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Respiratory muscle activation patterns during maximum airway pressure efforts are different in women and men

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ABSTRACT

Maximum inspiratory and expiratory pressure values (PI_{max} and PE_{max}) are indirect measures of respiratory muscle strength that, in healthy adults, are known to be significantly lower in women compared to men. In part, sex differences in breathing kinematics, lung size, body composition, muscle mass, and muscle fiber composition are thought to be responsible for these effects. However, it is not known whether respiratory muscle activation during maximum respiratory efforts is also sex-specific. In this study, we addressed whether respiratory multi-muscle activation patterns during PI_{max} and PE_{max} efforts are different between healthy women and men. Forced vital capacity (FVC), forced expiratory volume in one second (FEV_1), PI_{max}, PE_{max}, and surface electromyographic (sEMG) activity recorded from respiratory muscles during these maximum airway pressure efforts were obtained in 13 women and 11 men. Percent predicted values of FVC and FEV_1 were not significantly different in these two groups (women vs. men: 112 ± 14 vs. 105 ± 15%, p = 0.29; and 92 ± 12 vs. 93 ± 13, p = 0.82, Mean ± SD, respectively), while PI_{max} and PE_{max} measures were significantly lower in women compared to men (68 ± 16 vs. 88 ± 19 cmH_2O, p = 0.011; and 69 ± 13 vs. 94 ± 17, p = 0.0004, respectively). Using vector-based methodology, by calculating the Similarity Index (SI) as measure of the resemblance between two sEMG patterns and the Magnitude (Mag) representing the overall amount sEMG during motor task, we have found that although the Mag values for both PI_{max} and PE_{max} tasks were not significantly different in two groups, the SIs revealed significant sex-dependent differences in muscle activation patterns (0.89 ± 0.08 vs. 0.97 ± 0.02, p = 0.016; and 0.77 ± 0.11 vs. 0.92 ± 0.04, p = 0.0006, respectively). During the PI_{max} effort, presented as the percentage of total sEMG amplitude, activity of upper trapezius muscle was significantly larger (p = 0.001) while activation of rectus abdominus, oblique, and lower paraspinal muscles were significantly smaller (p = 0.002, p = 0.040, p = 0.005, respectively) in women when compared to the men (50 ± 21 vs. 22 ± 11%; 2 ± 2 vs. 8 ± 7; 4 ± 3 vs. 9 ± 7, 2 ± 3 vs. 7 ± 6, respectively). During PE_{max} effort, the percentage of sEMG activity were significantly larger in upper and lower trapezius, and intercostal muscles (p = 0.038, p = 0.049, p = 0.037, respectively) and were significantly smaller in pectoralis, rectus abdominus, and oblique muscles (p = 0.021, p < 0.0001, p = 0.048, respectively) in women compared to men (16 ± 10 vs. 9 ± 4%; 16 ± 9 vs. 8 ± 5; 36 ± 12 vs. 25 ± 9; 6 ± 3 vs. 15 ± 5; 14 ± 5 vs. 20 ± 7, respectively). These findings indicate that respiratory muscle activation patterns during maximum airway pressure efforts in healthy individuals are sex-specific. This information should be considered during respiratory motor control evaluation and treatment planning for people with compromised respiratory motor function.

1. Introduction

Pulmonary diseases affect women differently and with a greater severity than men (Caracta, 2003; Pinkerton et al., 2015). Maximum inspiratory pressure (PI_{max}) and maximum expiratory pressure (PE_{max}) values, two indirect measures of inspiratory and expiratory respiratory muscles strength, are commonly used to evaluate respiratory motor function (Black and Hyatt, 1969; Gil Obando et al., 2012). Lower pressure values are indicative of respiratory muscle weakness that is present in a number of conditions including neurological injury, neuromuscular disorders, chronic obstructive pulmonary disease, obesity, and other conditions (Caracta, 2003; Evans and Whitelaw, 2009;

