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Length-tension relationship of ventilatory muscles in young adults

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Introduction

Like other skeletal muscles, ventilatory muscles' performance is also assessed in terms of strength. This is generally determined by measurement of expiratory and inspiratory mouth pressures, expressed in P_{Emax} and P_{Imax} respectively, in centimetres of water ($cm\ H_2O$) and usually conducted with the person in sitting. The reason for why the ventilatory muscles, especially the diaphragm, work most efficiently in this position is described elsewhere[1-3]. The length-tension relationship of skeletal muscles of the human limbs is already well documented[4-7]. However, there is a dearth of studies on the relationship of human ventilatory muscles with the exception of the diaphragm[8-11], though researchers have compiled sizable evidence on such a relationship for all of the animal ventilatory muscles[12-15].

It was the purpose of this paper to present the results from a study on the length-tension relationship of the ventilatory muscles of college-age students. Specifically, the ratio of ventilatory strength at different lung capacities was investigated. Such a relationship should be of considerable interest to physiotherapists, since an understanding of it is of the utmost importance in the designing of protocols for the application of cardiopulmonary physiotherapy. Another implication of this study would be that the results might contribute to establishing a norm for ventilatory muscle strength of Japanese men and women in their early 20's.

Methodology

Participants

The test participants consisted of 41 men and 40 women physiotherapy students. The mean age (SD; range) of this convenience sample was 22.0 (2.4; 20–30) years old for men and 21.6 (2.6; 20–36) for women. For the men, the mean (SD; range) standing height was 171.4 (9.3; 158–185) cm, mean (SD; range) body mass 65.4 (8.1; 48–95) kg and the mean (SD; range) body-mass index 22.3 (2.9; 17.6–34.5) kg/m^2. For the women, the mean (SD; range) standing height was 159.6 (4.6; 149–169.8) cm, mean (SD; range) body mass 49.9 (4.7; 42–62) kg and the mean (SD; range) body-mass index 19.6 (1.4; 16.9–22.8) kg/m^2. None of the participants had previously been engaged in any regular athletic training, nor had they any cardiopulmonary dysfunction or musculoskeletal disorder of the thoracic cage and trunk. All the participants were non-smokers.

Measurement and procedure

Measurement of maximum respiratory pressure is the most widely used test for the assessment of ventilatory muscle strength, since it has no adverse effects and is non-invasive and easy to perform[16,17]. The instrument used for this study was the Vitalopower KH-101 (Chest M.I. Inc., Japan). The P_{Emax} was defined as the maximal positive pressure expressed in $cm\ H_2O$ that could be measured at the mouth when participants performed a maximal static expiratory effort against an occluded airway, which is taken as a measure of

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expiratory muscle strength[16]. Similarly, the P_{Imax} was defined as the maximal negative pressure expressed in *cm* H_2O that could be measured at the mouth when participants performed a maximal static inspiratory effort against an occluded airway, which is taken as a measure of inspiratory muscle strength[16]. In this study P_{Emax} was measured at total lung capacity (P_{Emax}TLC) and at resting end-expiratory level or functional residual capacity (P_{Emax}FRC), and P_{Imax} was measured at residual volume (P_{Imax}RV) and at FRC (P_{Imax}FRC).

The participants were given a thorough, precise and detailed 10-min explanation of the purpose and procedures for the measurements prior to their execution of them in a seated position. For measurement of P_{Emax}TLC the participants performed a maximal inspiration, but for P_{Emax}FRC, they inspired only up to the end-tidal point followed by a maximal expiratory effort. For measurement of P_{Imax}RV the participants were instructed to carry out maximal expiration, but for P_{Imax}FRC, they were asked to expire only up to the end-tidal point followed by a maximal inspiratory effort. Instruction to the participants on the inspiratory and expiratory end-tidal points was given particular emphasis so as to enable an accurate reading at the FRC level. As for the rest of the procedure, the reader is referred to *reference 3*.

Statistics

Student's t test was used for the comparison of P_{Emax}TLC and P_{Emax}FRC, and again, for the comparison of P_{Imax}RV and P_{Imax}FRC among the men and women. For calculating the mean ratio of the ventilatory muscle strength, TLC was taken as the standard of reference for the expiratory muscle strength and RV as the standard for the inspiratory muscle strength, though a certain amount of elastic recoil of the lungs and chest walls could not be denied. An alpha level of 0.05 was selected for statistical significance in this study, using the computer software *Microsoft Excel 2002* for the data analysis.

Results

The ventilatory muscle strength for men was significantly stronger than that for women at TLC, FRC and RV (Table 1). The mean ratio of P_{Emax}TLC to PEmaxFRC was 1.31 for men and 1.30 for women (Table 2). Similarly, the ratio of P_{Imax}RV to that at P_{Imax}FRC was 1.18 for men and 1.08 for women (Table 2). The mean ratio of the expiratory muscle strength to the inspiratory

Table 1. Participants' ventilatory muscle strength (*cm* H_2O).

