Breathing Techniques Affect Female but Not Male Hip Flexion Range of Motion

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Abstract

Hamilton, AR, Beck, KL, Kaulbach, J, Kenny, M, Basset, FA, DiSanto, MC, and Behm, DG. Breathing techniques affect female but not male hip flexion range of motion. *J Strength Cond Res* 29(11): 3197–3205, 2015—Two protocols were undertaken to help clarify the effects of breathing techniques on hamstrings (hip flexion) range of motion (ROM). The protocols examined effects of breathing conditions on ROM and trunk muscle activity. Protocol 1: Thirty recreationally active participants (15 male, 15 female, 20–25 years) were monitored for changes in single-leg raise (SLR) ROM with 7 breathing conditions before or during a passive supine SLR stretch. Breathing conditions included prestretch inhale, prestretch exhale, inhale-during stretch, exhale-during stretch, neutral, hyperventilation, and hypoventilation before stretch. Protocol 2: Eighteen recreationally active participants (9 male, 9 female, 20–25 years) were monitored for electromyographic (EMG) activity of the rectus abdominus, external obliques, lower abdominal stabilizers, and lower erector spinae while performing the 7 breathing conditions before or during a passive SLR stretch. Control exhibited less ROM ($p = 0.008$) than the prestretch inhale (7.7%), inhale-during stretch (10.9%), and hypoventilation (11.2%) conditions with females. Protocol 3: Greater overall muscle activity in the prestretch exhale condition was found compared with inhale-during stretch (43.1%↓; $p = 0.029$) and hypoventilation (51.2%↓; $p = 0.049$) conditions. As the inhale-during stretch and hypoventilation conditions produced the lowest levels of muscle activity for both sexes and the highest ROM for the females, it can be assumed that both mechanical and neural factors affect female SLR ROM. Lesser male ROM might be attributed to anatomical differences such as greater joint stiffness. The breathing techniques may have affected intra-abdominal pressure, trunk muscle cocontractions, and sympathetic neural activity to enhance female ROM.

Key Words electromyography, respiration, stretching, flexibility, breathing

Introduction

Traditionally, various breathing techniques have been suggested by exercise professionals when performing stretches to enhance range of motion (ROM) (36). However, there have been no studies conducted to evaluate the effectiveness of such recommendations. The ROM seems to be affected by various neural and mechanical factors although the exact mechanisms and level of involvement still need to be clarified. Breathing patterns can modify various physiological parameters and possibly affect both neural (14,25) and mechanical (36) mechanisms of muscle control.

Mechanical factors have been reported to be the largest contributor to supine single-leg raise (SLR) ROM (19). It has been estimated that 79% of passive SLR variability is attributable to passive mechanical factors as opposed to neural factors (19). McHugh et al. (19) characterized the mechanical factors as viscoelastic properties of muscle and surrounding tissue. Neural factors include reflex responses and modified electromyographic (EMG) activity in involved muscles. Slow and maintained static stretching can decrease the neural or stretch reflexes (3).

One theory of how breathing primarily affects stretching ability is based on its postural or mechanical effects. According to Welge (36), a deep diaphragmatic breath extends the lumbar spine and increases the lordotic curvature, which creates an anterior pelvic tilt (36). For instance, when completing a straight-leg hamstring stretch, a diaphragmatic breath allows a slight anterior pelvic tilt and increases the distance between the attachments of the hamstrings. Previous research has shown greater improvement in hamstring ROM when an anterior pelvic tilt is held throughout a flexibility-training regimen as opposed to a posterior pelvic tilt (34). Some exercise professionals recommend exhaling into a forward bend, however, as it should move the hips towards

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a posterior tilt and thereby place less acute strain on the hamstrings to allow for a deeper forward bend (10,36).

Along with pelvic tilt, pelvic or lumbar stiffness can be significant factors in forward flexion ROM (31). Pelvic stiffness can be affected by intra-abdominal pressure (IAP) and trunk muscle activity, factors that are directly modified by breathing condition (16,29). Intra-abdominal pressure is the highest with full inhalations (11) and correlated with diaphragmatic activity (7,11). Thus, large inhalations maintained during the stretch may limit trunk flexion (7). Conversely, lumbar and pelvic stiffness are negatively correlated with increases in IAP with greater lumbar stiffness at full exhalation compared with full inhalation (11,29). Because males have greater spinal stiffness and less opportunity for changes in ROM (5), the effect of different breathing techniques on flexibility might be more apparent with women. There has been no research exploring these questions in the literature.

