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Changes of abdominal wall tension across various resistance exercises during maximal and submaximal loads in healthy adults: a cross-sectional study

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Abstract

Introduction Resistance exercises are effective for maintaining health and activating stabilizing muscles, as they trigger abdominal wall tension responses. This study compared the effects of multi-joint and single-joint, upper-body and lower-body exercises (Lat pulldown, Rows, Peck deck, Chest press, Biceps curls, Triceps extensions, French-Press, Step up, Hip abduction/adduction, Squat, Leg press, Romanian deadlift, Hamstring curls) performed at maximal and submaximal intensities.

Methods This cross-sectional study included 12 men and 18 women (age:47.8 ± 5.9 years, height:174.8 ± 10.2 cm, weight: 77.7 ± 15.4 kg, BMI:25.3 ± 3.6), who wore a noninvasive sensor Ohmbelt to measure abdominal wall tension performing exercises at 15 repetition maximum (RM), 10RM, 5RM, and 1RM. Differences across exercises and sex were compared by Friedman test with Durbin-Conover post-hoc, and intensities were analyzed by Wilcoxon test.

Results The study found significant differences ($p < 0.05$) in abdominal wall tension changes based on the type of exercise and training intensity. Multi-joint lower-body exercises, such as the Romanian deadlift, dumbbell front squat, and leg press, led to the greatest increases in abdominal tension in both sexes in comparison to single-joint upper-body exercises. Males had higher abdominal wall tension changes than females ($p < 0.05$) at 1RM, 5RM, and 10RM. However, no significant difference was found at 15RM, indicating that lower intensities produce similar abdominal wall tension changes in both sexes.

Conclusions This study showed that multi-joint lower-body exercises were found to produce greatest abdominal wall tension increases, especially compared to single-joint upper-body exercises. The abdominal wall tension was higher in males than females due to higher loads, emphasizing the need for exercise-specific approaches.

Keywords Exercise prescription, Intra-abdominal pressure, Muscle activation, Noninvasive monitoring, Resistance exercise

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Introduction

Postural stabilization is a fundamental aspect of human body movement, crucial for maintaining equilibrium and having implications for overall health [1]. This dynamic process involves the coordinated efforts of various musculoskeletal components, primarily the diaphragm, abdominal muscles, and pelvic floor, working in synergy to establish and regulate intra-abdominal pressure (IAP) under the influence of the central nervous system [2]. This coordination is pivotal for stabilizing the spine and trunk, providing structural support against external forces and gravitational challenges [3–5]. It plays an essential role in everyday activities and training conditions, particularly during exercises that involve lifting weights and high-intensity movements. Generating IAP is a protective measure, mitigating the risk of injury associated with excessive mechanical loading during physical exertion. As a result, understanding and controlling IAP becomes crucial in exercises aimed at injury prevention, rehabilitation, and enhancing core stability during training.

IAP has substantial inter-individual variability, and specific activities induce significant variations. Additionally, variability in the measurement method itself can contribute to these differences. Under resting conditions, healthy individuals typically have IAP values between 5 and 7 mmHg [6]. IAP increases during different activities, with sitting at 17 mmHg, standing at 20 mmHg, and significantly higher during standing cough (108 mmHg) and jumping (171 mmHg) [4]. Thus, body position, movement type, and exercise intensity all play a key role in IAP fluctuation [7–9]. The review by Blazek et al. [10] on exercise-induced IAP demonstrated that lower-body multi-joint exercises, such as squats and deadlifts, significantly increase IAP values, reaching 201 ± 26 mmHg during squats and 156 ± 27 mmHg during deadlifts at maximal and submaximal loads. These values are notably higher than those observed in upper-body exercises. At the same time, significant differences in reported IAP values across studies increase inconsistencies in both the findings and the measurement methods used. For example, deadlift was reported for 90 mmHg [8] in one study and 161 mmHg in another [7], although both performed at same high intensity. However, there is a question of whether this IAP is transferred to the demands of the entire abdominal wall. Measuring abdominal wall expansion could provide valuable insights, as it may better reflect how IAP is distributed and utilized during exercise. This study employs abdominal wall expansion as a measurement method to capture these effects more accurately.

Resistance exercises (REs) can induce significant hemodynamic changes [11–13], especially when performed with maximum load or to failure. These high intense REs may pose health risks, including brain blackouts [14], temporary visual impairment, or other vascular brain injuries [15–17]. The risk of injury increases when physical capacities are surpassed, and cumulative loading can lead to microtrauma, spine overloading possibly contributing to tissue failure including ruptures and fractures [18–20]. To mitigate the risk of injury under excessive loads during RE, the abdominal wall and diaphragm must increase IAP and stabilize the trunk to unload the spine [21].