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Ovechkin et al., 2016; Terson de Paleville et al., 2011). In healthy individuals, these values are lower in women compared to men (Adamiak-Kardas, 2002; Charfi et al., 1991; Evans and Whitelaw, 2009; Gil Obando et al., 2012; Vincken et al., 1987b). Although lesser lung volumes and smaller respiratory muscle mass in women are thought to be involved, underlying mechanisms of this difference are not clearly understood (Caracta, 2003; Cory et al., 2015; Vincken et al., 1987b). Sex differences in respiratory muscle activation during exercise and deep breathing have been reported (Bernardi et al., 2001; Kaneko and Horie, 2012; MacBean et al., 2016; Mesquita Montes et al., 2016; Mitchell et al., 2018; Molgat-Seon et al., 2018; Romei et al., 2010; Schaeffer et al., 2014). However, it is not known whether differences in PI_{max} and PE_{max} generation are associated with sex-specific multi-muscle activation. The objective of this study was to identify if maximum respiratory muscle activation strategies differ between healthy adult women and men.

2. Methods

2.1. Participants

This study was conducted in the Neuroscience Collaborative Center at the Frazier Rehab Institute after informed consent was obtained as approved by the Institutional Review Board for Human Research at the University of Louisville. Twenty-four individuals (thirteen women and eleven men) with no history of respiratory and cardiovascular dysfunction or smoking participated in this study (Table 1).

2.2. Data acquisition

Pulmonary Function Test: Forced Vital Capacity (FVC) and Forced Expiratory Volume in one second (FEV_1) were obtained using BreezeSuite Spirometer (MedGraphics, St. Paul, MN) and expressed as the percentage of the predicted values for each participant (American Thoracic Society/European Respiratory Society, 2002). A Differential Pressure Transducer (MP45-36-871-350) with UPC 2100 PC card and software (Validyne Engineering, Northridge, CA) was used to measure PI_{max} and PE_{max}. The PI_{max} was measured during maximal inspiratory effort beginning at residual volume and PE_{max} was measured during maximal expiratory effort starting from total lung capacity (American Thoracic Society/European Respiratory Society, 2002) using a three-way valve system with flanged tube as mouthpiece (Airlife 001504, Allegiance Healthcare Corp., McGaw Park, IL). The pressure meter incorporated a 1.5 mm diameter leak to prevent glottic closure and to reduce buccal muscle contribution during measurements (Griffiths and McConnell, 2007). The assessment required a sharp, maximally forceful effort be maintained for a minimum of 2 s. All measures were taken in sitting position with 70-degree back support and full arm and leg support with mouthpiece held by the recording team member. Participants were instructed do not make postural changes during respiratory efforts.

Respiratory Motor Control Assessment: Maximum airway pressure and surface electromyography (sEMG) from respiratory muscles were recorded simultaneously using the MA300 System (Motion Lab Systems, Baton Rouge, LA) and PowerLab 16/30 (ADInstruments, Colorado Spring, CO) as previously described (Aslan et al., 2013). Skin over the muscles was cleaned by 70% isopropyl alcohol swabs and bipolar, pre-amplified surface electrodes with a fixed center-to-center distance of 17 mm, were placed parallel to the muscle fibers for the left and right respiratory muscles: upper trapezius on midclavicular line (UT), clavicular portion of pectoralis on midclavicular line (PEC), intercostal at 6th intercostal space on anterior axillary line (IC), rectus abdominus at the umbilical level (RA), obliquus abdominus on midaxillary line (OB), lower trapezius paraspinally at midscapular level (LT), and paraspinal

Table 1
Characteristics of participants, pulmonary function outcomes, respiratory muscle activity pattern and total amount of sEMG activity quantified by SI and Mag indexes during PE_{max} and PI_{max} efforts in women (n = 13) and men (n = 11).