The link between breathing techniques and nervous system activity is also well documented in research and is relied on for various physiological or psychosomatic tests (30). Breathing can be controlled by the autonomic or somatic nervous system (15). Some traditional healing systems have used breathing exercises as a way to influence autonomic or neural processes to control blood pressure, muscle tone, and the level of sympathetic or parasympathetic neural control (10,14,25). Higher lung volumes found with the deeper slower breaths associated with hypoventilation activate pulmonary stretch reflexes affecting sympathetic output (28). A sympathetic nervous system-induced decrease in muscle tone could help to improve flexibility. Slow breathing may be a useful tool in counteracting many conditions associated with sympathetic overactivity such as psychological stress and hypertension (26). Whereas slow breathing has consistently shown significant decreases in central sympathetic activity, some research indicates that it may not decrease muscle sympathetic activity (28). A potential lack of sympathetic downregulation at the muscle site may limit benefits to ROM from slow breathing.

Hyperventilation, however, is believed to enhance sympathetic activation as frequent breaths have been linked to anxiety and stress-related conditions including exercise (30,33). Hyperventilation has been shown to produce cerebral vasoconstriction and other generalized increases in sympathetic activity (12,22). More importantly, sympathetic activity has been shown to produce a vasoconstricting effect in the periphery (32). There are no studies examining the effect of breathing techniques on trunk muscle activity.

Breathing is one element that could contribute to changes in both mechanical and neural factors of ROM although the strength of possible relationships is unclear. In an effort to bridge this gap, the purpose of this study was to clarify the effects of different breathing techniques on (a) SLR ROM and (b) trunk muscle EMG activity during the SLR stretch. Clarifying the role of trunk muscle EMG activity with SLR ROM is important to determine the relative impact of mechanical and neural factors to SLR ROM. It was hypothesized that the exhale-during and hypoventilation conditions would result in greater ROM due to possible changes in pelvic tilt and central nervous system relaxation, respectively.

Methods

Experimental Approach to the Problem

Two protocols were used to investigate the effects of 7 breathing conditions on hamstrings (hip flexion) ROM and trunk EMG activity. The first protocol involved 30 participants (15 male, 15 female) who were monitored for changes in a supine SLR ROM test when performing the 7 breathing conditions. Breathing conditions included (a) prestretch inhale, (b) prestretch exhale, (c) inhale-during stretch, (d) exhale-during stretch, (e) neutral, (f) hyperventilation before stretch, and (g) hypoventilation before stretch. Upon completion and analysis of the first protocol, the data illustrated a sex difference in ROM; and thus, a second protocol was initiated to examine whether there were differences in muscle activation that could explain the sex-related ROM differences. Based on a statistical power analysis of previous EMG-related studies (1,2,24), 18 participants (9 male, 9 female) were recruited for the second protocol. The second protocol examined rectus abdominus (RA), external obliques (EOs), lower abdominal stabilizers (LAS), and lower erector spinae (LES) EMG activity while performing the 7 breathing conditions before or during a passive supine SLR stretch.

Subjects

To examine the experimental hypothesis of the effects of ventilation on hamstrings (hip flexion) ROM, 30 participants were recruited. For the first protocol, all subjects were healthy recreationally active individuals (15 males, 15 females) with an average age of 22.2 $\pm$ 1.2 years (range, 20–25 years), height (males 1.76 $\pm$ 0.21 m; females 1.64 $\pm$ 0.18 m), and weight (males 81 $\pm$ 11.3 kg; females 67 $\pm$ 9.7 kg). For the second protocol, 18 healthy recreationally active individuals (9 males, 9 females) with an average age of 23.1 $\pm$ 1.5 years (range, 20–25 years), height (males 1.77 $\pm$ 0.28 m; females 1.62 $\pm$ 0.23 m), and weight (males 79 $\pm$ 12.4 kg; females 65 $\pm$ 8.7 kg) were recruited. Recreationally active was defined as not regularly being involved in organized activity but participating in physical activity on average of 1–2 times per week for less than 1 hour per session. All participants were screened for low back or other musculoskeletal limitations that would inhibit their participation through the use of the Physical Activity Readiness Questionnaire consent form. Participants took part in the study on a volunteer basis and provided written informed consent in accordance with the Declaration of Helsinki and ethical approval from the Human Investigation Committee at Memorial University (Reference #09.183).

