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EFFECTS OF AGE AND SEX ON INSPIRATORY MUSCLE ACTIVATION PATTERNS DURING EXERCISE

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ABSTRACT

Purpose: Characterize the effects of age, sex, and their interaction on inspiratory muscle activation patterns during exercise. *Methods:* Twenty younger (20-30y, n=10 women) and twenty older (60-80y, n=10 women) subjects performed an incremental cycle exercise test. Electromyography of the scalene (EMG_{sca}) and sternocleidomastoid (EMG_{scm}) muscles were measured using skin surface electrodes, while diaphragm electromyography (EMG_{di}) and esophageal and transdiaphragmatic pressures were measured using an esophageal catheter. Electromyography data were transformed into root-mean-square with a 100ms time constant. Esophageal (PTP_{es}) and diaphragmatic (PTP_{di}) pressure-time products were used as indices of total inspiratory muscle pressure production and diaphragmatic pressure production, respectively. *Results:* At absolute minute ventilations ($\dot{V}_E$), women and older subjects had greater EMG_{di} than men and younger subjects, respectively (all $p<0.05$), but no differences were noted when $\dot{V}_E$ was expressed in relative terms (all $p>0.05$). Women had greater EMG_{sca} activity than men at absolute and relative levels of $\dot{V}_E$ (all $p<0.05$). Older subjects had greater EMG_{sca} than younger subjects when $\dot{V}_E$ was expressed relative (all $p<0.05$) but not absolute terms (all $p>0.05$). At absolute and relative levels of $\dot{V}_E$, women and older subjects had greater EMG_{scm} than men and younger subjects, respectively (all $p<0.05$). Women and older subjects had a greater PTP_{di}/PTP_{es} at a $\dot{V}_E$ of 70 $l \cdot min^{-1}$ than men and younger subjects, respectively (both $p<0.05$), but no differences were noted when $\dot{V}_E$ was expressed in relative terms (all $p>0.05$). No significant interactions between age and sex were noted (all $p>0.05$). *Conclusion:* Age and sex significantly affect inspiratory muscle activation patterns during exercise; however, the extent of the effects depends on whether comparisons are made at absolute or relative $\dot{V}_E$.

KEY WORDS

aging, diaphragm, electromyography, respiratory mechanics, scalene, sternocleidomastoid

INTRODUCTION

During incremental exercise, minute ventilation ($\dot{V}_E$) increases progressively in order to meet the demands associated with rising oxygen uptake and carbon dioxide production. Generating the pressure required to achieve a given $\dot{V}_E$ is accomplished via the coordinated action of the respiratory muscles (1). During inspiration at rest, the diaphragm performs the majority of respiratory muscle work with other obligatory inspiratory muscles, such as the scalenes, contributing less to overall inspiratory pressure generation (2,3). As $\dot{V}_E$ increases during incremental exercise, the relative contribution of the diaphragm to overall inspiratory pressure generation decreases, while the contributions of other obligatory inspiratory muscles as well as accessory inspiratory muscles (e.g., sternocleidomastoids) increase progressively (4,5). The activation of extra-diaphragmatic inspiratory muscles effectively serves to distribute the work needed to support exercise hyperpnea (6-9).

It is well known that sex-differences in the structure and function of the respiratory system exist (6-8,10). For example, on average, women have smaller absolute lung volumes and maximal flows than age- and height-matched men (11,12). Moreover, when men and women are matched for absolute lung size, the large conducting airways are narrower in women (13). During exercise, the narrower airways in women are thought to increase the mechanical and metabolic cost of generating a given $\dot{V}_E$ above ~55 $l \cdot min^{-1}$ (14,15). Previous work suggests that the higher work of breathing in women may be achieved by a different pattern of respiratory muscle activation than that observed in men (6,16). Indeed, during constant-load exercise to exhaustion, young women have greater relative electromyography (EMG) activity of the scalene and sternocleidomastoid muscles for a given relative exercise intensity than young men (17).

However, the aforementioned sex-differences in inspiratory muscle activation patterns were noted during high-intensity constant-load exercise (i.e., 85% of peak work rate), where men have a greater absolute ventilatory response and a higher propensity towards diaphragm fatigue than women (16). In theory, both factors could influence the pattern of inspiratory muscle activation. Therefore, it is unclear whether differences in inspiratory muscle activation patterns during exercise between men and women are the product of biological sex or exercise protocol.

Healthy aging results in significant structural changes to the respiratory system that decrease pulmonary function (18) and alter the mechanics of breathing during exercise (19). In particular, the respiratory muscles undergo structural changes that result in a progressive loss in strength, as evidenced by reductions in maximal respiratory pressures (20). Although data in humans is lacking, work in rodent models demonstrates an age-related change in the morphology of the diaphragm that reduces its force generating capacity (21). During exercise, older individuals have a higher work of breathing for a given $\dot{V}_E$ than their younger counterparts (19) that must be accomplished by relatively weaker respiratory muscles. Therefore, it is likely that the pattern of respiratory muscle activation during exercise is also affected by the healthy aging process. However, to our knowledge, no study has assessed the effect of healthy aging on inspiratory muscle activation patterns during exercise.

Given that biological sex and age independently affect the load on the respiratory muscles during exercise, it stands to reason that when compared to men and younger individuals, women and older individuals may rely on extra-diaphragmatic inspiratory muscles to a greater extent throughout incremental exercise in order to minimize the load on the diaphragm. It is also possible that sex and age interact to affect inspiratory muscle activation patterns during exercise in healthy individuals. Accordingly, the aim of the present study was to characterize the effects of age, sex, and their interaction on inspiratory muscle activation patterns during exercise. We hypothesized that women and older individuals would exhibit greater diaphragm, scalene, and sternocleidomastoid activation for a given $\dot{V}_E$ during exercise than men and younger individuals, respectively. If present, sex- and age-differences in respiratory muscle activation patterns during exercise may have important physiological implications, such the response to inspiratory muscle training, the mechanisms dyspnea, as well as the mechanical and metabolic cost of breathing.

METHODS

Subjects. After providing written informed consent, twenty healthy older men and women (60-80 y), and twenty healthy younger men and women (20-30 y) participated in the study. Men and women were evenly distributed between groups. All subjects had previously participated in a study designed to characterize the mechanical ventilatory and perceptual responses to incremental exercise (13). The primary outcome measures in the present prospective study do not overlap with any of the previous analyses. Inclusion criteria were as follows: normal pulmonary function parameters based on predicted values (22-24), a body mass index between 18 and 30 $kg \cdot m^{-2}$, and peak aerobic power ≥80% predicted based on population-specific normative values (25,26). Subjects were excluded if they were current smokers or had previously smoked >5 pack-years, had a history or current symptoms of cardiorespiratory disease, were currently taking medication that would interfere with the ventilatory or metabolic response to exercise, or any contraindications to exercise testing. All healthy younger subjects had never smoked. Six of twenty older subjects (n=3 men, n=3 women) had previously smoked <5 pack/years, all of whom had quit smoking >25 y prior to participation in the study. Subjects were divided into 4 groups based on sex and age: younger men (20-30 y), younger women (20-30 y), older men (60-80 y), and older women (60-80 y). All study procedures were approved by the University of British Columbia Providence Health Care Research Institute Ethics Board, which adheres to the *Declaration of Helsinki.*

Experimental Overview. Testing took place over 2 separate days. On Day 1, anthropometric measurements were taken followed by detailed pulmonary function testing. Subjects then completed an incremental cycle exercise test to volitional exhaustion for familiarization purposes. On Day 2, subjects were instrumented with a dual-balloon catheter (Guangzhou Yinghui Medical Equipment Co. Ltd., Guangzhou, China) for the assessment of esophageal pressure (P_{es}), gastric pressure (P_{ga}) and EMG of the crural diaphragm (EMG_{di}). The technical specifications of this catheter are described by Luo *et al.* (27). Briefly, the catheter is equipped with two balloons for the measurement of P_{es} and P_{ga}, respectively. Between the P_{es} and P_{ga} balloons are ten 1 cm silver coils, each separated by a 0.5 mm gap, that form five sequential EMG_{di} recording pairs with an interelectrode distance of 3.2 cm. The placement of the catheter was performed as previously described (28), and the validity of P_{es} was verified by performing an occlusion test (29). The quality of the EMG_{di} signals was assessed according to standard criteria (27). In all cases, proper placement of the catheter based on P_{es} pressure resulted in optimal EMG_{di} signals. Skin surface electrodes were used to measure EMG of the scalene (EMG_{sca}) and sternocleidomastoid (EMG_{scm}). Subjects then performed an incremental cycle exercise test with the same protocol as on Day 1.

Pulmonary Function Testing. Spirometry, whole-body plethysmography, single breath diffusing capacity for carbon monoxide, maximum voluntary ventilation, as well as maximum inspiratory and expiratory pressures were assessed using a commercially available system (Vmax Encore 229, V62J Autobox; CareFusion, Yorba Linda, USA) according to standard recommendations (30-33). Pulmonary function measurements were expressed in absolute values and as a percentage of predicted values (22-24).