	Men			Women		
	mean	SD	range	mean	SD	range
P_{Emax} at TLC	164.9*	37.2	74.7–234.0	93.2	25.0	50.2–147.7
P_{Emax} at FRC	128.9*	33.3	72.0–194.2	72.9	21.9	41.5–124.7
P_{Imax} at RV	124.6*	24.2	79.5–182.5	86.2	19.9	46.5–133.0
P_{Emax} at FRC	107.0*	24.0	65.7–165.2	81.1	18.4	43.0–137.0

TLC: total lung capacity; FRC: functional residual capacity; RV: residual volume;
SD: standard deviation; *significant at $p < 0.01$

Table 2. The mean ratio of the expiratory muscle strength at TLC to that at FRC and the mean ratio of the inspiratory muscle strength at RV to that at FRC.

	No. of participants	Expiratory muscles			Inspiratory muscles		
		mean	SD	range	mean	SD	range
Men	41	1.31	0.26	0.97–2.09	1.18	0.18	0.89–1.56
Women	40	1.30	0.22	1.01–2.02	1.08	0.17	0.72–1.49
Total	81	1.31	0.24	0.97–2.09	1.13	0.18	0.72–1.56

TLC: total lung capacity; FRC: functional residual capacity; RV: residual volume; SD: standard deviation

Table 3. The ratio of expiratory muscle strength to inspiratory muscle strength

	Number of participants	At TLC or RV			At FRC		
		mean	SD	range	mean	SD	range
Men	41	1.33	0.25	2.04-0.86	1.22	0.25	1.90-0.80
Women	40	1.11	0.29	1.85-0.65	0.92	0.30	2.05-0.47
Total	81	1.22	0.29	2.04-0.65	1.07	0.31	2.05-0.47

TLC: total lung capacity; RV: residual volume; FRC: functional residual capacity;
SD: standard deviation

muscle strength for men at TLC or RV and FRC was 1.33 and 1.22, and for women, 1.11 and 0.92 (Table 3).

Discussion

As was predicted, the men showed stronger ventilatory muscle strength than the women. It is a well-known fact that women's skeletal muscle strength is two-thirds of that of men. However, in this study of the ventilatory muscle strength, only the ratio of women's P_{Imax}RV to that of the men's was approximately so (69.2%). On the contrary, the ratio of women's P_{Imax} to that of the men's at FRC exceeded the aforementioned norm (75.8%) stated for skeletal muscles, but the ratio of women's P_{Emax}TLC, and P_{Emax}FRC was only slightly over one-half (56.5% and 56.6%, respectively) of that of the men. The major function of the expiratory muscle is to generate an instantaneous thoracic compression force such as in an execution of a cough or when used in a forced expiration technique (FET) or huffing, the uses of which are occasional and somewhat irregular in nature. Therefore, the above finding in this study of a lower expiratory force for the women suggests that they may be at a disadvantage when executing these manoeuvres, and, consequently, their efforts will be less effective against airway congestion.

In the healthy individual the resting end-expiratory level occurs at 40 per cent of the lung volume with a vital capacity encompassing a range from maximum expiratory level to maximum inspiratory level; ie. this is where outward and inward elastic recoils of the lungs and chest wall balance out. In other words, the ratio of the length of the expiratory muscles between the maximal inspiratory level and the resting end-expiratory level to that of the inspiratory muscles between the maximal expiratory level and the resting end-expiratory level is three to two during quiet breathing. This signifies that the expiratory muscles at TLC are in a more mechanically advantageous position than the inspiratory muscles at RV, which explains why the ratio of the expiratory muscle strength at TLC to that at FRC in this study was larger than that of the inspiratory muscle strength at RV to that at FRC. Another factor for the larger strength of the expiratory muscles at FRC than to that of the inspiratory muscles at RV is that the muscle bulk of the former is large compared to that of the latter.

The manoeuvre for P_{Emax}TLC is analogous to the active forced expiration technique at high lung volumes, as opposed to the manoeuvre for P_{Emax}FRC being analogous to that at low lung volumes. The former requires greater magnitude and duration of expiration than the latter, and its execution down to FRC increases the velocity of airflow in the first six or seven generations of airways, consequently, clearing excess secretions in these airways including the trachea. However, with the manoeuvre for P_{Emax}FRC, one must expire rapidly forcing air out to RV using all of the thoracoabdominal musculature, which produces high velocity airflow and a tussive-like squeeze effect on the small airways. In this study the mean ratio of the expiratory muscle strength at FRC to that at TLC was found to be 0.79 for both sexes. The well-known fact that the state of low lung volumes promotes secretion accumulation in the small airways in chest pathologies implies that strengthening manoeuvres for the expiratory muscles at FRC is of the utmost importance for bronchial hygiene.

The inspiratory muscle strength in both sexes in this study remained relatively constant at RV and FRC compared to that of the expiratory muscle strength at TLC and FRC. This may be attributable to the fact that, unlike the occasional forced expiratory function required of expiratory muscles, the inspiratory muscles' work is generally constant throughout one's life.

An unexpected finding was that, in the women, P_{Imax}FRC was greater than P_{Emax}FRC (81.1 vs. 72.9 *cm* H_2O), though standard deviation was shown to be largest (0.30) amongst the other parameters. This finding may be attributable to the natural physiological phenomenon of an increase in minute ventilation of approximately 50 per cent during pregnancy, consequently, with deeper inspiration and a slight increase in respiratory rate[18]. Further study is necessary to clarify the women's inspiratory muscle strength at FRC *vis-à-vis* their expiratory muscle strength at FRC.

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若年成人の呼吸筋の長さ・張力関係

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