Table 1. Gender range of motion for each condition.*

Condition	Range of motion	
	Males	Females
Control	65.9 ± 13.9 (85–42)	82.9 ± 16.3 (113–60)
Prestretch inhale	66.5 ± 15.4 (85–42.5)	91.9 ± 19.8 (137–60)†
Prestretch exhale	68.4 ± 16.1 (93–44)	89.3 ± 16.2 (115–60)
Inhale-during stretch	68.4 ± 15.1 (92–47.5)	92.0 ± 19.1 (132–62)†
Exhale-during stretch	69.1 ± 15.7 (92–46.5)	88.7 ± 19.6 (126–59.5)
Neutral	71.5 ± 18.1 (101–43)	89.7 ± 20.6 (134–57)
Hyperventilation	69.7 ± 17.6 (103–46)	86.9 ± 16.2 (114–60)
Hypoventilation	71.9 ± 17.7 (108–47.5)	92.2 ± 20.6 (132–56)†

*Mean range of motion ± *SD* (range) in degrees are listed for both the male and female groups.
†Statistical difference from control ($P \leq 0.05$).

Protocol 1: Procedure

Each subject participated in a single testing session of approximately 1 hour. During the testing session, participants were connected to the Moxus Modular $\dot{V}O_2$ System (AEI Technologies Inc., Naperville, IL, USA) by a facemask. The Moxus system recorded heart rate (HR), breathing frequency (BF), tidal volume (Vt), and minute ventilation (Ve) in a breath-by-breath format. The Moxus system has been reported to have a 2% between-subject variation with a repeated-test coefficient of variation of 2.5% (20). To begin each session, participants laid supine on a table while attached to the Moxus system for 5 minutes to obtain an average baseline measurement of HR, BF, Vt, and Ve. These baseline measurements were recorded and used as comparisons for later testing conditions.

After the baseline recordings and for both protocols, all participants completed a 5-minute warm-up on the Monark cycle Ergomedic 874E (Monark Exercise AB, Vansbro, Sweden) at 70 W to decrease risk of musculoskeletal injury during the stretching protocol. After the warm-up, a control measure of ROM was conducted. With the participant again supine on the table and attached to the Moxus system, the researcher applied an SLR, lifting the participant's fully extended right leg until a point of discomfort was reached as indicated by the participant. At this point, a second researcher used a manual goniometer (Baseline Plastic 360 ISOM 12 inch DJO-43058) to measure the ROM at the hip. The axis of the goniometer was landmarked against the greater trochanter of the participant. One arm of the goniometer was kept horizontal along the participant's trunk and one arm was located along the long axis of the leg as landmarked by the lateral epicondyle according to previously validated methods (9). Two researchers examined and compared the change in goniometer position arm. The intertester reliability of goniometry measurement was 0.99 with a coefficient of variation of less than 2%. The participant's left leg was braced against the table in a straight and neutral position throughout.

Once a control measure of SLR ROM had been taken after the bike warm-up (control condition), each subject completed 7 randomized breathing conditions with an SLR ROM measure immediately following each condition. Randomization procedure included pulling a condition printed on a piece of paper out of a box. Conditions were as follows: (a) control, (b) prestretch inhale: from the end of a normal exhalation, participants were required to perform 1 large inhalation over a period of 10 seconds to their maximum lung capacity. After the inhalation, participants were instructed to hold their breath while the researcher applied the stretch, (c) prestretch exhale: from the end of a normal inhalation, participants fully exhaled over a period of 10 seconds. Once fully exhaled, they were required to hold their breath while the researcher applied the stretch, (d) inhale-during stretch: participants inhaled slowly within normal tidal volumes while the researcher was applying the stretch, (e) exhale-during stretch: participants performed a slow exhalation as the researcher was applying the stretch, (f) neutral: participants held their breath with a neutral chest throughout the application of the stretch. Neutral chest was defined as holding the breath within normal tidal volumes, (g) hyperventilation: during this condition, the test of ROM was preceded by a 2-minute fast-paced breathing. After a metronome, participants were required to breathe at a frequency of 30 breaths per minute. The frequency was chosen as it represented approximately double the typical resting BF (12–15 breaths per minute) (18). As the subject performed the breathing condition, researchers monitored the tidal volume of the participant making sure that a Vt of equal or greater value to the baseline measurement was completed for each subject. At the conclusion of the 2 minutes, participants were instructed to return to a normal breathing pattern as the researcher applied the stretch,

Table 2. Male physiological parameters before stretch for each breathing condition (mean ± *SD*).*