Exercise Protocol. The incremental cycle exercise test was conducted on an electronically braked cycle ergometer (Ergoselect 200P, Ergoline, Bitz, Germany). Testing began with a 6 min rest period followed by 1 min of unloaded pedaling, then 20 W step-wise increases in work rate (starting at 20 W) every 2 min until volitional exhaustion. The exercise protocol was selected in order to allow for comparisons between groups across a wide range of $\dot{V}_E$. Peak work rate was defined as the highest work rate sustained for at least 30 s.

Inspiratory Muscle Electromyography. EMG_{di} was measured using a multi-pair esophageal electrode catheter as previously described (27). The raw signal was processed using an amplifier (bio-amplifier model RA-8, Yinghui Medical Technology Co. Ltd., Guangzhou, China) through a 60 Hz notch filter, and band-pass filtered between 20 and 1000 Hz. EMG_{sca} and EMG_{scm} were assessed with bipolar skin surface electrodes over the medial scalene and the sternocleidomastoid muscles after carefully cleaning and abrading the skin. The positions of the surface electrodes were as follows: for the scalene, electrodes were placed within the posterior triangle of the neck at the level of the cricoid process, and for the sternocleidomastoid, electrodes were placed at the midpoint along the longitudinal axis of the sternocleidomastoid muscle between the mastoid process and the medial clavicle (7,17). EMG_{scm} and EMG_{sca} electrodes were placed unilaterally on the right side of the body. Raw EMG_{scm} and EMG_{sca} signals were recorded and low-pass filtered at 500 Hz using a wireless system (TeleMyo DDTS, Noraxon, Scottsdale, USA). All EMG data were transformed into root mean square (RMS) with a time constant of 100 ms. For EMG normalization, subjects performed inspiratory capacity maneuvers at rest and during each stage of exercise as previously described (34). For each subject, the maximal EMG activity of each inspiratory muscle was defined as the peak RMS for each respective inspiratory muscle during any inspiratory capacity maneuver at rest or during exercise (35).

Flow, Volume, and Pressure. At rest and during exercise, subjects breathed through a low resistance (0.3-0.7 $cmH_2O \cdot l^{-1} \cdot s^{-1}$ at 0.5-8.0 $l \cdot s^{-1}$) circuit with minimal dead-space (130 ml). Bi-directional flow was measured using a heated, calibrated pneumotachograph (model 3813, Hans Rudolph, Kansas City, USA). Volume was obtained by numerical integration of the flow signal. P_{es} and P_{ga} were measured by connecting the distal end of each respective balloon on the dual-balloon catheter to independent, calibrated differential pressure transducers (DP15-34, Validyne Engineering, Northridge, USA). Transdiaphragmatic pressure (P_{di}) was calculated online as the difference between P_{ga} and P_{es}.

Cardiorespiratory Responses. Standard metabolic and ventilatory responses were measured breath-by-breath using a metabolic cart (Vmax Encore 229; CareFusion, Yorba Linda, USA). In the younger subjects, heart rate was measured using a heart rate monitor (Polar T34; Polar Electro, Kempele, Finland). In the older subjects, heart rate was measured using a 12-lead electrocardiogram (Cardiosoft Diagnostics System v6.71, GE Healthcare, Mississauga, Canada).

In all subject, arterial oxygen saturation was estimated using a finger pulse oximeter (Radical-7 Pulse Oximeter, Masimo, Irvine, USA).

Data Processing and Analysis. At rest and during exercise, all data were collected using a 16-channel analog-to-digital data acquisition system (PowerLab 16/35, ADInstruments, Colorado Springs, USA), sampled at 2000 Hz, and recorded using LabChart 7.3.7 software. All EMG data were analyzed at rest and during the last 30 s of each 2 min exercise stage. For each breath within a given 30 s epoch, peak RMS data for EMG_{di}, EMG_{sca} and EMG_{scm} were obtained by manually selecting RMS signals. In the case of EMG_{di}, significant cardiac artefact is present in the EMG signal (Figure 1). Thus, analysis was performed only on portions of the EMG_{di} RMS signals falling between zones of cardiac artefact. This approach has previously been used to assess EMG_{di} during exercise by us and others (6-8). EMG data for each inspiratory muscle were expressed as a percent of maximum EMG activity (10). Flow, volume, and pressures were composite averaged by selecting breaths within the same 30 s epochs as the EMG data. Diaphragm pressure-time product (PTP_{di}) and esophageal pressure-time product (PTP_{es}) were determined by integrating P_{di} and P_{es}, respectively, over time during inspiration and then multiplying these values by breathing frequency (16,36). The quotient of PTP_{di} and PTP_{es} was calculated to determine the fraction of total inspiratory muscle pressure production performed by the diaphragm.

Statistical Analysis. Descriptive characteristics, pulmonary function data, and peak exercise data were compared using a 2x2 analysis of variance for age and sex differences between the four groups. In the case of a significant interaction between age and sex, four pairwise comparisons were performed (older men vs. older women, younger men vs. younger women, older men vs. younger men, older women vs. younger women). The relationships between EMG_{di} and PTP_{di}, EMG_{sca} and PTP_{di}/PTP_{es}, and EMG_{scm} and PTP_{di}/PTP_{es} were assessed via random-coefficients regression (37). All EMG and PTP data were compared between groups at absolute $\dot{V}_E$ (i.e., 30, 50, and 70 $l \cdot min^{-1}$) and relative fractions of maximal $\dot{V}_E$ (i.e., at 20%, 40%, 60%, 80%, and 100% of maximal $\dot{V}_E$) using mixed model analyses of variance (i.e., age x sex x $\dot{V}_E$) with repeated measures on $\dot{V}_E$. In the case of a significant two-way interaction between $\dot{V}_E$ and age, $\dot{V}_E$ and sex, or a significant three-way interaction between $\dot{V}_E$, age and sex, Bonferroni-adjusted post-hoc comparisons were conducted where appropriate. All analyses were performed using a statistical software package (SPPS v20.0, IBM, Armonk, USA), and the level of statistical significance was set at $p<0.05$. All data are presented as means±SD unless otherwise noted.

RESULTS

Subject Characteristics. A subset of the subject characteristics data and peak exercise data is shown in Table 1. A more detailed description of subject characteristics, pulmonary function, and peak exercise data is reported elsewhere (13). Men were taller and heavier than women, regardless of age (both $p<0.05$). When expressed as a percentage of predicted values, resting pulmonary function was within the normal range (80-120% predicted) for all groups and did not differ on the basis of sex or age. Subjects in each group achieved near maximum heart rates based on predicted values and respiratory exchange ratios >1.10, indicating that maximal effort was exerted in all groups. There was a significant effect of sex and age on maximal inspiratory pressure (both $p<0.05$). At peak exercise, there was a significant effect of sex and age on absolute and relative $\dot{V}O_2$, as well as $\dot{V}_E$ (all $p<0.05$); however, there was no significant differences in the fractional utilization of maximum voluntary ventilation (i.e., $\dot{V}_E$/MVV) between group ($p>0.05$). When $\dot{V}O_2$ at peak exercise was expressed as a percentage of predicted values (25,26), there was no significant effect of sex or age, indicating that subjects had similar levels of relative fitness across groups. There were no significant interaction effects between age and sex on any variable at peak exercise.

Inspiratory Muscle EMG. Figure 1 shows a representative trace of the electrical activity of the diaphragm, scalene, and sternocleidomastoid muscles, as well as the corresponding esophageal pressure, transdiaphragmatic pressure, and airflow in a young female subject at three levels of relative exercise $\dot{V}_E$. Figure 2 shows the electrical activity of the inspiratory muscles as a function of absolute $\dot{V}_E$ during exercise with subjects pooled based on age (Panels A, C, and E) or sex (Panels B, D, and F). Women and older subjects had a higher EMG_{di} at $\dot{V}_E$ of 30, 50 and 70 $l \cdot min^{-1}$ (all $p<0.05$) and a higher EMG_{scm} at $\dot{V}_E$ of 50 and 70 $l \cdot min^{-1}$ than men and younger subjects, respectively (both $p<0.05$). Furthermore, regardless of age, women had a higher EMG_{sca} at $\dot{V}_E$ of 30, 50 and 70 $l \cdot min^{-1}$ than men (all $p<0.05$). When the same comparisons were repeated as a function of relative $\dot{V}_E$ (Figure 3), there were no significant effects of sex or age on EMG_{di} (all $p>0.05$). However, when compared to men, women had a higher EMG_{sca} at 20, 40, 60, 80 and 100% of peak $\dot{V}_E$ above rest and a higher EMG_{scm} at 40, 60, 80 and 100% of peak $\dot{V}_E$ (both $p<0.05$). Moreover, older subjects had a lower EMG_{sca} at 60% and 80% of maximal $\dot{V}_E$, and a higher EMG_{scm} at 40% of maximal $\dot{V}_E$ than younger subjects (all $p<0.05$). There were no significant interaction effects between sex and age.

