Does Intra-abdominal Pressure Have a Causal Effect on Muscle Strength of Hip and Knee Joints?

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Abstract

Tayashiki, K, Kanehisa, H, and Miyamoto, N. Does intra-abdominal pressure have a causal effect on muscle strength of hip and knee joints? *J Strength Cond Res* XX(X): 000–000, 2018—It remains unclear whether intra-abdominal pressure (IAP) has a causal effect on lower-limb muscle strength. This study aimed to clarify whether or not changes in IAP, induced by changing breathing state, influence muscle strength of hip and knee extensor and flexor. Eighteen healthy males (age: 22.0 ± 2.2 years, height: 1.71 ± 0.03 m, and body mass: 68.1 ± 6.1 kg) performed maximal voluntary isometric contractions (MVICs) of hip and knee extensor and flexor during breath-hold at full inspiration (inspiratory condition) or expiration (expiratory condition), or during normal breath-hold (normal condition). Intra-abdominal pressure was obtained by a pressure transducer placed in the rectum and determined at the time at which the developed torque reached to the maximum. The IAP during each MVIC was significantly greater in inspiratory condition than in expiratory condition ($p < 0.05$). The maximal torque of hip extensor was significantly greater in inspiratory condition than in expiratory condition ($p < 0.05$). By contrast, the maximal torque of each of hip flexor, knee extensor, and knee flexor was not different among the 3 breath-hold conditions. The IAP was significantly correlated with the maximal torque of hip extensor in each breath-hold condition. The current results suggest that a sufficient increase in IAP has a causal effect to specifically improve muscle strength of hip extensor.

Key Words hip extension, lung volume, diaphragm, core stability

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Introduction

It is generally considered that a strong and stable trunk provides a solid foundation for high force production by limbs (8,12,23). Recently, athletes and coaches have paid increasing attention to core stability exercise and training as a modality to improve the function of trunk muscles, especially abdominals. In fact, several studies have reported improvements in lower-limb muscle strength (8,19) and physical performances (8,10,17,18) after core stability training. However, physiological background for the training-induced improvements is not well known. A better understanding of the underlying mechanisms would be useful to establish effective core training programs aiming to enhance sports performances.

As one of the factors explaining the effects of core stability training, the influence of intra-abdominal pressure (IAP) may be involved. Intra-abdominal pressure is produced by the activities of trunk muscles (e.g., abdominals, paraspinal, and diaphragm) (1,6,7,20) and has been suggested to play an important role for achieving high trunk stability, especially during movement involving lower limbs (1,3,5,6,14). To the best of our knowledge, however, available information on the direct association of IAP and lower-limb muscle strength is limited to the reports of Tayashiki et al. (21) and Hagins et al. (6). Tayashiki et al. (21) showed that IAP was significantly correlated with single-joint muscle strength of hip extensor but not with that of hip flexor. Hagins et al. (6) have reported that IAP was not significantly associated with maximal lifting force. Taken together, whether or not IAP is associated with muscle strength seems to depend on the muscle and task examined.

Because association does not imply causality, the causal relationship between IAP and muscle strength remains unclear from the aforementioned results of cross-sectional studies (6,21). Hagins et al. (6) reported that when IAP and maximal lifting force were compared between 2 breath-hold conditions (i.e., inspiratory vs. expiratory states), a significant difference was observed in IAP but not in maximal lifting force (6). By contrast, an 8-week voluntary cocontraction of abdominal muscle (abdominal bracing) training improved maximal IAP during abdominal bracing and single-joint muscle strength of hip extensor (but not of knee extensor) (19). Based on the previous findings, it is reasonable to hypothesize that IAP has a causal effect on muscle strength, at least of hip extensor and thereby an increase in IAP leads to an enhancement of muscle strength of hip extensor.

One of the ways for changing IAP during a given task is controlling lung volume by changing breathing state. Intra-abdominal pressure has been shown to vary with breathing state and lung volume (11,14,15). This is because the diaphragm contraction intensity is proportional to the lung volume (i.e., depth of inspiration) (2,7) and plays a significant role in producing high IAP (7,11). To test the aforementioned hypothesis, this study investigated IAP and muscle strength of hip and knee extensor and flexor in 3 different breath-hold conditions (i.e., 3 different depths of inspiration).