	Control	Preinhale	Pre-exhale	Inhale-during stretch	Exhale-during stretch	Neutral	Hyperventilation	Hypoventilation
BF (breaths per min)	14.9 ± 4.4	18.3 ± 4.9	17.7 ± 4.4	18.6 ± 3.9	17.1 ± 3.9	15.5 ± 3.6	30.1 ± 0.3	7.1 ± 0.7
Vt (ml)	1,211.6 ± 398.1	993.2 ± 230.7	1,099.9 ± 381.7	994.9 ± 200.9	1,034.1 ± 209.3	946.8 ± 264.9	1,565.0 ± 596.4	2,625.2 ± 658.8
Ve ($L \cdot min^{-1}$)	16.1 ± 4.8	16.1 ± 5.4	17.1 ± 5.8	17.5 ± 4.9	15.9 ± 5.1	13.5 ± 4.1	46.7 ± 17.6	17.3 ± 3.7
HR ($b \cdot min^{-1}$)	70.5 ± 12.6	68.9 ± 11.4	72.9 ± 12.4	72.1 ± 13.1	69.6 ± 10.6	71.1 ± 14.1	78.4 ± 13.0	70.7 ± 12.9
RPE	13.4 ± 3.3	13.9 ± 2.7	13.9 ± 3.2	13.5 ± 2.9	13.6 ± 3.0	13.8 ± 3.1	13.2 ± 2.9	14 ± 2.7

*BF = breathing frequency; Vt = tidal volume; Ve = minute ventilation; HR = heart rate; RPE = rating of perceived exertion.

Table 3. Female physiological parameters before stretch for each breathing condition (mean ± *SD*).*

	Control	Preinhale	Pre-exhale	Inhale-during stretch	Exhale-during stretch	Neutral	Hyperventilation	Hypoventilation
BF (breaths per min)	15.7 ± 3.6	16.2 ± 3.7	18.4 ± 5.4	16.5 ± 4.6	18.2 ± 4.1	16.5 ± 3.1	29.9 ± 0.4	7.1 ± 1.2
Vt (ml)	881.9 ± 273.3	901.5 ± 371.5	895.7 ± 273.8	806.2 ± 294.3	781.5 ± 348.7	834.2 ± 335.9	1,090.4 ± 278.3	2,320.4 ± 809.0
Ve ($L \cdot min^{-1}$)	12.8 ± 3.3	14.0 ± 6.8	14.3 ± 4.9	12.5 ± 3.2	12.8 ± 4.3	12.7 ± 4.3	32.5 ± 8.2	15.4 ± 5.6
HR ($b \cdot min^{-1}$)	83.8 ± 15.4	72.4 ± 10.9	74.6 ± 11.1	68.2 ± 15.5	72.7 ± 12.9	73.2 ± 13.7	81.5 ± 10.1	72.6 ± 10.5
RPE	11.7 ± 2.2	12.0 ± 2.9	12.2 ± 2.6	11.9 ± 2.6	12.1 ± 3.1	11.9 ± 2.4	12.5 ± 2.2	12.1 ± 2.4

*BF = breathing frequency; Vt = tidal volume; Ve = minute ventilation; HR = heart rate; RPE = rating of perceived exertion.

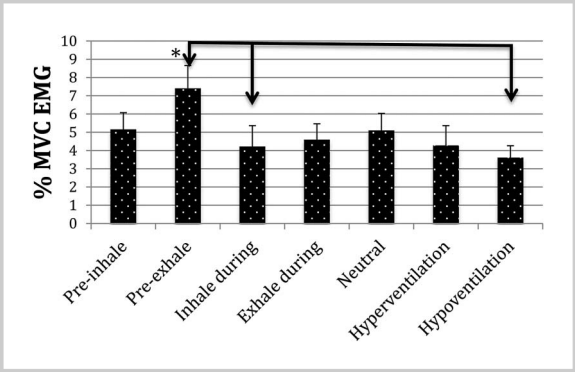

Figure 1. Breathing condition effects on overall normalized (percentage of maximum voluntary contraction) electromyography (EMG) with data from both sexes combined. Mean and SE bars are illustrated. Asterisk indicate that the pre-exhale condition provided significantly ($P \leq 0.05$) greater normalized EMG activity than with (A) inhale-during stretch and (B) hypoventilation conditions.

(h) hypoventilation: with the use of the metronome, participants were required to slow their breathing to a tempo of 6 breaths per minute. This frequency was chosen as it represented approximately half the typical resting BF (12–15 breaths per minute) (18). After 2 minutes of this breathing pattern, the subject returned to a normal breathing pattern as the researcher applied the stretch. Conditions were performed in a random order with 2-minute breaks between each condition. After each condition, participants were asked to rate each stretch according to the Borg Scale from 6 to 20 of rate of perceived exertion. Rate of perceived exertion and ROM values were recorded by researchers for each condition. Measurements for HR, BF, Vt, and Ve were taken as averages for the 2 minutes before the stretch as recorded by the Moxus system.