							PE_{max}			PI_{max}		
Participant	Sex	Age (year)	Height (cm)	Body mass (kg)	FVC (%)	FEV_1 (%)	PE_{max} (cmH_2O)	SI	Mag	PI_{max} (cmH_2O)	SI	Mag
N73	F	32	165	55	96	84	76	0.816	123	75	0.946	96
N76	F	29	165	63	115	92	68	0.815	23	54	0.982	84
N78	F	25	160	57	119	100	93	0.874	51	49	0.946	138
N79	F	50	168	81	88	88	79	0.603	111	74	0.942	68
N81	F	32	160	55	116	97	67	0.892	77	80	0.97	175
N84	F	29	160	66	120	91	67	0.548	58	38	0.697	70
N116	F	30	157	50	111	87	67	0.891	21	82	0.913	27
N117	F	55	168	60	121	95	70	0.842	46	62	0.924	156
N118	F	31	160	53	125	104	47	0.721	53	53	0.901	79
N123	F	27	160	57	122	87	67	0.847	136	98	0.965	65
N155	F	53	163	95	92	76	68	0.684	27	67	0.841	19
N156	F	23	165	55	95	71	85	0.753	123	78	0.864	129
N157	F	25	170	52	134	119	47	0.739	121	74	0.8	102
Mean ± SD (n = 13)	***F***	***34 ± 11***	***163 ± 4***	***61 ± 13***	***112 ± 14***	***92 ± 12***	***69 ± 13***	**0.77 ± 0.11**	**75 ± 43**	**68 ± 16**	**0.89 ± 0.08**	**93 ± 47**
N74	M	30	168	73	120	106	90	0.919	44	81	0.948	116
N75	M	38	185	93	111	103	134	0.907	34	81	0.959	37
N77	M	27	173	81	104	111	73	0.953	16	81	0.98	83
N80	M	46	188	109	92	89	97	0.936	67	91	0.989	136
N119	M	64	185	95	91	85	77	0.969	17	115	0.984	34
N120	M	27	178	77	96	89	106	0.98	161	55	0.987	117
N124	M	29	188	94	121	100	96	0.861	91	106	0.969	120
N125	M	27	175	78	108	92	101	0.872	23	111	0.976	104
N158	M	22	175	82	100	76	89	0.896	30	99	0.969	72
N159	M	23	183	77	133	100	94	0.918	148	76	0.942	98
N160	M	22	178	61	82	70	82	0.938	38	69	0.942	31
Mean ± SD (n = 11)	***M***	***32 ± 13***	***180 ± 7***	***84 ± 13***	***105 ± 15***	***93 ± 13***	***94 ± 17***	***0.92 ± 0.04***	***61 ± 51***	***88 ± 19***	***0.97 ± 0.02***	***86 ± 38***

Note that FVC and FEV_1 were not significantly different in two groups, while PE_{max} and PI_{max} values were significantly lower in women than in men ($p = 0.0004$, $p = 0.011$ respectively). SIs during PE_{max} and PI_{max} were significantly lower in women compared to men ($p = 0.0006$, $p = 0.016$).