Methods

Experimental Approach to the Problem

Hip and knee tasks were conducted in 3 different breath-hold conditions (see below) to achieve the goal of this study. In each task, torque, IAP, and surface electromyogram (EMG) signals were measured. The 2 tasks were performed on separate days spaced at least 2 days apart, in a randomized order across subjects.

Subjects

Eighteen male subjects aged 20–27 years (22.0 ± 2.2 years; 1.71 ± 0.03 m; 68.1 ± 6.1 kg; mean ± SD) who did not have any history of musculoskeletal injuries in the back or lower extremity within 12 months before the experiments were recruited in this study. The subjects had regularly performed sport activities such as running, cycling, dancing, football, or sepak takraw (≥30 $\text{min}\cdot\text{d}^{-1}$, ≥2 $\text{d}\cdot\text{wk}^{-1}$), and participated in recreational competitive activities at regional level within the preceding year. However, they did not perform any systematized strength training programs. They were instructed to refrain themselves from strenuous exercise and unfamiliar physical activities for 24 hours before the test. All subjects visited the laboratory to become familiar with each task before the start of the test. This study was approved by the Ethics Committee on Human Research of National Institute of Fitness and Sports in Kanoya and performed in accordance with the Declaration of Helsinki. Before the participation in this study, the subjects were fully informed of the purpose and procedure of this study and possible risks of the measurements. Written informed consent was obtained from all subjects.

Procedures

Experimental Setting and Torque Recording. In hip task, each subject lay supine on a dynamometer (CON-TREX MJ; PHYSIOMED, Schnaittach, Germany) bed with his right hip and knee flexed at 90° (anatomical position: 0°) in accordance with the procedure used in previous studies (21,22). The rotation axis of the right hip joint was aligned with that of the dynamometer and the right thigh was firmly secured to the lever arm. The torso, pelvis, and left thigh were firmly secured to the bed with nonelastic belts to prevent extraneous movement during the measurements. The shoulders were fixed with pads attached to the bed.

In knee task, each subject sat on the dynamometer seat with his right hip and knee flexed at 90° as described in previous studies (19,22). The rotation axis of the right knee was aligned with that of the dynamometer. The lever arm of the dynamometer was attached to the right lower thigh. The torso and hip were tightly held to the seat with nonelastic straps.

In each task, after familiarization with submaximal and maximal voluntary isometric contractions (MVICs) of extensor and flexor, the subjects performed extension or flexion MVIC in 3 different breath-hold conditions: (a) inspiring fully before the MVIC and holding the breath during the task (inspiratory condition), (b) expiring fully before the MVIC and holding the breath during the task (expiratory condition), and (c) breathing normally before the MVIC and holding the breath during the task (normal condition). The order of the measurements of 3 conditions was randomized across the subjects. In each condition of hip and knee tasks, 2 measurements were conducted. An interval of at least 2 minutes was provided between trials. In each condition, additional trials were performed if the difference in the maximal torque of the 2 trials was more than 5%, and the 2 trials with <5% difference were used for further analyses. The repeatability of torque measurement was confirmed in previous studies (≥0.98 for intraclass correlation coefficient [ICC] and ≤3.0% for the coefficient of variation [CV]) (19,22).

Intra-abdominal Pressure Recording. Intra-abdominal pressure was obtained using a sterilizing pressure transducer (MPC-500; Millar Instruments, Houston, TX, USA). The transducer was placed in the rectum about 15 cm from the anus in accordance with previous studies (11,21). Before the test, the pressure transducer was calibrated with a transducer control unit (TCB-500; Millar Instruments). McCarthy (13) showed that the pressure measured using a transducer inserted into the rectum (i.e., 10 cm or more from the anus) corresponded to that using a transducer inserted into the abdominal cavity. Responses from the pressure transducer during each task were monitored to confirm that the transducer was correctly positioned. The repeatability of IAP measurement was confirmed in a recent study (ICC = 0.98 and CV = 7.9%) (20).