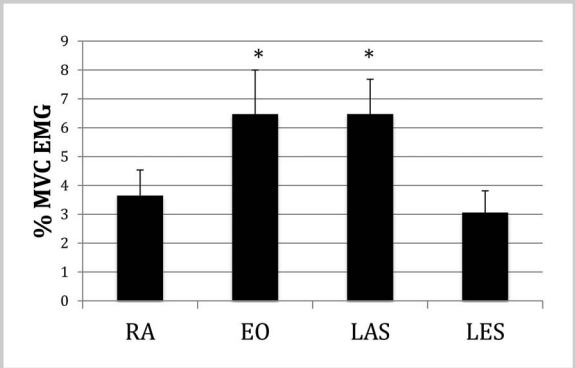

Figure 2. Normalized (percentage of maximum voluntary contraction) electromyographic (EMG) data with all conditions and sexes combined. Mean and SE bars are illustrated. Asterisks indicate significantly ($P \leq 0.05$) greater normalized external oblique and lower abdominal stabilizers' EMG activity than the rectus abdominus and lower erector spinae.

Protocol 2: Procedure

Each subject participated individually in a single testing session of approximately 1 hour. During each testing session, participants had surface EMG electrodes (Ag/AgCl, disc shape, and 10 mm in diameter) placed on the RA, LAS, LES, and EO muscle groups. The skin around landmarked areas was shaved and cleansed with isopropyl rubbing alcohol (70%). The EMG activity from the selected muscles was recorded on the right side only with the electrodes being placed 2 cm apart. The electrode placement was as follows: RA: 3 cm lateral to the umbilicus, EO: two-thirds the distance from the iliac crest to the 10th rib, LAS: inguinal space 3 cm medial to the iliac crest, and LES: 3 cm lateral to the spinous process of the fifth lumbar vertebrae. Electrode position for these muscle groups have been reported previously (1,2,24).

Electromyographic data were sampled at 2,000 Hz with a Blackman −61 dB band pass filter between 20 and 500 Hz. The electrode channels were connected to a Biopac MP150 system (Gain = 2,000, Sample rate = 2,000 samples per second) with AcqKnowledge 4.1 software for processing of muscle activity signals (Biopac Systems Inc., Goleta, CA, USA). Muscle activity was recorded for 15-second periods to encompass the application of a SLR stretch by the researcher to a point of maximum discomfort as indicated by the participant. The absolute value of the filtered signals were taken and integrated over a 3-second period to obtain the mean volume of muscle activity, while the SLR stretch was being held in each breathing condition. The start of the 3-second period coincided with the identification of maximum static stretch discomfort (maximum ROM) by the participant. Thus, EMG was monitored at similar relative muscle lengths for each condition.

After the warm-up, electrodes were connected to the participant and a maximum voluntary contraction (MVC) protocol was performed to normalize muscle activity levels during analysis. For the RA and EO, an MVC sit-up test was conducted. Participants lay supine with legs straight and arms crossed against chest and shoulders. Tester resisted the sit-up motion by applying pressure to shoulders. Subjects relaxed for 3–5 seconds and then contracted maximally for 5 seconds. For the LAS MVC, subjects performed a drawing-in (abdominal hollowing) maneuver. Participants were instructed to pull their umbilicus towards their spine and squeeze the muscles to simulate a bowel movement for 5 seconds.

Finally, the LES MVC used a back extension test (modified Biering-Sorensen test). Participants lay prone with hands behind head and performed maximal back extension while resisted by tester's hands on shoulders hold for 5 seconds (24). Each MVC test was performed twice with 30-second rest intervals between trials. The