Respiratory Pressure Generation. Figure 4 shows PTP_{di} and PTP_{es} as well as their quotient as a function of absolute $\dot{V}_E$ at rest and during exercise. Regardless of sex, older subjects had a higher PTP_{di} at $\dot{V}_E$ of 30, 50 and 70 $l \cdot min^{-1}$ than younger subjects (all $p<0.05$), and women and older subjects had a higher PTP_{es} at $\dot{V}_E$ of 30, 50 and 70 $l \cdot min^{-1}$ than men and younger subjects, respectively (all $p<0.05$). There was a significant effect of sex and age on PTP_{di}/PTP_{es} at a $\dot{V}_E$ of 70 $l \cdot min^{-1}$ (both $p<0.05$). Additionally, when the same comparisons were repeated with $\dot{V}_E$ expressed in relative terms (Figure 5), there were no significant effects of sex or age on PTP_{di}, PTP_{es} or PTP_{di}/PTP_{es} (all $p>0.05$). There were no significant interaction effects between sex and age.

Association Between Inspiratory Muscle Activation and Pressure Generation. Assessing the link between electrical activity of the inspiratory muscles and measures of pressure generation is complicated by the fact that the diaphragm is the only respiratory muscle where the pressure resulting from its contraction can be measured directly (38). To confirm that an increase in EMG_{di} was in fact associated with an increase in P_{di} generation, we assessed the relationship between EMG_{di} and PTP_{di} across all subjects and found that there was a strong, significant correlation (r=0.92, $p<0.001$). While this same analysis cannot be performed for the scalene or the sternocleidomastoid, it can be surmised that as the relative contribution of the diaphragm to total inspiratory pressure generation decreases, the balance must be performed by the extra-diaphragmatic inspiratory muscles (4). We found a significant negative correlation between EMG_{sca} and PTP_{di}/PTP_{es} (r=0.63, $p<0.001$), as well as EMG_{scm} and PTP_{di}/PTP_{es} (r=0.58, $p<0.01$). Lastly, there were no significant effects of sex or age on the slopes of the regressions lines for EMG_{di} and PTP_{di}, EMG_{sca} and PTP_{di}/PTP_{es}, and EMG_{scm} and PTP_{di}/PTP_{es} (all $p>0.05$).

DISCUSSION

Major Findings. We assessed the effects of age and sex on inspiratory muscle activation patterns during incremental exercise in healthy subjects. The major findings were three-fold. First, regardless of age, women relied on scalene and sternocleidomastoid muscles to a greater extent during exercise than did men. Second, regardless of sex, older subjects relied on sternocleidomastoid muscles to a greater extent during exercise than did younger subjects. Third, the effects of sex and age on inspiratory muscle activation patterns corresponded to measures of inspiratory pressure generation when comparisons were made as a function of absolute but not relative $\dot{V}_E$, whereby women and older subjects had a lower diaphragmatic contribution to total inspiratory pressure generation at a $\dot{V}_E$ of 70 $l \cdot min^{-1}$ than men and younger subjects, respectively. Collectively, our findings suggest that age and sex have significant independent effects on inspiratory muscle activation patterns during exercise, but that the magnitude of the effect depends on if comparisons are made at relative or absolute $\dot{V}_E$.

Sex-Differences in Inspiratory Muscle Activation Patterns. Given that women have a higher mechanical and metabolic cost of breathing for a given absolute $\dot{V}_E$ (14), we would expect women's inspiratory muscles to exhibit a correspondingly higher degree of relative activation. When older and younger subjects were pooled, we found that at a $\dot{V}_E$ of 30, 50, and 70 $l \cdot min^{-1}$ women had higher relative EMG_{di} than men (Figure 2, Panel B), a finding that is in keeping with a previous study in healthy young men and women (6). Although the increased activation of the diaphragm in women relative to men likely contributes to accomplishing the increased work required to breathe, it has been suggested that women may also have a greater activation of the extra-diaphragmatic inspiratory muscles than men (6,16). A recent study in healthy young individuals found that women activate their scalene and sternocleidomastoid muscles to a greater extent than men during constant-load cycle exercise at 85% peak work rate (17); however, these data may be affected by the ventilatory response to constant-load exercise or the potential presence of diaphragm fatigue, both of which have been shown to differ on the basis of biological sex (16). In the current study, we simultaneously assessed the electrical activity of the diaphragm, scalene, and sternocleidomastoid muscles during incremental exercise to enable the comparison of inspiratory muscle activation patterns between groups across a wide range of $\dot{V}_E$. Additionally, diaphragm fatigue is unlikely to occur during incremental exercise to exhaustion (39). We observed that, in addition to a higher EMG_{di}, women had substantially greater EMG_{sca} at a $\dot{V}_E$ of 30, 50, and 70 $l \cdot min^{-1}$, and EMG_{scm} at a $\dot{V}_E$ of 50, and 70 $l \cdot min^{-1}$ than men (Figure 2, Panels D and F). The important question then becomes: does the increased activation of the accessory muscles correspond to increased inspiratory pressure generation? We found that at a $\dot{V}_E$ of 30, 50, and 70 $l \cdot min^{-1}$, women had a higher PTP_{es} but a statistically similar PTP_{di} than men (Figure 4, Panels B and D). We also observed that the diaphragm contributed significantly less to total inspiratory pressure generation at a $\dot{V}_E$ of 70 $l \cdot min^{-1}$ in women than in men (Figure 4, Panel F).

When comparisons were made as a function of relative $\dot{V}_E$, women still had a higher EMG_{sca} and EMG_{scm}, but a similar EMG_{di} (Figure 3, Panels D and F). However, despite the higher EMG_{sca} and EMG_{scm}, there were no significant differences in PTP_{es} or PTP_{di} for a given relative $\dot{V}_E$ (Figure 5, Panels B and D). Our finding that women have a higher EMG_{sca} and EMG_{scm} at 20, 40, 60, 80, and 100% of maximal $\dot{V}_E$ could be due to four potential factors. First, we previously found that younger women have lower respiratory muscle efficiency than younger men at any fraction of maximal $\dot{V}_E$ while accurately mimicking exercise hyperpnea (14). The increased activation of the scalene and sternocleidomastoid in the absence of increased inspiratory pressure generation could be a reflection of sex-differences in efficiency respiratory muscles. Second, women have smaller absolute lung volumes than men which is thought to affect the regulation of operating lung volumes and breathing pattern during exercise (40). In the present cohort of subjects, we previously showed that sex had no effect on operating lung volumes (when expressed relative to total lung capacity) during exercise, but that women had the tendency to adopt a relatively rapid and shallow breathing pattern compared to men (13). Thus, it is likely that sex-differences in breathing pattern during exercise influence inspiratory muscle activation patterns. Third, contraction of the scalene and sternocleidomastoid muscles during inspiration serves to increase tidal volume by expanding the volume of the rib cage (1). Therefore, if women rely on the scalene and sternocleidomastoid muscles during inspiration more than do men, one would expect to observe a corresponding sex-difference in rib cage and abdominal volumes during exercise. Using optoelectronic plethysmography, it has been shown that women expand tidal volume during incremental exercise by increasing chest wall volume to a greater extent and increasing abdominal volume to a similar extent than men (41). It is possible that some of the work done on the chest wall by the scalenes and sternocleidmastoids is not accounted for by measures of P_{es} and P_{di} (4). Lastly, the aforementioned sex-differences in the volume of the chest wall likely alters the length of the scalene and sternocleidomastoid, which would in turn affect the level of muscle activation required to generate a given pressure (42). Collectively, we interpret our findings to mean that regardless of age, women recruit their scalene and sternocleidomastoid muscles during exercise to a greater extent than do men. This apparent sex-difference in the pattern of inspiratory muscle activation during exercise may reflect sex-differences in work of breathing in women, breathing pattern, respiratory muscle efficiency, chest wall kinematics, or a combination thereof.

Effect of Aging on Inspiratory Muscle Activation Patterns. The healthy aging process is known to decrease the strength of the respiratory muscles (20), and to increase the mechanical and metabolic costs of breathing during exercise (43). It follows that the increased load on the respiratory muscles during exercise in older individuals may alter the pattern of inspiratory muscle activation. We found that independent of sex, aging was associated with a higher EMG_{di} at $\dot{V}_E$ of 30, 50, and 70 $l{\cdot}min^{-1}$, and a higher EMG_{scm} at $\dot{V}_E$ of 50 and 70 $l{\cdot}min^{-1}$, but a similar EMG_{sca} at a $\dot{V}_E$ of 30, 50, and 70 $l{\cdot}min^{-1}$ (Figure 2, Panels C and E). Additionally, PTP_{di} and PTP_{es} were greater in the older subjects than the younger subjects at $\dot{V}_E$ of 30, 50, and 70 $l{\cdot}min^{-1}$ (Figure 4, Panels A and C). When comparisons were made as a function of relative $\dot{V}_E$, we found that older subjects had a similar EMG_{di}, a lower EMG_{sca} at 40, 60, and 80% of maximal $\dot{V}_E$, and a higher EMG_{scm} at 40% of maximal $\dot{V}_E$ than younger subjects (Figure 3, Panels A, C, and E), whereas there was no significant effect of age on PTP_{di} or PTP_{es} (Figure 5, Panels C and E).