Electromyogram Recording. In this study, EMG signals of the gluteus maximus (GM), rectus femoris (RF), vastus lateralis (VL), biceps femoris (BF), and semitendinosus (ST) on the right side of the body were recorded using preamplified surface electrodes (electrode shape: parallel-bar, interelectrode distance: 10 mm; DE-2.1; DELSYS, Natick, MA, USA) with band-pass filtering between 20 and 450 Hz (Gain: × 1,000; Bagnoli 8 EMG System, DELSYS). During hip task, the EMG signals of GM and BF were recorded. During knee task, the EMG signals of RF, VL, BF, and ST were obtained. After appropriate skin preparation (i.e., shaving, abrading, and cleansing with 70% ethanol), the electrodes were placed

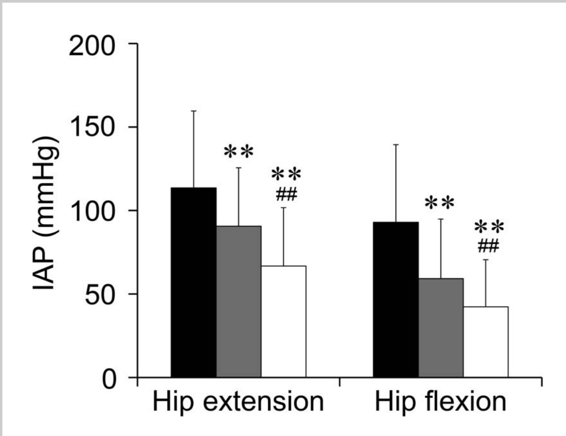

Figure 1. Intra-abdominal pressure (IAP) in inspiratory condition (black closed bar), normal condition (gray closed bar), and expiratory condition (open bar) during maximal voluntary isometric hip extension (left) and flexion (right). Values are expressed as mean ± *SD*. An asterisk (**) indicates a significant ($p < 0.01$) difference from the inspiratory condition. A number sign (##) indicates a significant ($p < 0.01$) difference from the normal condition.

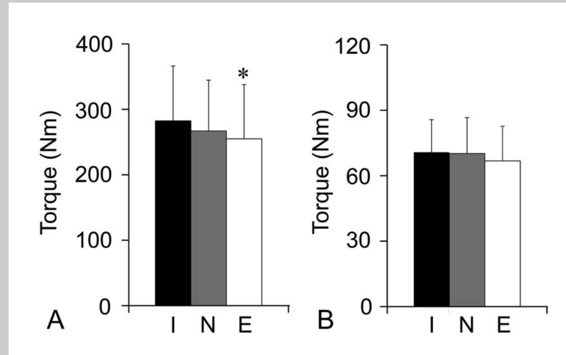

Figure 2. Maximal torque of hip extensor and flexor in inspiratory condition (black closed bar), normal condition (gray closed bar), and expiratory condition (open bar) during maximal voluntary isometric hip extension (A) and flexion (B). Values are expressed as mean ± *SD*. An asterisk (*) indicates a significant ($p < 0.05$) difference from the inspiratory condition.

over each muscle along the muscle fascicles. The electrode sites were halfway between the trochanter and the sacral vertebrae for the GM and halfway of the thigh length (the distance from the greater trochanter to lateral joint space of knee joint) for RF, VL, BF, and ST (9,16,19).

Data Analysis. The IAP, torque, and EMG signals during hip and knee tasks were simultaneously recorded using a personal computer through a 16-bit A/D converter (PowerLab 16/35; ADInstruments, Bella Vista, Australia). All data were analyzed using data analysis software (LabChart version 7; ADInstruments, Bella Vista, Australia). In each MVIC, the IAP was calculated as the change from the value at rest to the value at the time at which the maximal torque was attained. The EMG signals were high-pass filtered at 20 Hz and full-wave rectified (19). For each MVIC, the average amplitude value of the rectified EMG (AEMG) for each muscle was determined over a 500-ms window centered on the time at which the maximal torque was attained. The average value across the 2 trials in each condition was used for further analyses. For knee task, the AEMGs for RF and VL during knee extension MVIC in normal condition and those for BF and ST during knee flexion MVIC in normal condition were used as EMGmax of the corresponding muscles. For hip task, the AEMGs for GM and BF of hip extension MVIC in normal condition were referred to as EMGmax of the corresponding muscle. The AEMG for each muscle during both tasks in each breath-hold condition was expressed as the value relative to EMGmax (%EMGmax).