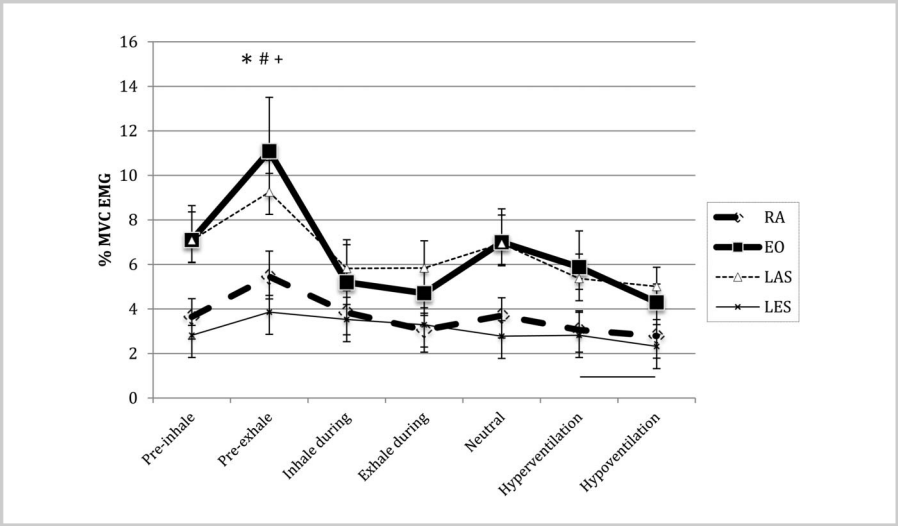

Figure 3. Breathing condition effects on specific muscle normalized (percentage of maximum voluntary contraction) electromyography (EMG) with data from both sexes combined. Mean and SE bars are illustrated. The following symbols illustrate that the prestretch exhale condition showed higher lower abdominal stabilizers (#: $p = 0.005$ vs. inhale-during stretch, exhale-during stretch, and hypoventilation), lower erector spinae (LES) (*: $p = 0.05$ vs. hypoventilation), and a trend for greater external oblique (+: $p = 0.07$ vs. hypoventilation) muscle activity. The horizontal line illustrates greater LES EMG activity with hyperventilation vs. hypoventilation conditions ($p = 0.03$).

absolute value of the filtered signals were taken and integrated over a 3-second period to obtain the mean volume of muscle activity during each MVC. After the MVC protocol, a supine position on a mat was assumed for the breathing condition protocol.

The same 7 previously described breathing conditions were examined throughout this second protocol and were presented in random order to each participant. In the same manner as the first protocol, the researcher applied the SLR by lifting the participant's right leg until a point of total discomfort as indicated by the participant. The participant's left leg was braced against the mat in a straight and neutral position throughout. The ROM data from this protocol were added to the data from protocol 1 and analyzed together (24 males and 24 females).

Statistical Analyses

Descriptive statistics (mean ± *SD*) for all demographic variables were calculated. Greenhouse-Geisser corrections were used for tests of within-subject effects where sphericity could not be assumed. Single-leg raise ROM from both protocols was analyzed using a 2-way repeated measure of analysis of variance (ANOVA) (8 breathing conditions × 2 sexes). For the EMG activity measured in the second protocol, a 3-way repeated-measures ANOVA (7 breathing conditions × 4 muscles × 2 sexes) was conducted to compare overall muscle activity for the 7 breathing conditions. A repeated-measures ANOVA (7 breathing conditions × 2 sexes) was also conducted for each individual muscle (RA, EO, LAS, and LES). Normalized EMG values to represent muscle activity are presented for each breathing condition as percentage of MVC (%MVC) values. Normalized values were calculated by dividing the processed EMG signals for each condition by the processed signal value from the appropriate MVC protocol and multiplying by 100%. The significance of main effects was based on an alpha level of $p \leq 0.05$. In the case of significant main effects or interactions, post hoc comparisons were then conducted using the Bonferroni correction factor.

Because each protocol involved a single session, intersession was not an issue although the ROM and EMG procedures have been shown to be reliable and valid in a number of other investigations from this laboratory (1,2,24).

Results

Protocol 1

The male participants showed no significant differences between conditions. Contrary to the male participants, the female participants showed a significant effect of ventilatory patterns on ROM ($F_{2.639,\ 36.946} = 4.818$, $p = 0.008$). The post hoc analysis showed that for the females, the control condition exhibited less ROM than the prestretch inhale (7.7%), inhale-during stretch (10.9%), and hypoventilation (11.2%) conditions. Females showed greater ROM for all conditions compared with males (Table 1: 29.4%↑ overall).

The tidal volumes were consistent for all conditions except the hypoventilation condition where tidal volume approximately doubled all other condition ($p \leq 0.05$). Minute ventilation values were also consistent across the majority of conditions. Hyperventilation produced Ve values approximately double the other conditions and hypoventilation resulted in similar Ve values as compared with the other conditions except hyperventilation. Heart rate was significantly higher only when comparing the hyperventilation to the hypoventilation condition (10.9%). There were no significant differences in RPE values across conditions. Although the RPE does not provide indisputable evidence regarding consistent force application for each stretch, it is important to note that perceptions of the stretch intensity did not differ among participants (Tables 2 and 3).

Protocol 2

Overall Muscle Activity. There was a significant within-subject effect of breathing condition ($F_{2.908,\ 46.521} = 5.92$, $p = 0.002$) and muscle group factors ($F_{2.646,\ 42.343} = 11.471$, $p = 0.000$). There was a significant interaction between breathing condition and muscle group ($F_{2.923,\ 46.775} = 3.914$, $p = 0.015$) and a near-significant interaction between breathing condition and gender ($F_{2.908,\ 46.521} = 2.317$, $p = 0.090$). Post hoc comparisons indicated significantly greater overall muscle activity in the prestretch exhale condition compared with the inhale-during stretch (43.1%↓; $p = 0.029$) and hypoventilation (51.2%↓; $p = 0.049$) conditions (Figure 1). Electromyographic activity in the EO muscle group was higher than in the RA (43.4%↓; $p = 0.016$) and the LES (52.6%↓; $p = 0.011$) groups, respectively, across all conditions (Figure 2). The LAS muscle group also exhibited higher muscle activity relative to RA (43.5%↓; $p = 0.001$) and LES (52.7%↓; $p = 0.001$) groups (Figure 2); no other comparisons were significant.