Older individuals have a higher work of breathing for a given $\dot{V}_E$ and breathe at a higher fraction of total lung capacity than younger individuals (19). The higher work of breathing in older individuals requires increased inspiratory muscle activation, which is evidenced in our study by a higher diaphragm and sternocleidomastoid activation at a $\dot{V}_E$ of 30, 50, and 70 $l{\cdot}min^{-1}$ (Figure 3). Breathing at a higher fraction of total lung capacity does not necessarily require a greater degree of inspiratory muscle work, unless breathing occurs along the relatively flat portion of the pressure-volume relationship of the respiratory system. However, lung volume is known to affect inspiratory muscle activation patterns (42). the sternocleidomastoid starts becoming active once tidal volume encroaches on approximately 70% of inspiratory capacity (5), which is likely to occur at a lower absolute and relative $\dot{V}_E$ in older individuals due to the age-related decrease in ventilatory efficiency (44). Indeed, the older subjects in our study had greater end-expiratory lung volumes, but similar end-inspiratory lung volumes, at rest and throughout incremental exercise, as described elsewhere (13). Overall, it would seem that aging affects inspiratory muscle activation via its impact on total respiratory muscle work and the regulation of operating lung volumes during exercise.

Combined Influence of Sex and Age on Inspiratory Muscle Activation Patterns. It should be noted that we did not find a statistically significant interaction effect between sex and age on any measure within the current study. We interpret this to mean that during exercise, the effect of aging on the pattern of inspiratory muscle activation is similar in men and women, and that the effect of sex on the pattern of inspiratory muscle activation is present regardless of age. Thus, we believe that biological sex and healthy aging exert independent influences on the activation of inspiratory muscles during incremental exercise.

Association Between Inspiratory Muscle Activation and Pressure Generation. We are cognizant that increased EMG activity does not equate directly to increased force production (or in this case, pressure generation) by a muscle. However, we did observe a significant linear relation between absolute EMG_{di} and PTP_{di} across all subjects, whereby 84% of the variance in PTP_{di} was explained by EMG_{di}. We also assessed the relationship between EMG_{sca} and PTP_{di}/PTP_{es} as well as EMG_{scm} and PTP_{di}/PTP_{es} under the pretext that as the relative contribution of the diaphragm to overall inspiratory pressure generation decreased, that the activation of extra-diaphragmatic inspiratory muscles (such as the scalene and sternocleidomastoid) would increase. Indeed, we found a significant negative correlation between EMG_{sca} and PTP_{di}/PTP_{es} as well as EMG_{scm} and PTP_{di}/PTP_{es}, with PTP_{di}/PTP_{es} explaining 40% and 34% of the variance in EMG_{sca} and EMG_{scm}, respectively. Nevertheless, there are some considerations with respect to our findings and interpretation that merit discussion. The fact that we observed sex- and age-related differences in EMG_{sca} and EMG_{scm} when $\dot{V}_E$ was expressed in relative terms despite no significant differences in PTP_{es} and PTP_{di} implies that: i) there is increased inspiratory muscle activation that does not result in increased muscular work, and/or ii) that there is work conducted on the structures of the respiratory system that are not accounted for by P_{es} and P_{di}. Another caveat of this approach is that we are not recording the electrical activity of all muscles involved in inspiration. Therefore, it is likely that a portion of the inspiratory pressure generation is not explained by the activation of the diaphragm, scalene, or sternocleidomastoid muscles. We propose that the discrepancy between electrical activity of the inspiratory muscles we assessed and the associated pressure generation is likely related to a combination of the aforementioned factors. Clearly, additional research is required to further characterize the link between age- and sex-differences in respiratory mechanics and respiratory muscle activation patterns.

Limitations. There are important limitations of our study that merit discussion. First, we did not assess the activity of the expiratory muscles, which could also be affected by biological sex and the aging process. We chose to focus on the inspiratory muscles due to the fact that during cycle exercise (where head movement is minimized), the scalene, sternocleidomastoid, and diaphragm muscles perform functions that are almost exclusively related to breathing. By contrast, expiratory muscles (e.g., rectus abdominis) are active independent of breathing in order to ensure trunk stability. The presence of non-respiratory muscle activity would have greatly impacted our ability to address our primary hypotheses. Second, the intricate anatomical arrangement of the respiratory muscles, particularly the scalene and sternocleidomastoid muscles, presents a significant difficulty in accurately measuring the electrical activity of the respiratory muscles in humans. Given the proximity of the scalene and sternocleidomastoid muscles to one another, it is possible that our measures of the electrical activity of these two muscles were affected by “cross-talk” from the surrounding musculature. While there is no way of eliminating this possibility, we took great care placing the surface electrodes on the precise anatomical location of each muscle and ensured that the subjects limited unnecessary head or neck movement during analysis periods. Third, although it is unlikely to have occurred, we cannot conclusively eliminate the possibility that diaphragm, scalene, and/or sternocleidomastoid fatigue were present following incremental exercise. Fourth, our recordings of the electrical activity of respiratory muscles were made using skin surface electrodes and therefore were susceptible to artifact due to factors such as inter-individual differences in subcutaneous adipose tissue. We minimized this source of error by normalizing EMG signals to the maximal level of activity achieved during a volitional inspiratory maneuver on a muscle-specific and subject-specific basis. Lastly, our measure of EMG_{di} only represents crural diaphragm activation, and does not represent costal diaphragm activation (27). By contrast, P_{di} represents overall diaphragm pressure generation. It is possible therefore that some of the pressure generated by the diaphragm during inspiration was not captured by the esophageal electrode catheter.

Perspectives. There are several potential implications of age- and sex-differences in inspiratory muscle activation during exercise. First, we’ve previously shown that the variable patterns of inspiratory muscle activity during a single bout of inspiratory muscle training (45). Based on our present findings, it is reasonable to assume that the response to an inspiratory muscle training program may differ on the basis of age and sex. Second, the perception of dyspnea during exercise at an absolute work rate is higher in older individuals and women than in younger individuals and men, respectively (46,47). The increased motor output to the scalene and the sternocleidomastoid could increase the perception of dyspnea (48). It is therefore possible that age- and sex-differences in inspiratory muscle activation may be involved in age- and sex-differences in dyspnea. Third, the oxygen cost of breathing reflects the collective metabolic cost of generating a given $\dot{V}_E$, which is directly influenced by the mechanical cost and the efficiency of the respiratory muscles (14). For a given mechanical work of breathing, it is possible that activation of extra-diaphragmatic muscles results in a lower overall respiratory muscle efficiency, which would increase the oxygen cost of breathing. Thus, the observed patterns of inspiratory muscle activation may be associated, at least in part, with age- and sex-differences in the oxygen cost of breathing (14,43). While the abovementioned implications are physiologically plausible, we emphasize that further research is required in order to elucidate the implications of our findings.

Conclusions. During incremental exercise, biological sex and the aging process influence the pattern of inspiratory muscles activation in healthy humans; however, the extent of the effects of sex and age depends on whether comparisons are made at absolute or relative $\dot{V}_E$. We noted that women had a greater activation of the diaphragm, scalene, and sternocleidomastoid muscles during exercise than men at absolute $\dot{V}_E$ of 30, 50 and 70 $l \cdot min^{-1}$. Moreover, the effect of sex on scalene and sternocleidomastoid activation was still present when comparisons were made as a function of relative $\dot{V}_E$ above rest. We also found that older subjects exhibited a greater degree of diaphragm activation at absolute $\dot{V}_E$ of 30, 50 and 70 $l \cdot min^{-1}$, and higher sternocleidomastoid muscle activation at absolute $\dot{V}_E$ of 50 and 70 $l \cdot min^{-1}$. The effect of age on sternocleidomastoid activation was still present at 20% of maximal $\dot{V}_E$, but older subjects had lower scalene activity than younger subjects at 40, 60 and 80% of maximal $\dot{V}_E$. Overall, our results suggest that the increased pressure required to generate a given $\dot{V}_E$ during exercise in women and older individuals is achieved by recruiting diaphragm and extra-diaphragmatic muscles, such as scalenes and sternocleidomastoids, to a greater extent than in men and younger individuals, respectively. However, there were no age or sex-differences in indices of inspiratory pressure generation at relative fractions of maximal $\dot{V}_E$, suggesting that effects of age and sex on inspiratory muscle activation may also be related to other factors such as differences in respiratory kinematics or respiratory muscle efficiency. The effect of age and sex on inspiratory muscle activation may have implications for the integrated physiological response to exercise.