Various methods exist for assessing IAP, with instrumental measurements considered the most accurate [22, 23]. IAP can be measured indirectly (via methods such as ultrasonography and electromyography) [23] or directly (transperitoneal approach [22, 24], anorectal manometry [24, 25], femoral venous pressure [25], intravesical pressure [25, 26]. Direct measurement is considered more accurate, but it involves invasive procedures, influencing exercise comfort, posing a risk of infection, and interfering with the performance of REs. A suitable alternative method for measuring IAP during REs is assessing abdominal wall tension (AWT) [3]. This approach captures manifestations of trunk muscle activity and the level of IAP by measuring the external pressure generated by the expansion of the abdominal wall. Its non-invasive nature allows for evaluating pressure changes without the need for inserting measuring devices directly into the abdominal cavity. The IAP strongly correlates with AWT, with Pearson's correlation coefficients ranging from 0.651 to 0.921 across various postural-respiratory trunk activities [3]. The AWT can be monitored above the inguinal ligament and in the area of the superior trigonum lumbale, providing a non-invasive and indirect method for assessing IAP. Devices such as the Ohmbelt [27, 28] and DNS Brace [29] objectively measure AWT during these activities, indirectly reflecting IAP levels.

Several studies have investigated the effects of different RE on IAP, but the results vary depending on the type of exercise, indicating that different RE types produce distinct effects on IAP [7–9, 30]. The findings are often generalized and focus primarily on the role of exercise intensity in relation to specific types of RE [10]. However, there is a significant gap in the existing research when it comes to RE in relation to AWT measurement [3, 27, 28]. Despite evidence suggesting that factors such as sex and body position (standing, sitting, prone, and supine) [27, 28] may influence AWT and IAP, research in these areas remains limited. In particular, differences in connective tissue properties [31], including collagen content and fascial elasticity, could play a crucial role in these variations, yet their impact on performance and injury risk is not well understood. Additionally, studies comparing the

