing over and under FRC varies according to the condition and dynamic : i.e. only 30% of *p* BS playing is performed under FRC ; over 70% of *f* NBS playing is done under FRC ; and *f* BS and *p* NBS playing are performed equally over and under FRC (50%). Above FRC, the inspiratory muscles are more recruited during BS than during NBS. The curves suggest that inspiratory muscle activation decreases (relaxes) before reaching FRC. At the beginning of the phrase *p* BS, expiratory muscles are more contracted than during all other conditions. During *f* BS playing, expiratory muscle activation increases a bit before FRC to continue until the phrase ends. The highest expiratory activation is used at the end of the *f* NBS phrase.

3.2. Tones

3.2.1. Flow

Figure 4 shows flows for BS and NBS tone playing at *f* and *p* intensities for subjects 1, 2, and 3. The extremum flows were 84 ml/s for subject 3 BS D6 *p* playing and 1045 ml/s for subject 2 NBS C7 *f* playing (figure 4). Flow increased mostly with sound amplitude, *f* playing requiring higher flows than p playing (figure 4). Under both conditions (BS-NBS), flow decreases with amplitude for subjects 2 and 3.

The flow increase was statistically significant for dynamic changes under the same condition (BS/NBS) for subjects 1 and 2 but not for subject 3 during NBS (Table 3). Despite the small number of samples, the averaged values were clearly higher during *f* than during *p* playing. Subject 1 did not show average flow consistent changes between BS and BNS suggesting that condition does not affect flow (Table 3). Subject 4 showed an average flow of 292 ml/s during both BS and NBS *mf* playing for all notes. The t-tests did not show significant differences between the two conditions (Table 3).

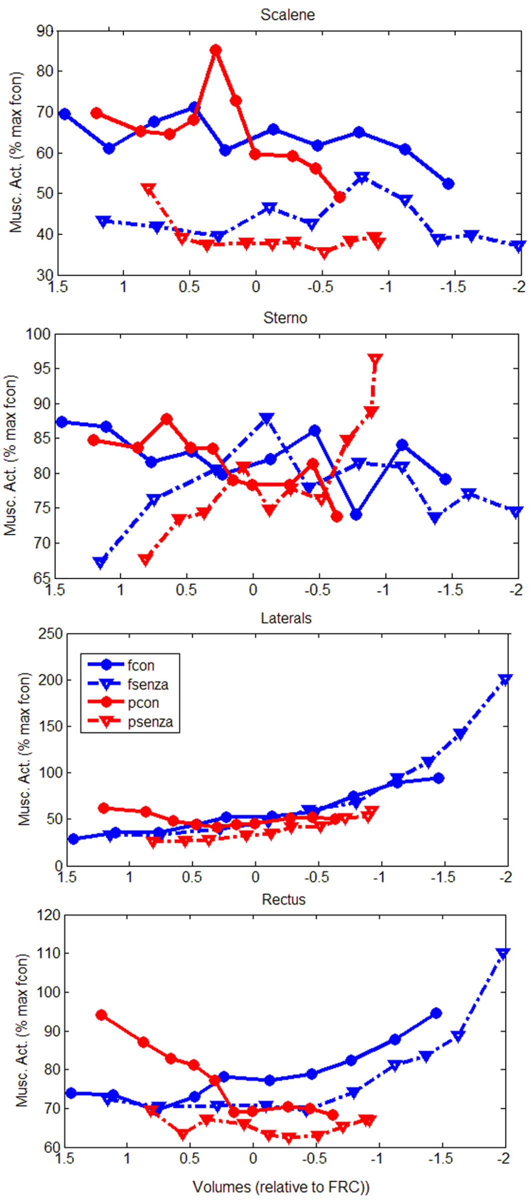

Figure 3. Subjects 1 and 2 averaged respiratory muscle activation (% of maximal activation during BS) in function of pulmonary volume relative to FRC (0 point on abcissa). Solid lines refer to BS playing, dashed lines, to NBS playing. Dark blue and light red lines respectively represent *forte* (*f*) and *piano* (*p*) playing.

t-test flow	S1	S2	S3	S4 *mf*
fBS-fNBS	0.925	0.056	0.127	
pBS-pNBS	0.161	**0.022**	**0.008**	0.979
fBS-pBS	**0.000**	**0.015**	**0.037**	
fNBS-pNBS	**0.012**	0.065	0.164	

Table 3. T-test p-value results for averaged flows for all subjects during tone playing in conditions BS and NBS at *f* and *p* intensities. P-values < 0.05 are considered significant.