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Conflicts of Interest: YM, PBD, AHR, MRS, LMR, JDR, JAG, and AWS do not have any conflicts of interest to report relevant to this manuscript. The results of the present study do not constitute endorsement by ACSM. The results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

REFERENCES

1. Rankin J, Dempsey JA. Respiratory muscles and the mechanisms of breathing. Am J Phys Med. 1967 Feb;46(1):198–244.
2. Raper AJ, Thompson WT, Shapiro W, Patterson JL. Scalene and sternomastoid muscle function. J Appl Physiol. 1966 Mar;21(2):497–502.
3. Levine S, Gillen M, Weiser P, Feiss G, Goldman M, Henson D. Inspiratory pressure generation: comparison of subjects with COPD and age-matched normals. J Appl Physiol. American Physiological Society; 1988 Aug;65(2):888–99.
4. Grimby G, Goldman M, Mead J. Respiratory muscle action inferred from rib cage and abdominal V-P partitioning. J Appl Physiol. 1976 Nov;41(5 Pt. 1):739–51.
5. Campbell E. The role of the scalene and sternomastoid muscles in breathing in normal subjects - an electromyographic study. J Anat. 1955;89(3):378–86.
6. Schaeffer MR, Mendonca CT, Levangie MC, Andersen RE, Taivassalo T, Jensen D. Physiological mechanisms of sex differences in exertional dyspnoea: role of neural respiratory motor drive. Exp Physiol. 2014 Feb;99(2):427–41.
7. Ramsook AH, Molgat-Seon Y, Schaeffer MR, Wilkie SS, Camp PG, Reid WD, et al. Effects of inspiratory muscle training on respiratory muscle electromyography and dyspnea during exercise in healthy men. J Appl Physiol. 2017 May 1;122(5):1267–75.
8. Faisal A, Alghamdi BJ, Ciavaglia CE, Elbehairy AF, Webb KA, Ora J, et al. Common Mechanisms of Dyspnea in Chronic Interstitial and Obstructive Lung Disorders. Am J Respir Crit Care Med. 2016 Feb 1;193(3):299–309.
9. Qin YY, Steier J, Jolley C, Moxham J, Zhong NS. Efficiency of neural drive during

exercise in patients with COPD and healthy subjects. Chest. 2010;138(6):1309–15.

10. Jolley CJ, Luo Y-M, Steier J, Reilly C, Seymour J, Lunt A, et al. Neural respiratory drive in healthy subjects and in COPD. Eur Repir J. European Respiratory Society; 2009 Feb;33(2):289–97.

11. Rohrer F. Der Strömungswiderstand in den menschlichen Atemwegen und der Einfluss der unregelmässigen Verzweigung des Bronchialsystems auf den Atmungsverlauf in …. Pflügers Arch Ges Physiol. 1915;162(5-6):225–99.

12. Otis AB, Fenn WO, Rahn H. Mechanics of breathing in man. J Appl Physiol. Am Physiological Soc; 1950;2(11):592–607.

13. Molgat-Seon Y, Dominelli PB, Ramsook AH, Schaeffer MR, Molgat Sereacki S, Foster GE, et al. The effects of age and sex on mechanical ventilatory constraint and dyspnea during exercise in healthy humans. J Appl Physiol. 2017 doi: 10.1152/japplphysiol.00608.2017.

14. Dominelli PB, Render JN, Molgat-Seon Y, Foster GE, Romer LM, Sheel AW. Oxygen cost of exercise hyperpnoea is greater in women compared with men. J Physiol. 2015 Apr 15;593(8):1965–79.

15. Dominelli PB, Molgat-Seon Y, Bingham D, Swartz PM, Road JD, Foster GE, et al. Dysanapsis and the resistive work of breathing during exercise in healthy men and women. J Appl Physiol. American Physiological Society; 2015 Nov 15;119(10):1105–13.

16. Guenette JA, Romer LM, Querido JS, Chua R, Eves ND, Road JD, et al. Sex differences in exercise-induced diaphragmatic fatigue in endurance-trained athletes. J Appl Physiol. 2010;109(1):35–46.

17. Mitchell RA, Schaeffer MR, Ramsook AH, Wilkie SS, Guenette JA. Sex differences in

respiratory muscle activation patterns during high-intensity exercise in healthy humans. Respir Physiol Neurobiol. 2017 Sep 7;247:57–60.

18. Janssens JP, Pache JC, Nicod LP. Physiological changes in respiratory function associated with ageing. Eur Respir J. 1999 Jan;13(1):197–205.
19. Johnson BD, Dempsey JA. Demand vs. capacity in the aging pulmonary system. Exerc Sport Sci Rev. 1991;19:171–210.
20. Enright PL, Kronmal RA, Manolio TA, Schenker MB, Hyatt RE. Respiratory muscle strength in the elderly. Correlates and reference values. Am J Respir Crit Care Med. 1994 Feb;149(2 Pt 1):430–8.
21. Elliott JE, Greising SM, Mantilla CB, Sieck GC. Functional impact of sarcopenia in respiratory muscles. Respir Physiol Neurobiol. 2016 Jun;226:137–46.
22. Burrows B, Kasik JE, Niden AH, Barclay WR. Clinical usefulness of the single-breath pulmonary diffusing capacity test. Am Rev Respir Dis. 1961 Dec;84(6):789–806.
23. Crapo RO, Morris AH, Clayton PD, Nixon CR. Lung volumes in healthy nonsmoking adults. Bull Eur Physiopathol Respir. 1982 May;18(3):419–25.
24. Morris JF. Fifteen-year interval spirometric evaluation of the Oregon predictive equations. Chest. American College of Chest Physicians; 1988 Jan 1;93(1):123–7.
25. Jones NL, Makrides L, Hitchcock C, Chypchar T, McCartney N. Normal standards for an incremental progressive cycle ergometer test. Am Rev Respir Dis. 1985 May;131(5):700–8.
26. Blackie SP, Fairbarn MS, McElvaney GN, Morrison NJ, Wilcox PG, Pardy RL. Prediction of maximal oxygen uptake and power during cycle ergometry in subjects older than 55 years of age. Am Rev Respir Dis. 1989 Jun;139(6):1424–9.

27. Luo Y-M, Moxham J, Polkey MI. Diaphragm electromyography using an oesophageal catheter: current concepts. Clin Sci. 2008 Oct;115(8):233–44.

28. Zin WA, Milic-Emili J. Esophageal Pressure Measurement. In: Hamid Q, Shannon J, Martin J, editors. Physiologic basis of respiratory disease. 1st ed. Hamilton, ON; 2005. pp. 639–47.

29. Baydur A, Behrakis PK, Zin WA, Jaeger M, Milic-Emili J. A simple method for assessing the validity of the esophageal balloon technique. Am Rev Respir Dis. 1982 Nov;126(5):788–91.

30. Green M, Road J, Sieck GC, Similowski T. Tests of respiratory muscle strength. Am J Respir Crit Care Med. 2002;166(4):528–47.

31. MacIntyre N, Crapo RO, Viegi G, Johnson DC, van der Grinten CPM, Brusasco V, et al. Standardisation of the single-breath determination of carbon monoxide uptake in the lung. Eur Respir J. 2005 Oct;26(4):720–35.

32. Miller MR, Hankinson J, Brusasco V, Burgos F, Casaburi R, Coates A, et al. Standardisation of spirometry. Eur Respir J. 2005 Aug;26(2):319–38.

33. Wanger J, Clausen JL, Coates A, Pedersen OF, Brusasco V, Burgos F, et al. Standardisation of the measurement of lung volumes. Eur Respir J. 2005 Sep;26(3):511–22.

34. Guenette JA, Chin RC, Cory JM, Webb KA, O'Donnell DE. Inspiratory capacity during exercise: measurement, analysis, and interpretation. Pulm Med. Hindawi; 2013;2013:956081.

35. Sinderby C, Beck J, Spahija J, Weinberg J, Grassino A. Voluntary activation of the human diaphragm in health and disease. J Appl Physiol. 1998 Dec;85(6):2146–58.

36. Romer LM, Lovering AT, Haverkamp HC, Pegelow DF, Dempsey JA. Effect of inspiratory muscle work on peripheral fatigue of locomotor muscles in healthy humans. J Physiol. Blackwell Science Ltd; 2006 Mar 1;571(Pt 2):425–39.

37. Xu RH. Measuring explained variation in linear mixed effects models. Stat Med. John Wiley & Sons, Ltd; 2003;22(22):3527–41.

38. Dempsey JA, Adams L, Ainsworth DM, Fregosi RF, Gallagher CG, Guz A, et al. Airway, lung, and respiratory muscle function during exercise. In: Handbook of Physiology. Hoboken, NJ, USA: John Wiley & Sons, Inc; 1996. pp. 448–514.

39. Romer LM, Miller JD, Haverkamp HC, Pegelow DF, Dempsey JA. Inspiratory muscles do not limit maximal incremental exercise performance in healthy subjects. Respir Physiol Neurobiol. 2007 Jun 15;156(3):353–61.

40. McClaran SR, Harms CA, Pegelow DF, Dempsey JA. Smaller lungs in women affect exercise hyperpnea. J Appl Physiol. 1998;84(6):1872–81.

41. Layton AM, Garber CE, Thomashow BM, Gerardo RE, Emmert-Aronson BO, Armstrong HF, et al. Exercise ventilatory kinematics in endurance trained and untrained men and women. Respir Physiol Neurobiol. 2011 Sep 15;178(2):223–9.

42. Brancatisano A, Engel LA, Loring SH. Lung volume and effectiveness of inspiratory muscles. J Appl Physiol. 1993 Feb;74(2):688–94.

43. Takishima T, Shindoh C, Kikuchi Y, Hida W, Inoue H. Aging effect on oxygen consumption of respiratory muscles in humans. J Appl Physiol. 1990 Jul;69(1):14–20.