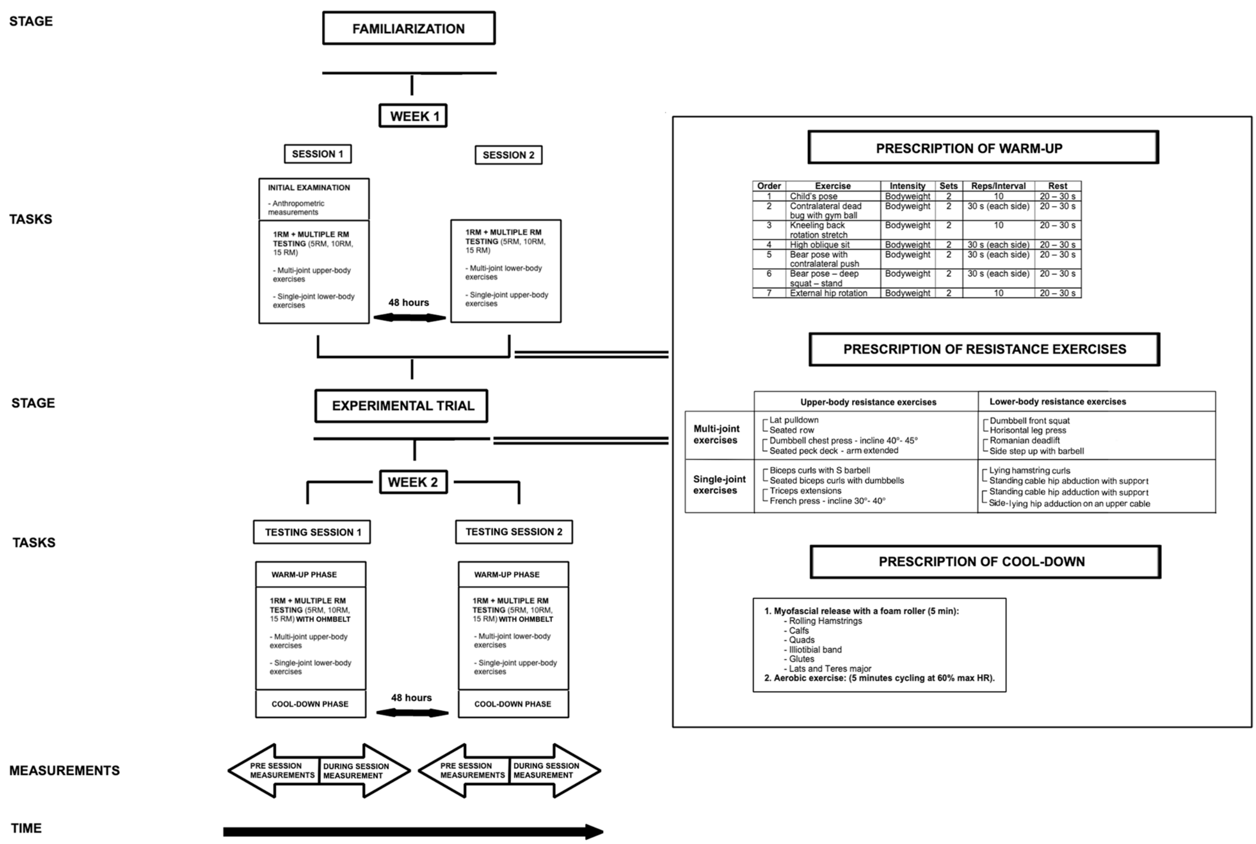

Fig. 1 Schematic overview of study design

effects of multi-joint and single-joint exercises on AWT are limited [27, 28], highlighting the need for further investigation into these key variables.

The aim of this study is to compare changes in AWT across different REs under submaximal and maximal loads to address this gap in the scientific literature. Specifically, we compare multi-joint versus single-joint exercises, upper- versus lower-body exercises, and explore potential sex differences. We hypothesize that multi-joint exercises, especially those targeting the lower body, will result in greater increases in AWT compared to single-joint exercises. We also hypothesize that sex-based differences in AWT will emerge due to variations in connective tissue properties and hormonal fluctuations between men and women.

Methods

Design

This cross-sectional study consisted of four sessions, with two sessions dedicated to familiarization, followed by two testing sessions. The structure of both the familiarization and testing sessions was designed to reflect a real training session, including a warm-up, 1RM and Multiple RM testing, and cool-down. All sessions were completed within 14 days. The changes in AWT induced by 15, 10, 5, and 1 repetition maximum (15RM, 10RM, 5RM, and 1RM) intensities were assessed during sixteen REs commonly used in gym settings. The REs were selected to represent upper-body, lower-body, single-joint and multi-joint exercises see in Fig. 1.

This study followed the Consolidated Standards of Reporting Trials (CONSORT) 2010 guidelines for reporting parallel group randomized trials [32] see in Supplementary material 3. The study was conducted with the approval of the Ethics Committee under protocol number 242/2018 and is registered in ClinicalTrials.gov database (no: NCT06047678), according to the Declaration of Helsinki 2013.

Participants

Thirty-five participants were recruitment from April 2022 to August 2023. The inclusion criteria for the study were as follows: Aged 40–63 years with normotensive blood pressure, health status allowing for participation in moderate to high-intensity resistance training (RT) and aerobic training, physically active with a minimum of 0.5 years of experience in RT but not professional athletes, and non-smoking status. Participant recruitment occurred in two private healthcare facilities with a cardiology clinic in Prague, Czech Republic. Potential participants were approached either by telephone based on a contact database or in person by physicians in their practices and facility staff. The exclusion criteria followed the recommendations of Williams et al. [33] and consisted of coronary artery disease, decompensated heart failure, heart rhythm disorders, severe and symptomatic aortic stenosis, acute myocarditis, endocarditis, or pericarditis, dissection of the thoracic aorta, and Marfan syndrome. Additionally, we excluded individuals with type 1 or type 2 diabetes mellitus, stroke, infectious diseases (COVID-19, influenza etc.) [34], grade 3 obesity (BMI $\geq$40.0 kg/m^2) [35], hypertension of grade I–IV (Systolic blood pressure $\geq$140 mmHg, Diastolic blood pressure $\geq$90 mmHg [36], those experiencing dizziness during exercise, acute or chronic musculoskeletal pain, or any neurological diseases.

To address potential confounding factors, participants were provided with detailed guidelines on nutrition, hydration and daily activities to minimize these variables. This approach aimed to ensure that the observed AWT changes were primarily attributed to the exercise variables rather than dietary and fluid balance inconsistencies.