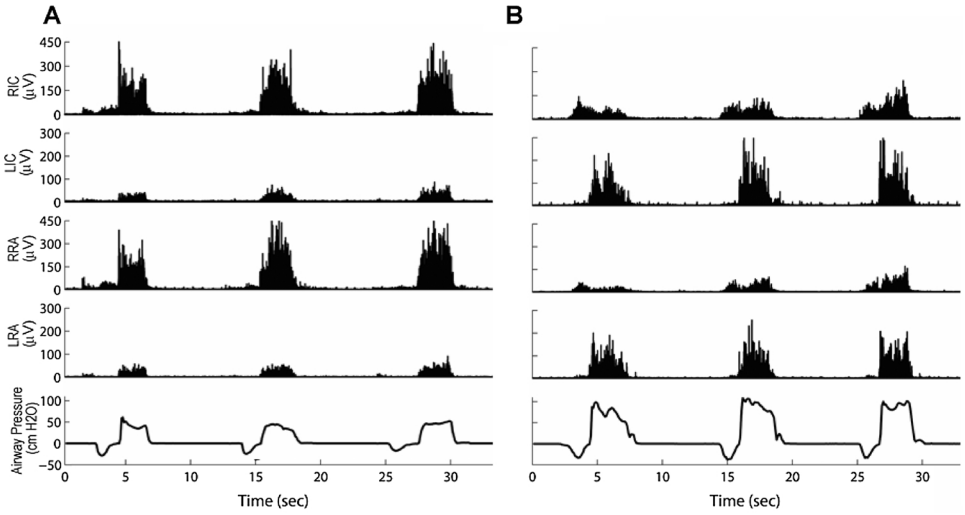

Fig. 1. sEMG and airway pessure during PE_{max} effort from a woman (Panel A, N157) and a man (Panel B, N159).
Note that lower airway pressure values are associated with lower RA and higher IC muscle activity in the woman compared to the man. RIC and LIC: right and left intercostal. RRA and LRA: Right and left rectus abdominus.

(PS) paraspinally on iliac intercrestal line (PS) (Aslan et al., 2013). The ground electrodes were placed over the acromion processes bilaterally. A Motion Lab System Back Pack Unit, with attached electrodes, was connected to a Motion Lab EMG Desk Top Unit and Powerlab System. sEMG input was amplified with a gain of 2000, filtered at 4–1000 Hz and sampled at 2000 Hz.

2.3. Data analysis

Three acceptable spirograms were obtained and the result of the best attempt was reported (American Thoracic Society/European Respiratory Society, 2002). The maximum expiratory and inspiratory efforts were performed three times with minimum 30 s intervals. The maximum pressure was taken as the highest value that is sustained for one second (Smyth et al., 1984). The maximum value was the average of three trials that varied by less than 20%. During maximum inspiratory and expiratory efforts, the Root Mean Square (RMS) of sEMG activity of each respiratory muscle was calculated for the window when the participant inhaled or exhaled from the residual volume or maximum lung capacity through the mouthpiece with maximum force. To eliminate any noise and electrocardiogram artifacts, sEMG values were corrected by subtracting, on a per-channel basis, the averaged activity computed from the same time window during quiescent recording preceding the maneuver. Three repeated trials for each task were averaged for each muscle for each time window. The multi-muscle activation patterns were evaluated via the Voluntary Response Index (VRI) methodology that produces two values: Magnitude (Mag) and the Similarity Index (SI) (Ovechkin et al., 2010). Each participant's VRI was calculated from the RMS values of sEMG activity for every muscle recorded during the time window as described previously (Aslan et al., 2013). The Prototype Response Vector (PRV) was generated from men's Response Vectors (RVs). The SI value was computed for each task as the inner product between women's RVs and PRV providing a value between 0 and 1 that quantifies how closely the multi-muscle distribution of activation in a test subject pattern matches the prototype. Mag values, representing the overall sEMG activity within analyzed windows, were calculated as the length of the RVs (Aslan et al., 2013). Individual amounts of sEMG activity were expressed as percentage of total sEMG amplitude within the analyzed windows. Data are presented as the mean with associated standard deviation of mean (SD), median with associated interquartile range, as well as full range (min-max). A linear model on log-transformed outcomes was applied to test the effects of sex on respiratory functional measures. Significance was reached at $p < 0.05$ with the level of significance (α) being set at 0.05. Data were analyzed in SAS 9.4.

3. Results

3.1. Pulmonary function test

Participants' sex, age (year), height (cm), body mass (kg), FVC and FEV_1 (% predicted), and PI_{max} and PE_{max} (cmH_20) are given in Table 1. Height and body mass were significantly lower in women compared to men ($p < 0.01$). FVC and FEV_1 values were not significantly different between the two groups (women vs. men: 112 ± 14 vs. 105 ± 15%, $p = 0.29$; and 92 ± 12 vs. 93 ± 13, $p = 0.82$, Mean ± SD, respectively), whereas PI_{max} and PE_{max} were significantly lower in women compared to men (68 ± 16 vs. 88 ± 19 cmH_2O, $p = 0.011$; and 69 ± 13 vs. 94 ± 17, $p = 0.0004$, respectively).