Females (6.3 ± 5.5% of MVC) showed 80% higher %MVC EMG values across all conditions compared with their male counterparts (3.5% ± 4.7 of MVC) with all muscle groups combined. Both sexes showed similar relative effects due to the different breathing conditions however.

Rectus Abdominus. Rectus abdominus showed a nearly significant within-subject effect of breathing condition ($F_{1.580,\ 25.285} = 3.506$, $p = 0.055$) (Figure 3).

External Oblique. External oblique demonstrated a significant within-subject effect of breathing condition ($F_{2.076,\ 33.209} = 4.849$, $p = 0.013$). Post hoc comparisons revealed no significant findings, but prestretch exhale illustrated a nonsignificant 61.2% ($p = 0.072$) higher EMG activity than the hypoventilation condition (Figure 3).

Lower Abdominal Stabilizers. There was a significant within-subject effect of breathing condition ($F_{3.316,\ 53.053} = 6.086$, $p = 0.001$) for the LAS. Post hoc comparisons revealed significantly higher activity during the prestretch exhale condition compared with the inhale-during stretch (37.1%↓; $p = 0.005$), exhale-during stretch (36.8%↓; $p = 0.015$), and hypoventilation conditions (45.8%↓; $p = 0.026$) (Figure 3).

Lower Erector Spinae. A significant within-subject effect of breathing condition ($F_{2.357,\ 37.706} = 5.316$, $p = 0.007$) was observed for the LES. Post hoc comparisons revealed significantly higher activity during the prestretch exhale (39.8%↑; $p \leq 0.05$) and hyperventilation (17.7%↑; $p = 0.033$) condition compared with the hypoventilation condition (Figure 3). The interaction of breathing condition and gender approached a significant within-subject effect ($F_{2.357,\ 37.706} = 2.566$, $p = 0.082$).

Discussion

The most important findings in the preliminary protocol were twofold: females had greater SLR ROM than males and females had greater ROM with the prestretch inhale, inhale-during stretch, and hypoventilation conditions. The various breathing conditions had no significant effect on the males' ROM. The subsequent protocol found higher overall EMG activity for the prestretch exhale condition compared with the inhale-during stretch and hypoventilation conditions. When examining separate muscle groups, there was less LAS EMG activity during the inhale-during stretch, exhale-during stretch, and hypoventilation conditions compared with prestretch exhale. In addition, the hypoventilation condition provided less LES EMG activity than the hyperventilation condition.

The sex difference in ROM is well documented for major joints and planes of movement such as ankle plantar flexion, elbow pronation, and hip flexion (31,37). Anatomical differences within the hip and shoulder girdles, as well as limb length differences permit greater ROM in females (31,37). Differences in hormone and neural regulation could also help account for certain differences in ROM. For example, changes in tissue pliability and joint laxity have been noted in females at particular times during pregnancy or menstruation (6).

Male ROM was unaffected by any of the breathing conditions. Male greater joint stiffness (4) may have contributed to their resistance to any of the breathing condition effects. Although McHugh et al. (19) report that mechanical factors contribute approximately 79% to the SLR ROM, the intrinsic mechanical restrictions of the males in this study may have overwhelmed any possible neural or mechanical breathing/ventilatory effects. It is unclear whether greater mechanical or neural resistance contributed most notably to the lack of significant breathing condition effects on male ROM.

Females had greater ROM with the prestretch inhale, inhale-during stretch, and hypoventilation conditions. The EMG analysis did not show a consistent relationship between muscle activity and ROM. Therefore, an interaction of neural, mechanical, and pressure-related factors likely contributed to the results. The interaction of muscle activity and breath position on IAP and lumbar/pelvic stiffness likely had the greatest influence. Intra-abdominal pressure contributes to stability through the trunk and may limit forward flexion (7). The transverse abdominus and diaphragm muscles are most highly correlated to changes in IAP (7,11). Previous studies have shown that holding a full inhalation produces the highest IAP compared with other breath positions (11). Therefore, the prestretch inhale condition that exhibited a higher ROM should have had the highest IAP of all conditions. The LAS was the only muscle group to provide significant EMG differences between breathing conditions that closely parallel ROM results in the preliminary study (i.e., greater ROM and the lowest LAS EMG with inhale-during stretch and hypoventilation). In this study, however, the EMG activity within the LAS was higher in

the condition that should have had a lower IAP (prestretch exhale) and lower in the conditions that should have had a higher IAP (higher ROM with prestretch inhale and exhale-during stretch conditions). The literature has not reported any sex differences in IAP in healthy persons (8). The higher ROM for the prestretch inhale condition for females contradicts the hypothesis that IAP significantly limited forward flexion in this study. The overall EMG activity for the prestretch inhale condition was also not significantly lower and indicates that more relaxed trunk muscle activity is not the single most important factor in higher ROM.