The participants were categorized according to sex (male or female) and randomly assigned to different testing sessions using a random number generator, with the allocation sequence kept confidential until assignment. The process was managed by the principal investigator. Participants were blinded to their testing sessions, and the statistical analysis was conducted without prior knowledge of the group assignments. All subjects were informed about the study procedure and potential risks, and they volunteered to participate, providing written informed consent.

Procedures

Anthropometric assessment

Anthropometric measurements were conducted to assess body composition using the INBODY 370S device (Biospace, North Korea). This method is non-invasive, safe, accurate, and suitable for scientific research [37]. All measurements were performed in the morning hours between 7:00 and 10:00, during the familiarization week, prior to the start of resistence testing sessions. Participants were instructed to arrive early as possible after waking up. The measured parameters included body weight (kg), BMI (kg/m^2), body fat mass (kg), and lean mass (kg). Body height (cm) was measured using the ADE MZ 10017 (Germany GmbH) device, following the same schedule as the body composition measurements.

Familiarization session

Participants first underwent a familiarization session with the cable machines (David Health Solutions Ltd, Finland), free weight (Stronggear, Czechia). Since all participants were already familiar with the selected upper and lower body exercises, as they routinely practiced them in their own training, no new exercises were introduced, which significantly expedited the familiarization process. The 1RM and multiple RM testing were preceded by a thorough warm-up session, which was identical for all participants. Special attention was given to breathing technique, with each participant being thoroughly instructed and familiarized with the correct breathing patterns for optimal performance. After completing the 1RM and multiple RM testing, the cool-down phase followed.

- *Warm-up:* 10 min (60% HR max) with Wattbike cycle ergometer (Wattbike ltd, United Kingdom) and Dynamic neuromuscular stabilization (DNS) [38] routine (supine leg raise position, bear position, and squat, each lasting 30 s and 2 sets). The rest interval between sets was 20 s, and between exercises, it was 30 s.
- *1RM and multiple RM testing:* The study included two familiarization sessions to progressively introduce participants to RM testing and ensure proper technique before the main testing phase. RM testing followed a structured approach, starting with 15RM and progressing to 10RM, 5RM, and finally 1RM, in line with Liguori et al. [39]. The initial load was estimated based on the participant's training history and adjusted accordingly. For each RM level, participants performed a set at their estimated RM load. If they completed the required number of repetitions, the load was increased in subsequent sets until they reached momentary failure within the target rep range (e.g., failing 15 reps for 15RM, 10 reps for 10RM, etc.). The number of sets varied depending on how quickly the appropriate load was identified, typically ranging from 1 to 3 sets per exercise. Load adjustments followed a stepwise increase of approximately 5–10% for upper-body exercises and 10–15% for lower-body exercises [39]. Specifically, participants practiced 16 exercises in total, split into two exercise sessions, with 4 multi-joint exercises followed by 4 single-joint exercises per session, in line with ACSM [40] recommendations. To ensure consistency and avoid fatigue during the testing sessions, the rest interval between sets and exercises was set at 3–5 min, with a movement tempo of 3–0–2 s (eccentric-isometric-concentric). Each familiarization session lasted 90–120 min, focusing on proper

technique for each exercise. During these sessions, a researcher provided active sparing, ensuring correct movement execution and addressing any potential issues during the 1RM attempts. This sparing was key to maintaining safety and proper form. The familiarization session ensured that the participants were fully prepared for the actual testing sessions, where they would apply the same techniques and effort.

- *Cool-down phase:* The cool-down phase began with 5 min of myofascial release using a foam roller, targeting the hamstrings, calves, quads, iliotibial band, glutes, lats, and teres major. This was followed by 5 min of AE, consisting of cycling at 60% of maximal HR.
- *Breathing technique:* The participants were instructed to follow a breathing technique: inhaling during the eccentric phase of the movement, breath hold and exhaling during the concentric phase [41]. We acknowledged that, at higher intensities (> 80% maximal voluntary contraction), a brief Valsalva maneuver (VM)—involving forced exhalation against a closed glottis—becomes unavoidable. Similarly, when performing repeated lifts with lighter loads until failure, the VM is necessary as motor units progressively fatigue [42]. Participants were thoroughly familiarized with this breathing technique to ensure proper implementation. In cases where the correct breathing technique was not followed, the attempt was repeated to ensure proper execution and compliance with the required technique.