44. Patrick JM, Bassey EJ, Fentem PH. The rising ventilatory cost of bicycle exercise in the seventh decade: a longitudinal study of nine healthy men. Clin Sci. Portland Press Limited; 1983 Nov 1;65(5):521–6.

45. Ramsook AH, Koo R, Molgat-Seon Y, Dominelli PB, Syed N, Ryerson CJ, et al. Diaphragm recruitment increases during a bout of targeted inspiratory muscle training. Med Sci Sports Exerc. 2016 Jun;48(6):1179–86.

46. Cory JM, Schaeffer MR, Wilkie SS, Ramsook AH, Puyat JH, Arbour B, et al. Sex differences in the intensity and qualitative dimensions of exertional dyspnea in physically active young adults. J Appl Physiol. American Physiological Society; 2015 Nov 1;119(9):998–1006.

47. Ofir D, Laveneziana P, Webb KA, Lam Y-M, O'Donnell DE. Sex differences in the perceived intensity of breathlessness during exercise with advancing age. J Appl Physiol. 2008;104(6):1583–93.

48. Gigliotti F. Mechanisms of dyspnea in healthy subjects. Multidisciplinary Respiratory Medicine 2010 5:1. 2010 Jun 30;5(3):195–201.

FIGURE LEGENDS

Figure 1. Representative traces of the electrical activity of the diaphragm, scalene, and sternocleidomastoid, esophageal pressure, transdiaphragmatic pressure, and airflow at three relative levels of $\dot{V}_E$ (60%, 80%, and 100%) in a young female subject. The grey shaded areas denote periods of expiration. EMG_{di}, electromyogram of the diaphragm; EMG_{sca}, electromyogram of the scalene; EMG_{scm}, electromyogram of the sternocleidomastoid; P_{es}, esophageal pressure; P_{di}, transdiaphragmatic pressure.

Figure 2. Electrical activity of the diaphragm, scalene, and sternocleidomastoid as a function of absolute minute ventilation during incremental cycle exercise in older men and women (Panels A, C, and E) as well as younger men and women (Panels B, D, and F). Subjects were compared at rest, at a $\dot{V}_E$ of 30 $l\cdot min^{-1}$, 50 $l\cdot min^{-1}$, and 70 $l\cdot min^{-1}$, and at peak exercise. Dashed lines within each group connect the 70 $l\cdot min^{-1}$ data point to the peak exercise data point. All EMG data were transformed into root-mean-square with 100 ms time constant, and subsequently average on a breath-by-breath basis. Data are presented as mean±SD. $\dot{V}_E$, minute ventilation; EMG_{di}, electromyogram of the diaphragm; EMG_{sca}, electromyogram of the scalene; EMG_{scm}, electromyogram of the sternocleidomastoid. * $p<0.05$, main effect of age (comparisons made between all older and all younger subjects, regardless of sex). † $p<0.05$, main effect of sex (comparisons made between all men and all women, regardless of age). No significant interaction effect was noted.

Figure 3. Electrical activity of the diaphragm, scalene, and sternocleidomastoid as a function of

relative minute ventilation during incremental cycle exercise in older men and women (Panels A, C, and E) as well as younger men and women (Panels B, D, and F). Subjects were compared at rest, as well as at 20%, 40%, 60%, 80%, and 100% of peak work rate. All EMG data were transformed into RMS with 100 ms time constant, and subsequently average on a breath-by-breath basis. Data are presented as mean±SD. $\dot{V}_E$, minute ventilation; EMG_{di}, electromyogram of the diaphragm; EMG_{sca}, electromyogram of the scalene; EMG_{scm}, electromyogram of the sternocleidomastoid. * $p<0.05$, main effect of age (comparisons made between all older and all younger subjects, regardless of sex). † $p<0.05$, main effect of sex (comparisons made between all men and all women, regardless of age). No significant interaction effect was noted.

Figure 4. Transdiaphragmatic and esophageal pressure-time products, as well as their quotient, as a function of absolute minute ventilation during incremental cycle exercise in older men and women (Panels A, C, and E) as well as younger men and women (Panels B, D, and F). Subjects were compared at rest, 30 $l \cdot min^{-1}$, 50 $l \cdot min^{-1}$, 70 $l \cdot min^{-1}$, and at peak exercise. Dashed lines within each group connect the 70 $l \cdot min^{-1}$ data point to the peak exercise data point. Data are presented as mean±SD. $\dot{V}_E$, minute ventilation; PTP_{di}, transdiaphragmatic pressure-time product; PTP_{es}, esophageal pressure-time product. * $p<0.05$, main effect of age (comparisons made between all older and all younger subjects, regardless of sex). † $p<0.05$, main effect of sex (comparisons made between all men and all women, regardless of age). No significant interaction effect was noted.

Figure 5. Transdiaphragmatic and esophageal pressure-time products, as well as their quotient as a function of relative minute ventilation during incremental cycle exercise in older men and

women (Panels A, C, and E) as well as younger men and women (Panels B, D, and F). Subjects were compared at rest, as well as at 20%, 40%, 60%, 80, and 100% of peak work rate. Data are presented as mean±SD. $\dot{V}_E$, minute ventilation; EMG_{di}, electromyogram of the diaphragm; EMG_{sca}, electromyogram of the scalene; electromyogram of the sternocleidomastoid. * $p<0.05$, main effect of age (comparisons made between all older and all younger subjects, regardless of sex). † $p<0.05$, main effect of sex (comparisons made between all men and all women, regardless of age). No significant interaction effect was noted.

Figure 1

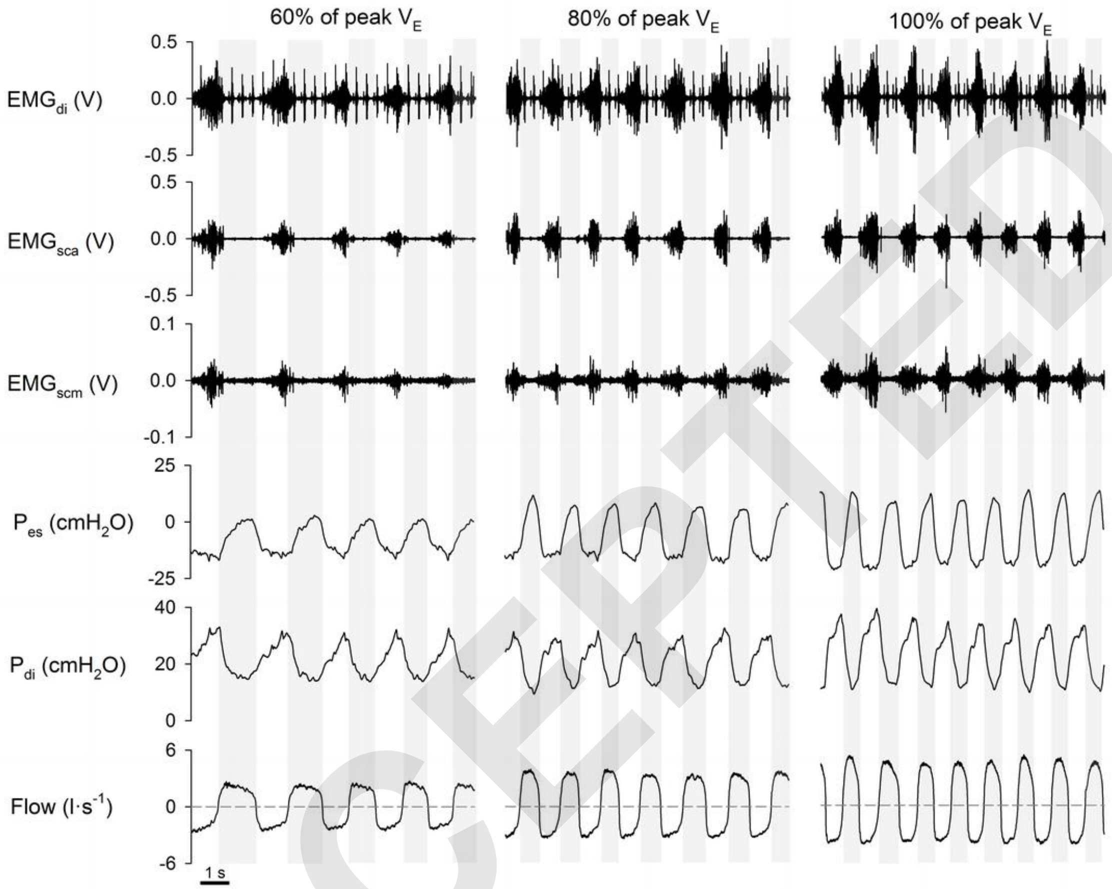

60% of peak V_E
80% of peak V_E
100% of peak V_E
EMG_{di} (V)
0.5
0.0
-0.5
EMG_{sca} (V)
0.5
0.0
-0.5
EMG_{scm} (V)
0.1
0.0
-0.1
P_{es} (cmH_2O)
25
0
-25
P_{di} (cmH_2O)
40
20
0
Flow ($l \cdot s^{-1}$)
6
0
-6
1 s