Lumbar and pelvic stiffness can be negatively correlated with increases in IAP and may provide a more direct influence over SLR ROM. Shirley et al. (29) have shown greater lumbar stiffness at full exhalation compared with full inhalation. Other studies have shown similar findings (11). Breathing condition may produce greater changes in lumbar stiffness for females as previous research has indicated that males have greater spinal stiffness and less opportunity for changes in ROM in spine motion segments (5).

Breathing condition may also impact the stiffness or tone of other muscles, such as the LES and the hamstrings, through other mechanisms such as muscle sympathetic nerve activity (MSNA). At rest, MSNA correlates well with global measures of sympathetic nerve activity such as total body norepinephrine spillover and with regional norepinephrine spillover (35). Muscle sympathetic nerve activity consists of baroreceptor reflex–controlled vasoconstrictor impulses to the muscle vascular bed and is involved in dynamic blood pressure regulation. Although the relationship between MSNA and ROM is unknown, it could help provide some explanation for the significant results found for the prestretch inhale and hypoventilation conditions.

Studies indicate that MSNA output is inhibited at higher lung volumes but not at lower lung volumes (28). A higher or lower lung volume is defined as a lung volume above or below normal tidal breath volume, respectively. It is believed that pulmonary stretch reflexes largely modulate MSNA activity and inhibit it at larger tidal volumes (28). Based on those findings, it can be assumed that there was lower MSNA for the prestretch inhale, inhale-during stretch, and hypoventilation conditions compared with prestretch exhale. The hypoventilation condition should have been a neutral condition for breathing position and therefore muscle activity and IAP at time of stretch. It still produced lower muscle activity compared with prestretch exhale and higher ROM for females, however. These results demonstrate that there is a lingering relaxation effect on muscle activity from hypoventilation as larger tidal breath volumes were maintained before the stretch for 2 minutes during the hypoventilation condition. Lambert et al. (17) found sex-related differences in MSNA showing that MSNA was affected more by blood pressure in females and body mass index in males. It is unclear therefore whether the breathing conditions produced greater changes in MSNA for females than males or whether similar changes in MSNA produced greater changes in muscle characteristics and ROM in females than males.

Slow deep breathing with an emphasis on larger tidal volumes is common with yoga (23,27). One of the goals of slow deep inhalations is to increase attentional capabilities (21) and relaxation (through downregulation of the hypothalamic-pituitary-adrenal axis and the sympathetic nervous system) (27). Hoge et al. (13) stretched ankle joints of men and women for 135 seconds and found that only the women's group increased ROM and this augmented ROM was not related to changes in musculoskeletal stiffness but rather to an increase in stretch tolerance. The improved ROM in females with the prestretch inhale, inhale-during stretch, and hypoventilation conditions might be connected with a greater effect of deep inhalations for females to improve task (stretching) concentration contributing to a greater tolerance to stretch and possible contributions from a decreased MSNA.

The results of this experiment indicate that there may be a cumulative effect of both neural and mechanical factors in achieving maximal ROM during a passive SLR stretch and that these may affect females more than males. In the preliminary protocol, the prestretch inhale, inhale-during stretch, and hypoventilation conditions resulted in greater ROM compared with control measures for females. The follow-up protocol demonstrated differences in trunk muscle activity for both genders with the prestretch exhale condition having higher activity than inhale-during stretch and hypoventilation conditions.

A limitation to the interpretation of the EMG data is the possibility of skin and muscle movement from the resting position to the stretched position affecting the muscle area under the EMG electrodes. However, the protocol was a repeated-measures protocol that compared EMG activity only during the stretch position (no comparison was conducted between the resting and stretch positions). The extent of signal dispersion between stretch conditions would be expected to be minimal as the difference between the breathing intervention conditions was on average 4–6° (Table 1).

Practical Applications

Based on the greater ROM and lower EMG activity with techniques that emphasized larger inhalations, women should take large breaths (inhale) at a slow frequency (hypoventilation) before and maintain that breath (inhalation) during the stretch to achieve a more effective hip flexion ROM.

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