3.2. Respiratory muscle activation during PI_{max} and PE_{max} efforts

During PI_{max} effort, group SI values were significantly different (women vs. men: 0.89 ± 0.08 vs. 0.97 ± 0.02, $p = 0.016$), whereas the sEMG Mag amount was not significantly different (Table 1). During this task, percent of UT muscle activity was significantly greater ($p = 0.001$) while the contribution of RA, OB, and PS were significantly smaller ($p = 0.002$, $p = 0.040$, $p = 0.005$, respectively) in women compared to those in men (50 ± 21 vs. 22 ± 11%; 2 ± 2 vs. 8 ± 7; 4 ± 3 vs. 9 ± 7; 2 ± 3 vs. 7 ± 6) (Fig. 2).

During PE_{max} task, group average respiratory muscle activation patterns, as determined by SIs, were significantly different (0.77 ± 0.11 vs. 0.92 ± 0.04, $p = 0.0006$) while the overall amounts of sEMG activity (Mags), were not significantly different between women and men (Table 1). During this task, percent of UT, LT, and IC muscle activity were significantly higher ($p = 0.038$, $p = 0.049$, $p = 0.037$, respectively) while PEC, RA and OB were significantly lower ($p = 0.021$, $p < 0.0001$, $p = 0.048$, respectively) in women compared to those in men (16 ± 10 vs. 9 ± 4%; 16 ± 9 vs. 8 ± 5; 36 ± 12 vs. 25 ± 9; 6 ± 3 vs. 15 ± 5; 14 ± 5 vs. 20 ± 7, respectively) (Figs. 1 and 3).

4. Discussion

The major finding of this study is that respiratory multi-muscle recruitment patterns during PI_{max} and PE_{max} efforts are different in women and men. In general, compared to men, women demonstrated smaller activity of the abdominal muscles and greater activation of the chest muscles during both tasks. These results indicate that sex-dependent strategy in respiratory multi-muscle activation during PI_{max} and PE_{max} efforts may contribute to lower airway pressure generation

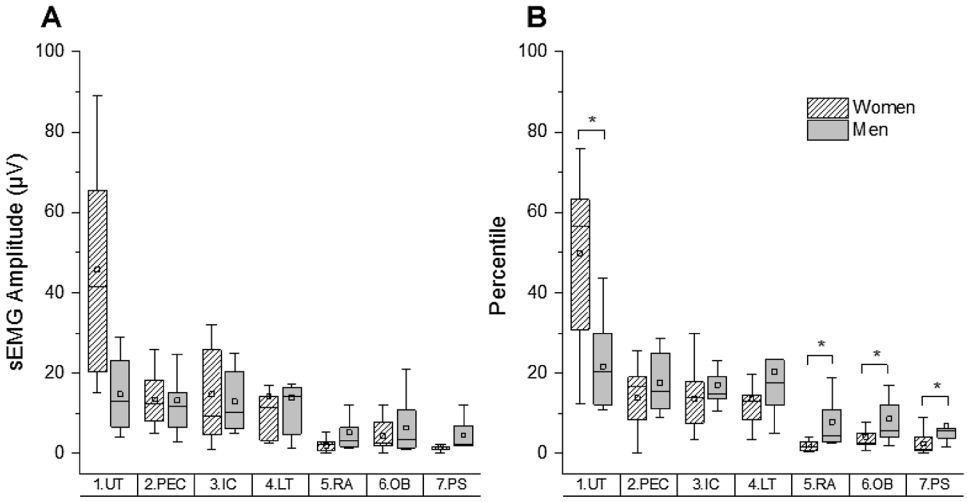

Fig. 2. Box plot of a comparison of the sEMG activity of respiratory muscles during PI_{max} effort in women (n = 13) and men (n = 11). Note that women presented significantly higher sEMG activation in UT, and lower sEMG activation in RA, OB, and PS compared to men (p = 0.001, p = 0.002, p = 0.040, p = 0.005, respectively). Upper trapezius (UT), pectoralis (PEC), intercostal (IC), rectus abdominus (RA), oblique (OB), paraspinal (PS).

in women.