Performing testing sessions

The testing sessions were based on the results from the familiarization phase for multiple RM and 1RM testing. One of the sessions consisted of four upper-body multi-joint exercises (Lat pulldown, Seated rows, Seated peck deck, Dumbbell chest press) and four lower-body single-joint exercises (Lying hamstring curls, Standing cable hip abduction, Standing cable hip adduction, Side-lying Hip Adduction). The other session consisted of four lower-body multi-joint exercises (Dumbbell front squat, Horizontal leg press, Romanian deadlift, Side step up with barbell) and four upper-body single-joint exercises (Biceps curls with s barbell, Seated biceps curls with dumbbells, Triceps extensions, French press). All REs were performed in a specific order, progressing from multi-joint to single-joint exercises, as shown in Fig. 1.

Each exercise was performed at increasing intensities: 15RM (3-min rest), 10RM (3-min rest), 5RM (5-min rest), and 1RM (5-min rest), with strict technique, tempo (3–0–2), and a regular breathing cycle required. Adequate rest periods were strategically used between varying intensities and exercises to prevent fatigue from earlier exercises from affecting the results of subsequent exercises or distorting AWT values. Participants completed the same warm-up and cool-down as in the familiarization phase. They were asked to avoid any resistance or high-intensity anaerobic workouts for the study's duration. Each session was supervised by the researcher to ensure proper performance in the gym, with active sparing provided throughout, while the Ohmbelt device was used to measure AWT.

Nutritional and hydratation recommendations

From the familiarization phase, participants followed a standardized dietary program, consuming approximately 3.7 L of fluids daily for men and 2.7 L for women [43], with alcohol intake strictly avoided. In the 2–3 days leading up to the testing session, they were instructed to avoid foods that could cause bloating [44] (e.g., beans, lentils carbonated drinks), as this could affect intra-abdominal pressure [45]. Additionally, participants refrained from eating for at least two hours prior to the exercise. To ensure consistency and adaptation to the dietary regimen, participants practiced abstaining from food for two hours before exercise during the 2–3 days leading up to the testing session. At the same time, they were instructed to drink 500–600 ml of water 2–3 h before exercise to ensure proper hydration. During exercise, they were advised to drink 180–200 ml of cold water every 15–20 min to maintain hydration and prevent fatigue [46].

Abdominal wall tension assessment

The Ohmbelt device (Nilus Medical LLC, Redwood City, CA, USA) was employed to evaluate abdominal wall activity. The tension of the abdominal wall during respiratory and postural maneuvers exerts pressure on sensors and is quantified as a force in grams per unit time (1 g = 0.01 N), a metric commonly employed in medical research [47, 48]. The device utilizes a capacitive force sensor to detect increases in pressure exerted by the abdominal wall, and it is securely fastened with an adjustable strap in, as shown in Fig. 2. The device was utilized for data collection, with information from the sensor being simultaneously recorded and processed through dedicated software. The Ohmbelt software, employing Bluetooth digital signal transmission, visually presents data from the sensor and facilitates seamless data exportation to MS Excel for immediate statistical analysis [3, 27, 28].

Assessments were conducted by a singular, clinician under standardized conditions during the 1RM and multiple RM testing sessions for REs. The Ohmbelt was securely positioned on the participant's trunk—one