Statistical Analyses

Based on our preliminary data ($n = 5$), a priori power analyses with an assumed type 1 error of 0.05 and a statistical power of 80% indicated that at least 7 and 14 subjects were required to find statistically significant differences in the IAPs during hip and knee tasks between the 3 conditions, respectively. Thus, 18 subjects were recruited to account for possible attrition.

Descriptive data are presented as mean ± *SD*. All statistical analyses were performed using statistical software (SPSS Statics version 22.0; IBM Corp., Armonk, NY, USA). For each variable, 1-way (3 conditions) repeated-measures analysis of variance followed by post hoc comparisons (Bonferroni) was used to test the differences in the measurement values between the 3 conditions. When a significant main effect was found, effect size (r) was also reported with a p value to express the magnitude of the difference between the conditions. Pearson product-moment correlation coefficients were calculated to determine the strength of relationships between IAP (independent variable) and maximal torque (dependent variable) during MVIC tasks in the 3 conditions. The level of significance was accepted at $p < 0.05$.

Results

Hip Task

Figure 1 shows IAP in each condition during hip extension and flexion MVICs. Significant main effects were found in the IAP during hip extension MVIC ($F = 26.942$, $p < 0.001$, partial $\eta^2 = 0.613$) and hip flexion MVIC ($F = 41.779$, $p < 0.001$, partial $\eta^2 = 0.711$). The IAP during hip extension MVIC was significantly greater in inspiratory condition than in normal ($p = 0.007$, $r = 0.53$) and expiratory conditions ($p < 0.001$, $r = 0.74$) and also greater in normal condition than in expiratory condition ($p = 0.001$, $r = 0.61$). The IAP during hip flexion MVIC was significantly greater in inspiratory condition than in normal ($p < 0.001$, $r = 0.68$) and expiratory conditions ($p < 0.001$, $r = 0.61$) and also greater in normal condition than in expiratory condition ($p = 0.001$,

TABLE 1. Descriptive data on %EMGmax for each muscle in inspiratory condition, normal condition, and expiratory condition during maximal voluntary isometric hip extension and flexion.*†

Task	Muscle	Condition: Inspiratory	Normal	Expiratory	ANOVA *p*
Hip extension	GM	119.5 ± 26.4	100.0 ± 0.0	103.0 ± 29.4	0.018
	BF	104.5 ± 34.2	100.0 ± 0.0	103.0 ± 22.5	0.843
Hip flexion	GM	25.0 ± 22.2	22.3 ± 16.7	26.1 ± 23.8	0.174
	BF	29.6 ± 19.9	22.9 ± 13.7	36.8 ± 31.2	0.122

*ANOVA = analysis of variance; GM = gluteus maximus; BF = biceps femoris.
†Values are expressed as mean ± *SD*.

$r = 0.74$). For the maximal torque of hip extensor (Figure 2A), a significant main effect was found ($F = 6.188$, $p = 0.005$, partial $\eta^2 = 0.267$). The maximal torque of hip extensor was significantly greater in inspiratory than in expiratory condition ($p = 0.010$, $r = 0.51$). There was no significant main effect in the maximal torque of hip flexor ($F = 1.972$, $p = 0.155$, partial $\eta^2 = 0.104$) (Figure 2B).

For hip extension MVIC, the IAP was significantly correlated with the maximal torque in all inspiratory ($r = 0.527$, $p = 0.025$), normal ($r = 0.677$, $p = 0.002$), and expiratory ($r = 0.659$, $p = 0.003$) conditions. For hip flexion MVIC, the IAP was not significantly correlated with the maximal torque in each condition ($r = 0.232$–0.289, $p = 0.244$–0.355).

A significant main effect was found in %EMGmax of GM during hip extension MVIC ($F = 4.512$, $p = 0.018$, partial $\eta^2 = 0.210$). The %EMGmax of GM during hip extension MVIC was significantly greater in inspiratory condition than in normal condition ($p = 0.022$, $r = 0.46$). For %EMGmax for the other muscles during hip extension and for all muscles during hip flexion MVIC, there were no significant main effects ($F = 0.172$–2.436, $p = 0.122$–0.843, partial $\eta^2 = 0.010$–0.125) (Table 1).