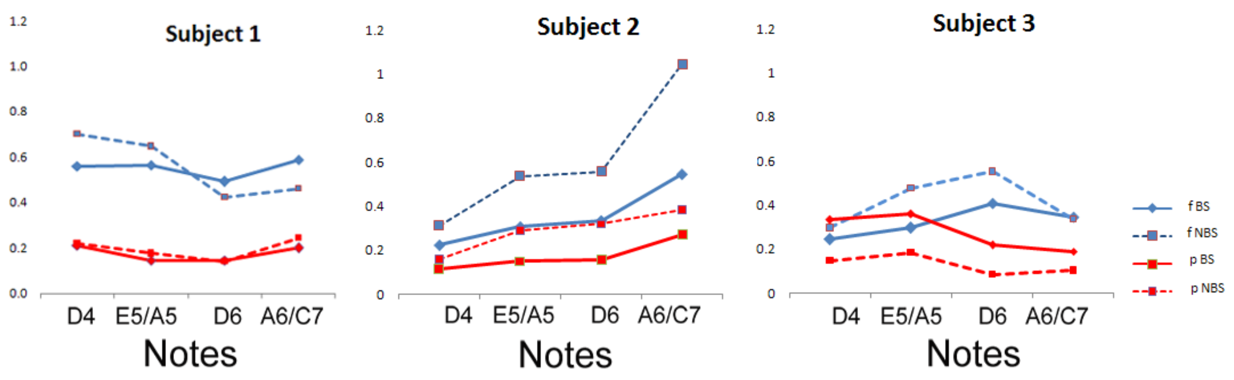

Figure 4. Flow during long tone playing for subjects 1, 2 and 3. Solid lines represent BS, dashed lines, NBS. Blue and red lines respectively refer to *f* and *p* playing.

3.1.2 Muscle activation and volumes

Figures 5 and 6 show the inspiratory muscle activation during low (D4) and high register (D6) long tone playing. As noted for the melody, BS playing requires a stronger inspiratory muscle activation than NBS playing in both registers and dynamics. In the soft high register (*p*D6), the inspiratory muscles are consitently more contracted than in the *f*BS condition. The expiratory muscles (not shown here) show similar patterns than during melody playing: i.e. similar patterns are reproduced for similar dynamics. Interestingly, the clear expiratory activation seen at the beginning and end of melody do not occur during tone playing. In addition, the recruitment seems to be of a lesser magnitude..

This might be explained by the fact that, to the contrary to melody playing, tone playing did not absolutely required the flautist to play until a very low lung volume was reached.

4 Discusssion

Cossette et al. (11) suggested that specific muscle activations may control specific parameters that are linked to specific musical tasks playing. In order to determine which parameters impact the most the muscle recruitment during flute playing, we correlated the respiratory muscle activation with pulmonary volumes, conditions (BS/NBS) and dynamics (*f*/*p*) during melody and tone playing.

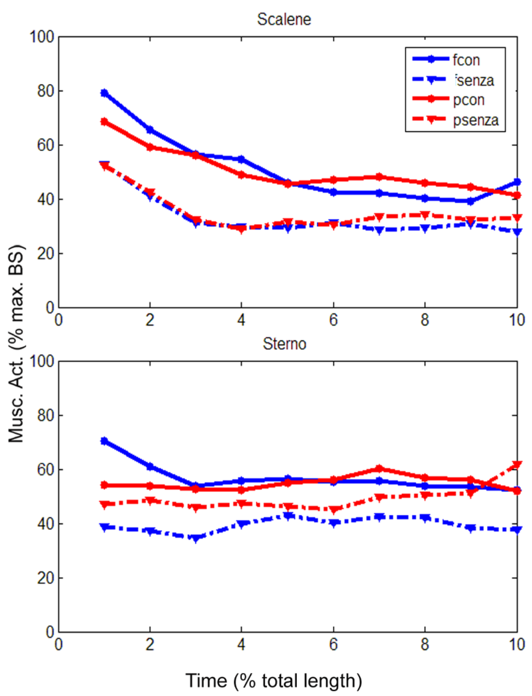

Figure 5 Subjects 1, 2, and 4 respiratory muscle activation (% of maximal activation during BS) during **D4** playing in relation to % time. Solid lines indicate BS, dashed lines indicate NBS. Blue lines: *f* ; red lines: *p*.