Maximal pressure outcomes in our participants were at the lower end of previously reported deviation range when flanged mouthpiece have been used (Vincken et al., 1987a; Wilson et al., 1984) and were lower in women compared to men. The overall amount of sEMG activity was not different between the two groups, but the distribution of multi-muscle activity was different, indicating that women and men use distinctly different muscle activation strategies. More specifically, women relied on upper/lower trapezius and intercostal muscles during maximal expiratory effort and on upper trapezius during maximal inspiratory effort while men employed greater activation of abdominal muscles (rectus and oblique) to perform both tasks. These sex-related strategies may contribute to previously published differences in chest / abdominal wall excursions (Bellemare et al., 2001; Kaneko and Horie, 2012; Mesquita Montes et al., 2016; Ragnarsdottir and Kristinsdottir, 2006; Romei et al., 2010) associated with greater reliance on the extra-diaphragmatic inspiratory muscles in women (Mitchell et al., 2018). Our results may explain the finding that women and men produce similar chest and abdominal wall excursions at rest, but women exhibit higher rib cage and lower abdominal wall excursions during deep breathing and exercise: the contribution of chest and abdominal muscles increase with increased respiratory drive during exercise or mechanical load (Aliverti, 2002; Han et al., 1993). The chest muscles contribute to upper rib cage expansion during inspiration. The diaphragm displaces the lower rib cage as it contracts during inspiration, and the force exerted by the diaphragm to the lower ribs is transmitted, via the rib cage tissues and the sternum, to the upper ribs (Troyer and Wilson, 2016). On the other hand, abdominal support on the inspiratory action of the diaphragm reduces the descent of the dome by opposing the shortening of the diaphragmatic muscle and allows the fibers to operate on a more advantageous portion of their length-tension curve, and therefore, to exert a greater force (Troyer and Wilson, 2016). Our results are consistent with these studies as both chest and abdomen muscles were active during PI_{max} effort both in women and men (Aliverti, 2002; Mesquita Montes et al., 2016). Additionally, our results showed that women had significantly higher activity in UT and significantly lower activity in RA, OBL, and PS muscles compared to men during the PI_{max} effort. Reduced abdominal support in women during PI_{max} effort can increase the shortening of the diaphragmatic muscle fiber and reduce the optimal functioning of the diaphragm that may result in lower PI_{max} values than those in men. In addition, higher activity in UT muscle in women than those in man could be due, in part, to the increase in diaphragm displacement that can cause greater displacement of lower and upper ribs in women during PI_{max} effort. Furthermore, our data showed that activity of PS muscles was higher in men than compared to women during PI_{max} effort. The PS muscles are extensors of the spine that stabilize the vertebral column during breathing (de Carvalho et al., 2010). Therefore, activation of PS could be due to further stabilization of the trunk during the maximum inspiratory effort.

In healthy adults, resting expiration is considered to be a passive process and is due to the elastic recoil of the lungs and relaxation of inspiratory muscles (Kenyon et al., 1997). The amount of muscle activity increased significantly in UT, IC, RA and OB muscles during PE_{max}