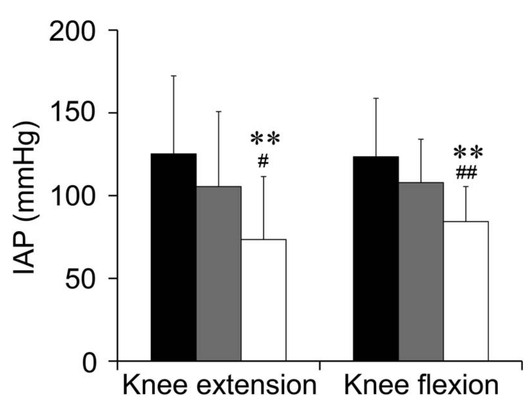

Figure 3. Intra-abdominal pressure (IAP) in inspiratory condition (black closed bar), normal condition (gray closed bar), and expiratory condition (open bar) during maximal voluntary isometric knee extension (left) and flexion (right). Values are expressed as mean ± *SD*. An asterisk (**) indicates a significant ($p < 0.01$) difference from the inspiratory condition. A number sign (# and ##) indicates a significant ($p < 0.05$ and 0.01, respectively) difference from the normal condition.

Knee Task

Figure 3 shows IAP in each condition during knee extension and flexion MVICs. Significant main effects were found in the IAP during knee extension MVIC ($F = 16.819$, $p < 0.001$, partial $\eta^2 = 0.497$) and knee flexion MVIC ($F = 18.109$, $p < 0.001$, partial $\eta^2 = 0.516$). During knee extension MVIC, the IAP was significantly greater in inspiratory condition than in expiratory condition ($p < 0.001$, $r = 0.70$) and also greater in normal condition than in expiratory condition ($p = 0.010$, $r = 0.50$). During knee flexion MVIC, the IAP was significantly greater in inspiratory condition than in expiratory condition ($p < 0.001$, $r = 0.67$) and also greater in normal condition than in expiratory condition ($p = 0.004$, $r = 0.55$). There were no

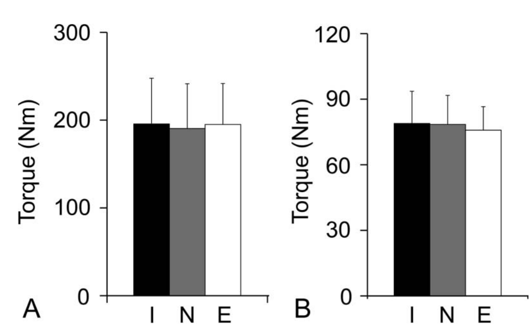

Figure 4. Maximal torque of knee extensor and flexor in inspiratory condition (black closed bar), normal condition (gray closed bar), and expiratory condition (open bar) during maximal voluntary isometric knee extension (A) and flexion (B). Values are expressed as mean ± *SD*.

Table 2. Descriptive data on %EMGmax for each muscle in inspiratory condition, normal condition, and expiratory condition during maximal voluntary isometric knee extension and flexion.*†

		Condition			
Task	Muscle	Inspiratory	Normal	Expiratory	ANOVA *p*
Knee extension	RF	101.8 ± 11.1	100.0 ± 0.0	102.0 ± 13.7	0.774
	VL	105.8 ± 12.3	100.0 ± 0.0	104.7 ± 11.4	0.173
Knee flexion	BF	99.6 ± 18.5	100.0 ± 0.0	100.6 ± 17.9	0.972
	ST	97.7 ± 19.6	100.0 ± 0.0	97.1 ± 18.8	0.799

*ANOVA = analysis of variance; RF = rectus femoris; VL = vastus lateralis; BF = biceps femoris; ST = semitendinosus.
†Values are expressed as mean ± *SD*.

significant main effects in the maximal torque of knee extensor ($F = 1.348$, $p = 0.273$, partial $\eta^2 = 0.073$) and flexor ($F = 1.746$, $p = 0.190$, partial $\eta^2 = 0.093$) (Figure 4).

For knee extension MVIC, the IAP was not significantly correlated with the maximal torque in each condition ($r = 0.060$–0.391, $p = 0.108$–0.813). For knee flexion MVIC, the IAP was not significantly correlated with the maximal torque in normal ($r = 0.265$, $p = 0.288$) and expiratory ($r = 0.165$, $p = 0.514$) conditions, whereas the IAP was significantly correlated with maximal torque of knee flexor in inspiratory condition ($r = 0.616$, $p = 0.006$).