Figure 2

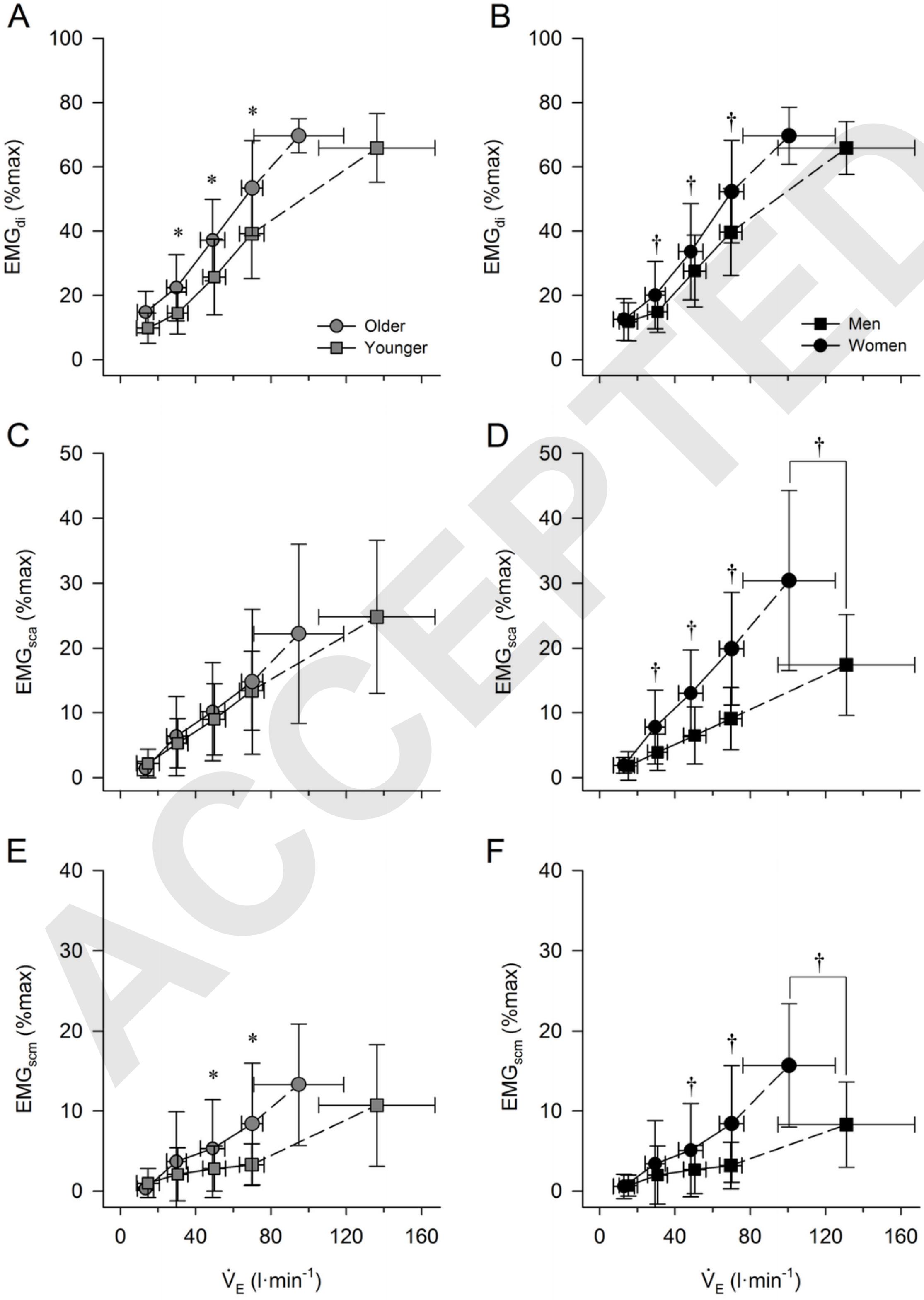

A
B
C
D
E
F
EMG$_{di}$ (%max)
EMG$_{sca}$ (%max)
EMG$_{scm}$ (%max)
100
80
60
40
20
0
50
40
30
20
10
0
40
30
20
10
0
0
40
80
120
160
$\dot{V}_E$ (l·min^{-1})
Older
Younger
Men
Women
*
†

Figure 3

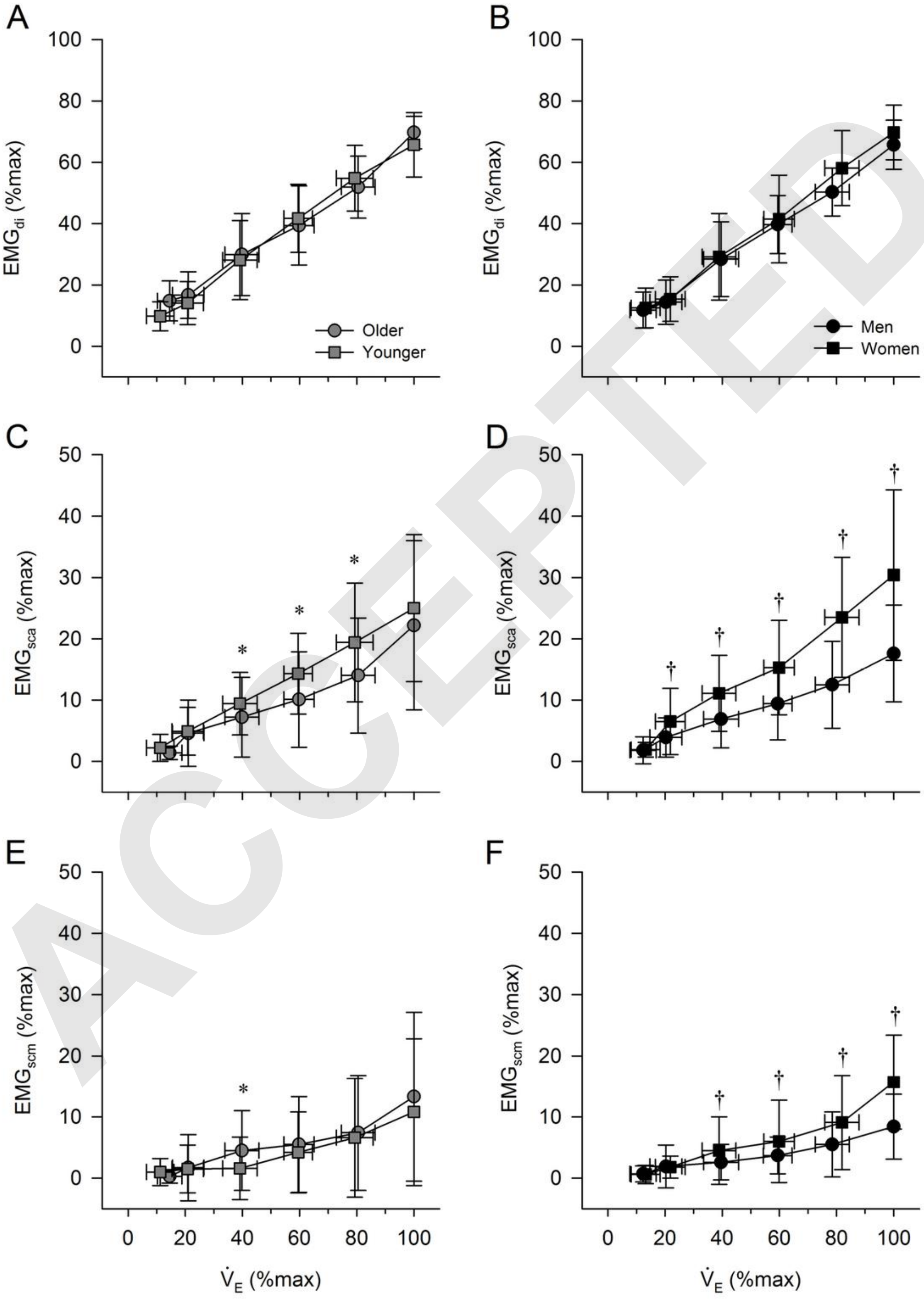

A
B
C
D
E
F
EMG$_{di}$ (%max)
EMG$_{sca}$ (%max)
EMG$_{scm}$ (%max)
Older
Younger
Men
Women
*
†
0
20
40
60
80
100
$\dot{V}_E$ (%max)
$\dot{V}_E$ (%max)