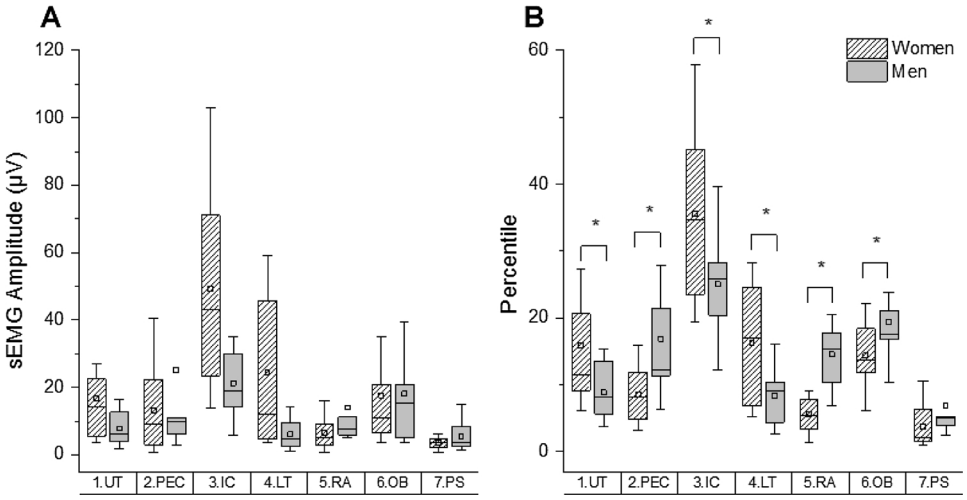

Fig. 3. Box plot of raw sEMG activity of respiratory muscles (A) and percent of their contribution to the total sEMG activity during PE_{max} effort in women (n = 13) and men (n = 11).
Note that women presented significantly higher sEMG activation in UT, LT, and IC while lower activity in PEC, RA, and OB compared to men (p = 0.038; p = 0.049; p = 0.037; p = 0.021; p < 0.0001; and p = 0.048, respectively). Upper trapezius (UT), pectoralis (PEC), intercostal (IC), rectus abdominus (RA), oblique (OB), paraspinal (PS).

effort in both groups. Similar to our findings, previous studies have also reported increased activation intensity of both RA and OB muscles with increased effort (Mesquita Montes et al., 2016). In addition, our data showed that not only the abdominal, but also the chest muscles were activated during maximum expiratory effort. Trunk plays an important role in maintaining head stability and its position in space by providing a stable base of support for the neck segment of the body via the vestibulocollic reflex and the cervicocollic reflex systems, respectively (Peng et al., 1996). Similarly, increased sEMG activity of UT muscle during PE_{max} effort in both groups indicates that shoulder elevation also occurs at the same time with neck flexion. Increased activation of PS muscles during maximum expiratory effort could be due to further stabilization of the trunk (de Carvalho et al., 2010).

4.1. Clinical relevance

Our findings indicate that differences in respiratory muscle recruitment strategies in women and men may contribute to lower normative PI_{max} and PE_{max} values in women. Lower maximum pressure values are indicative of respiratory muscle weakness that is often present in people with neuromuscular diseases, chronic obstructive pulmonary disease, or dyspnea. In addition, respiratory muscle fatigue can develop in healthy subjects during high intensity exercise, which may limit exercise tolerance in both trained and untrained individuals (Harms, 2006). Women are more prone to pulmonary limitations during exercise than men (Harms, 2006). Furthermore, sex-related differences in anatomy and physiology can influence severity and progression of respiratory diseases and the responsiveness to treatments (Townsend et al., 2012). Therefore, pulmonary diseases affect women with a greater degree of severity than men: women have a higher risk of developing chronic obstructive pulmonary disease associated with higher frequency of cough and more severe dyspnea than men (Pinkerton et al., 2015).

4.2. Study limitations

We did not control for body composition of the research participants which can contribute to the sEMG variability. However, only two participants (one female and one male) had a BMI of 30 and above indicating that our research groups were within normal range of body fat based on height and body mass (Sun et al., 2010). In addition, our sample size is relatively small. Therefore, controlled studies with large sample size need to be conducted to represent the populations.

5. Conclusion

We presented evidence that sex-specific ability to generate maximum airway pressure is associated with different respiratory muscles recruitment strategies in women and men. This information should be considered during evaluation and treatment planning for people with compromised respiratory function.

Authors' contribution

Sevda Aslan and Alexander Ovechkin: study design, data acquisition / analysis / interpretation, and manuscript writing, Barry McKay: study design, data interpretation, manuscript drafting and critical revision, Goutam Singh: manuscript drafting and critical revision.

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