For %EMGmax during knee extension and flexion MVIC, there was no significant main effect in each muscle ($F = 0.028$–1.849, $p = 0.173$–0.972, partial $\eta^2 = 0.002$–0.098) (Table 2).

Discussion

In the current study, IAP was significantly correlated with muscle strength of hip extensor but not hip flexor. This was in agreement with a previous finding (21). By contrast, there were no significant correlations between IAP and muscle strength of knee extensor and flexor in each breath-hold condition (except for knee flexor strength in inspiratory condition: see below). In addition to the correlation analyses, this study demonstrated that the IAP and maximal torque of hip extensor were significantly greater in inspiratory condition than in expiratory condition when controlling lung volume by changing breathing state (Figure 2), whereas the maximal torque of each of hip flexor, knee extensor, and knee flexor was not different among the 3 breath-hold conditions (Figures 2 and 4). Furthermore, an 8-week abdominal bracing training improved maximal IAP and hip extensor strength, but not muscle strength of knee extensor (19), hip flexor, and knee flexor (unpublished data). Taking these observations into account, we can conclude that an increase in IAP contributes to specifically improve hip extensor strength, i.e., IAP has a causal effect specifically on hip extensor strength, as we hypothesized.

However, we do not argue that IAP is the primary contributor to hip extensor strength because the relationships between IAP and hip extensor strength observed in the present and previous (21) studies were moderate ($r = 0.504$–0.677). This study showed that there was no significant difference in hip extensor strength between normal and inspiratory or expiratory conditions, whereas the differences in IAP during hip extension MVIC were significant between the breath-hold conditions. Taken together, a sufficient increase in IAP might be needed to enhance hip extensor strength.

As mentioned above, there was a significant correlation between IAP and knee flexor strength in inspiratory condition, suggesting an association between IAP and knee flexor strength. However, association does not imply causality. In this study, the knee flexor strength was not different among the 3 breath-hold conditions despite the finding that IAP during the task was greater in inspiratory condition than in expiratory condition. Taken together, it is reasonable to say that IAP does not have a causal effect on knee flexor strength. At present, because the reason for the exceptional relationship between IAP and knee flexor strength in inspiratory condition remains unclear, further studies are required to elucidate this point.

Although the precise mechanisms for the causal effect of IAP on hip extensor strength are difficult to explain, an action of IAP for hip extension torque might be involved. It has been suggested that extension torque is caused by the pressure acting on the diaphragm and pelvic floor (i.e., IAP) (15,19). The effect of breathing state on abdominal and agonistic muscle activities may be another potential mechanism because the activities of abdominal muscles such as the oblique muscles, which are needed to produce IAP, can generate lateral forces transmitted to the lumbodorsal fascia, causing trunk/hip extension (4,14). In this study, however, there were no significant differences in %EMGmax during MVICs among the 3 conditions in all muscles examined except for GM. The %EMGmax of GM during hip extension MVIC was significantly higher in inspiratory condition than in normal condition, whereas the significant difference in hip extensor strength was observed between inspiratory and expiratory conditions but not between inspiratory and normal conditions. Thus, it is likely that the effect of the increased muscle activity of GM is substantially small.

In conclusion, this study revealed that the breathing state during MVIC influenced IAP and hip extensor strength. In addition, significant correlations were found between IAP and hip extensor strength in all the breath-hold conditions. These findings suggest that a sufficient increase in IAP has a causal effect to specifically improve hip extensor strength.

Practical Applications

The present findings may explain the importance and mechanism of core stability training. Core stability training has been considered to be effective for improving the function of abdominal muscles, and it has been commonly performed in sport fields in recent years. Although several studies have reported that core stability training improves physical performance such as sprint running and jumping (8,10,17,18), the precise underlying mechanism remains unclear. Based on the present and aforementioned previous findings (19), an increase in IAP by core stability training can lead to enhancement of physical performance to which hip extensor strength is the primary contributor, such as sprint running and jumping. Thus, we recommend including core stability exercises into the training program to enhance sports performances.

Acknowledgments

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