Figure 4

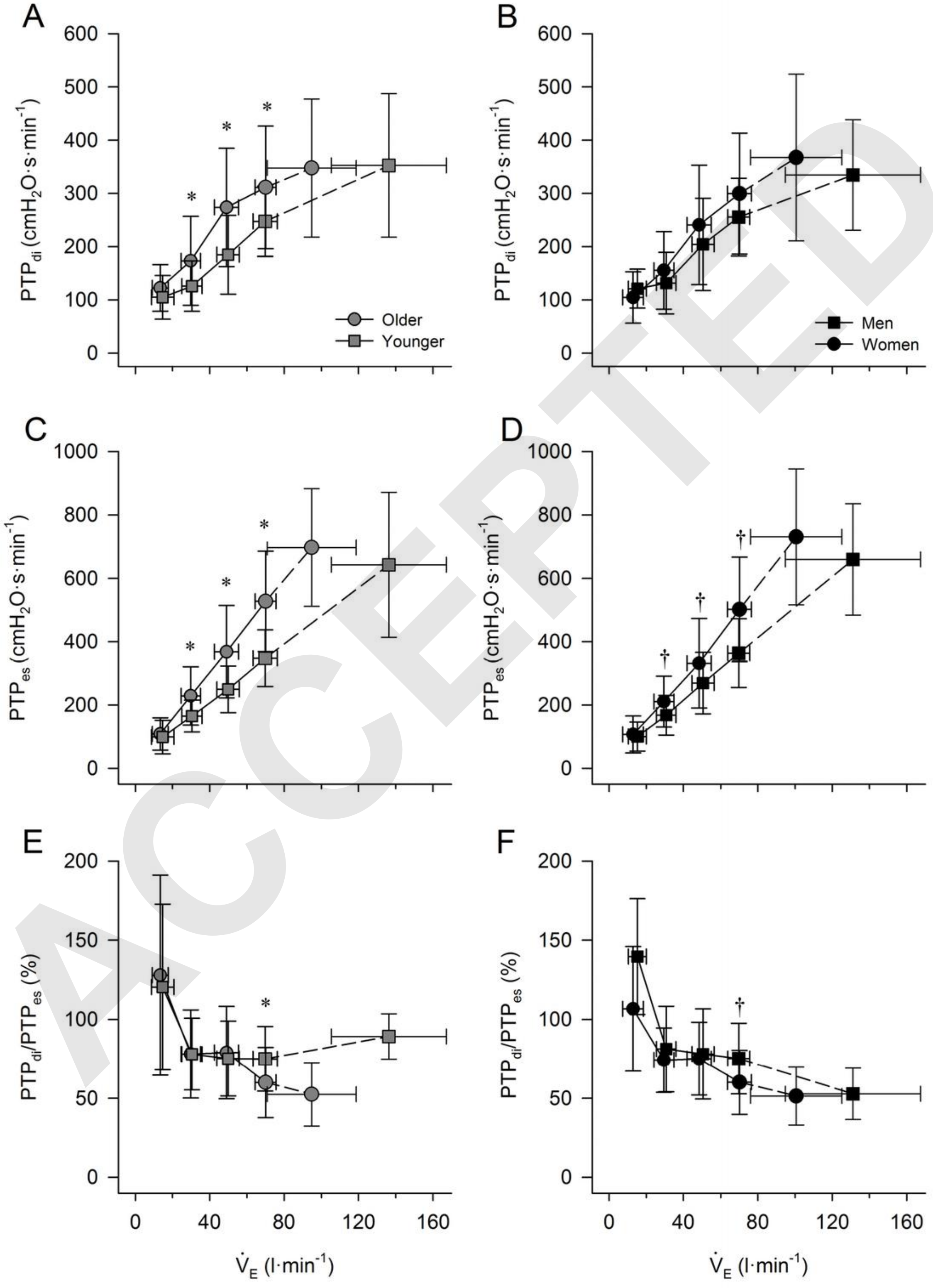
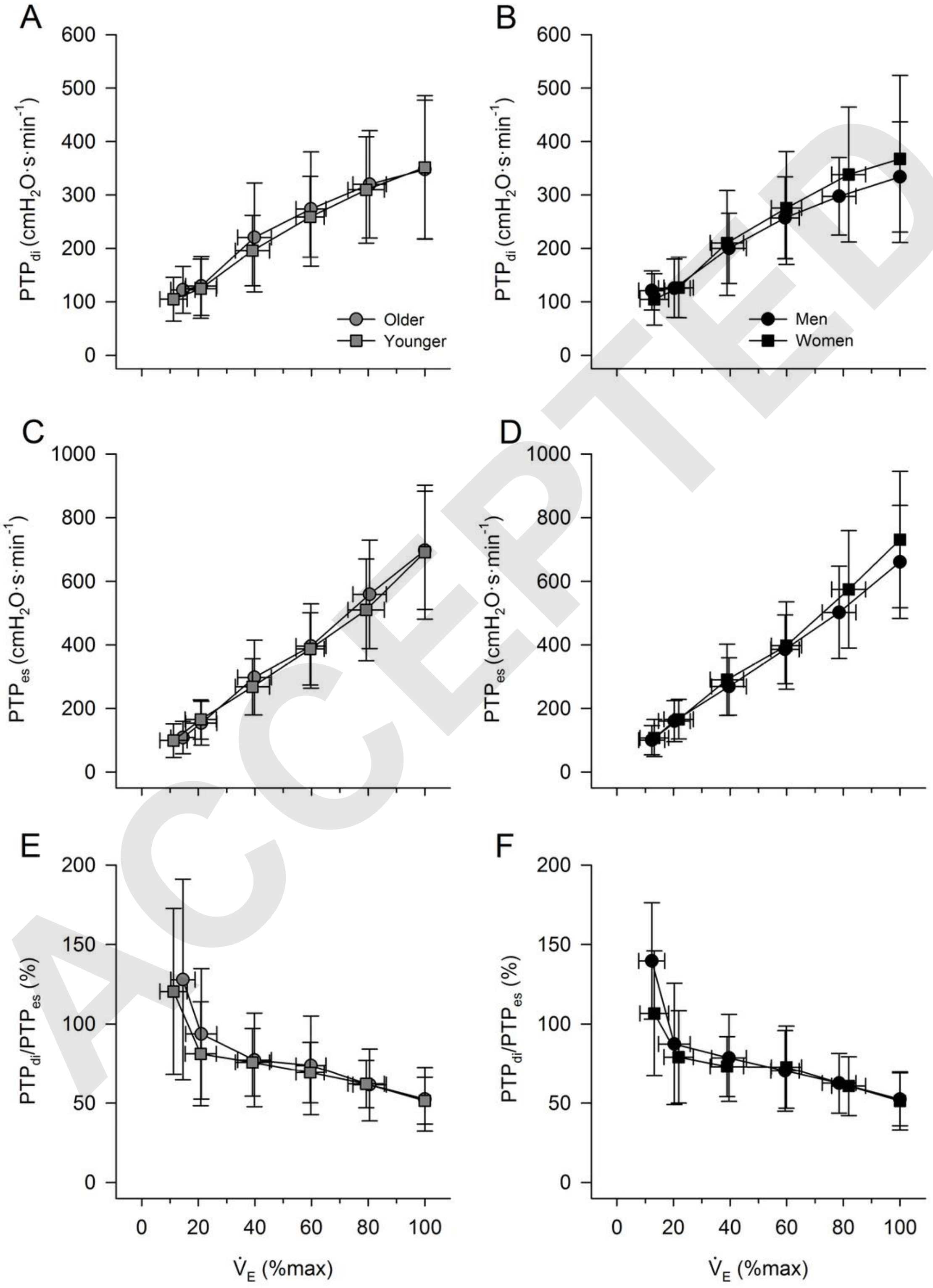

A
B
C
D
E
F
PTP$_{di}$ (cmH$_2$O·s·min^{-1})
PTP$_{es}$ (cmH$_2$O·s·min^{-1})
PTP$_{di}$/PTP$_{es}$ (%)
Older
Younger
Men
Women
*
†
0
100
200
300
400
500
600
800
1000
50
150
40
80
120
160
$\dot{V}_E$ (l·min^{-1})

Figure 5



A
B
C
D
E
F
PTP$_{di}$ (cmH$_2$O·s·min^{-1})
PTP$_{es}$ (cmH$_2$O·s·min^{-1})
PTP$_{di}$/PTP$_{es}$ (%)
0
100
200
300
400
500
600
800
1000
50
150
Older
Younger
Men
Women
20
40
60
80
$\dot{V}_E$ (%max)

Table 1. Subject Characteristics and Peak Exercise Data

	Older (n=20)		Younger (n=20)		
	Men (n=10)	Women (n=10)	Men (n=10)	Women (n=10)	
Demographics					
Age, y	70±2	67±2	25±1	24±1	*
Height, cm	173±2	163±3	178±2	166±2	†
Body mass, kg	76±4	65±4	74±3	59±2	†
MIP, cmH_2O	103±8	73±7	137±11	109±7	*†
Peak Exercise					
$\dot{V}O_2$, ml·kg^{-1}·min^{-1}	34.7±2.3	27.0±2.0	53.2±3.1	51.3±2.8	*†
$\dot{V}O_2$, % predicted	119±5	119±6	124±7	139±6	
$\dot{V}_E$, l·min^{-1}	108±25	80±9	152±33	119±17	*†
$\dot{V}_E$/MVV, %	81±11	82±14	82±12	85±14	
RER	1.12±0.02	1.18±0.02	1.12±0.03	1.11±0.02	
HR, % predicted	95±3	95±3	98±2	96±2	

Abbreviations: MIP, maximal inspiratory pressure; MVV, maximal voluntary ventilation; $\dot{V}O_2$, oxygen uptake; $\dot{V}_E$, minute ventilation; RER, respiratory exchange ratio; HR, heart rate. Data are presented as mean±SE. * $p<0.05$, main effect of age (comparisons made between all older and all younger subjects, regardless of sex). † $p<0.05$, main effect of sex (comparisons made between all men and all women, regardless of age). No significant interaction effects were noted.