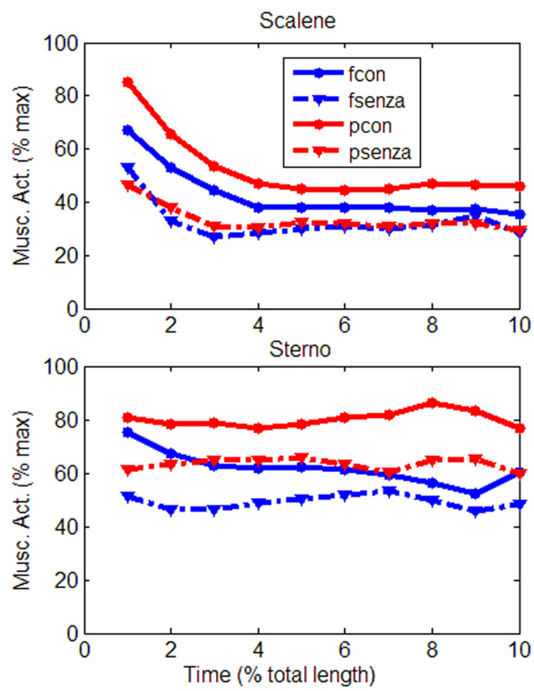

Figure 6 Subjects 1, 2, and 4 respiratory muscle activation (% of maximal activation during BS) during **D6** playing in relation to % time. Solid lines indicate BS, dashed lines indicate NBS. Blue lines: *f* ; red lines: *p*.

Our results are in accordance with previous authors (1, 6, 3, 6, 8, 9, 10, 11) who claimed that inspiratory muscle recruitment occurs during flute playing to brake the elastic recoil of the respiratory system and suggested some 'breath support' definition (11).

When comparing the flow measurements between melody and tone playing (Tables 1 and 3), we note that the only condition for which all results correlate is when comparing *f* BS to *p* BS. Results were significant and consistent among all subjects. Therefore, it appears that flow increases with sound amplitude, but that it does not seem to be strongly correlated with frequency and condition (BS/NBS).

Playing occurs over FRC whenever possible. As explained next to figure 3, the proportion of playing over and under FRC varies according to the condition and dynamic. *P* BS playing is mostly performed over FRC ; *f* NBS playing, mostly under FRC; and *f* BS and *p* NBS playing are performed equally over and under FRC. Accordingly, the inspiratory muscles are more recruited during BS playing than during NBS and more so during *p* playing. Inspiratory muscle activation decreases (relaxes) before reaching FRC almost simultaneously with the start of the expiratory muscle contraction just before FRC. During *f* NBS playing, expiratory muscles need to strongly contract to produce the required flow under FRC (against the inspiratory elastic recoil under FRC).

From looking at the individual averaged muscle activation results, it seems that for subject 1, the inspiratory muscle recruitment is not influenced by the change of dynamic during NBS playing nor is the expiratory muscle activation affected by the change of dynamic during BS playing (Table 2). It appears that the change of dynamic within a condition (BS or NBS) does not impact on subject 2 sternocleidomastoidian recruitment but does on his scalene muscle activation. Rectus abdominus seems to be dependent on dynamic changes but not on condition variations. Inspiratory muscle activation of subject 4 did not vary with condition and dynamic changes but the expiratory recruitment was influenced mostly by dynamic changes.

Conclusion

Our results showed that flow increases with sound amplitude, but is not be strongly correlated with frequency and condition (BS/NBS) changes. The inspiratory muscle activation seemed to depend mostly on the condition (BS/NBS) especially over FRC but condition seemed to impact less on expiratory muscle activation which varies more with dynamic and pulmonary volume. Individual differences were noted especially for inspiratory muscle recruitment – it was dependent on dynamic for one subject while it was less clear for another. Expiratory muscle activation was dependent on volume and dynamic for all subjects.

The number of participants was very limited, therefore the findings can not be generalised. Despite this, we propose a valuable method that allows to investigate the individual respiratory patterns associated with musical performance condition and dynamic changes. By using this method with a larger pool of participants, we will get additional insights to further investigate the practical implications and thereby make the teaching of wind instrument more efficient.

Acknowledgements

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