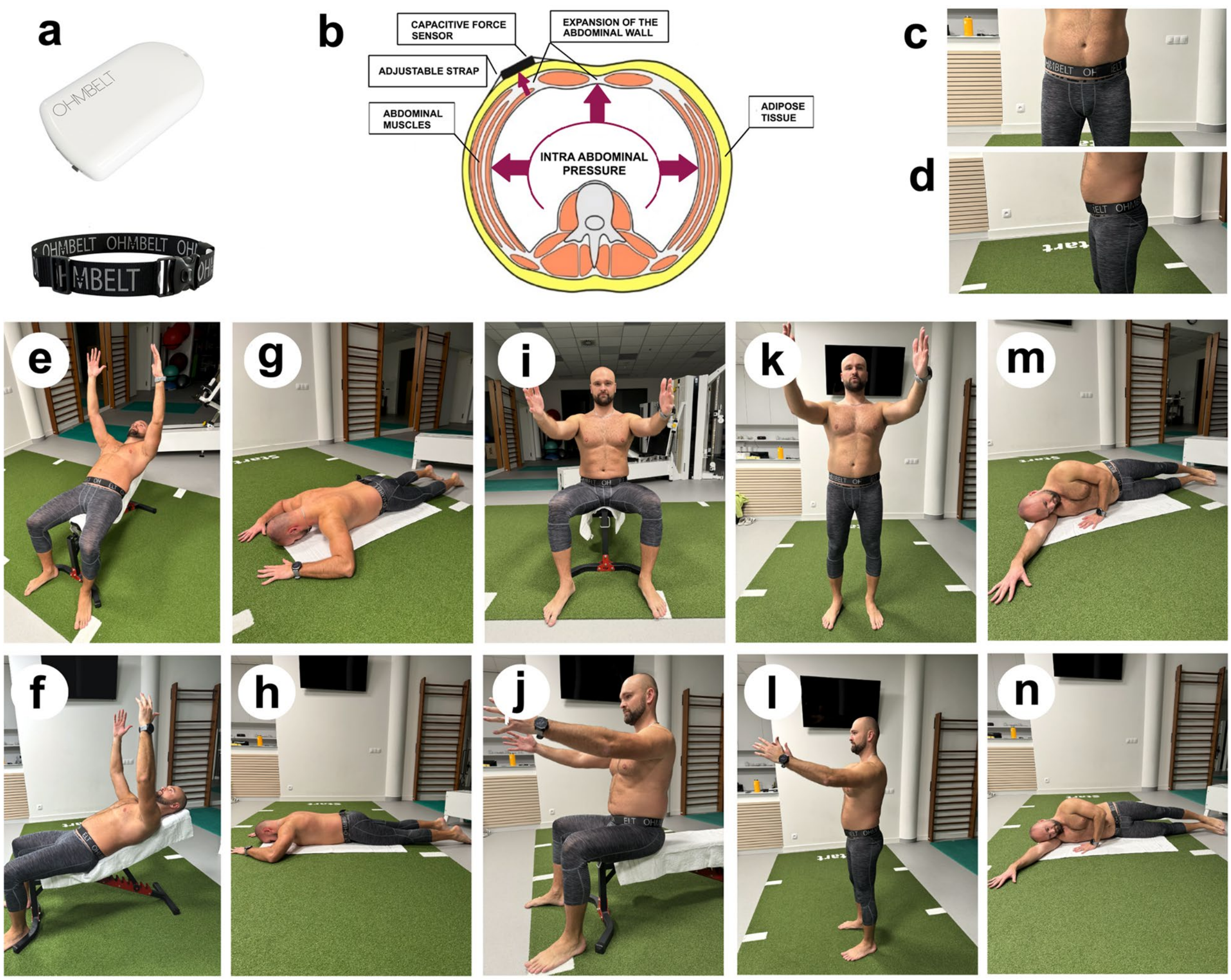

Fig. 2 a. Picture of the capacitive force sensor and belt; b. Scheme of abdominal cavity and attached sensor; c. anterior view, sensor placed above the inguinal ligament; d. lateral view, sensor placed above the inguinal ligament; e.-f. Initial supine position for Dumbbell chest press, French press and Horizontal leg press; g.-h. Initial prone position for lying hamstring curls; i.-j. Initial sitting position for Lat pulldown, Seated rows, Seated peck deck and Seated biceps curls with dumbbells; k.-l. Initial standing position for Biceps curls with s barbell, Triceps extensions, Dumbbell front squat, Romanian deadlift, Side step up with barbell, Standing cable hip abduction, Standing cable hip adduction; m.-n. Initial position for Side-lying hip adduction on an upper cable

for monitoring the force of AWT in the upper lumbar triangle contralaterally (anterior sensor—Fig. 2 cd). The Ohmbelt was affixed with a force of 100 g (± 10 g) and calibrated through repeated measures of unloaded breathing [3, 27]. The minimal detectable change was 9 g, while a meaningful change was considered to be 26 g. For each initial position, which included supine, prone, sitting, standing, and right and left lateral recumbent positions in Fig. 2, the Ohmbelt was recalibrated each time.

Statistical analysis

The Shapiro–Wilk test was used to assess the normality of the data distribution, which showed the deviations from normal distribution ($p < 0.05$). Therefore, median and interquartile range was used as descriptive statistics to establish central tendency and variability measures. The interrater intraclass correlation coefficient was used to check data reliability see in Supplementary material 1. The Friedman test with a Durbin-Conover post-hoc test for analysis was used to compare AWT between all exercises, four types of exercises and sex. To determine if there was a significant difference between exercise intensity the Wilcoxon signed-rank test was applied. This approach was chosen because the data did not follow a normal distribution. For all intensities beyond 1RM, comparisons were consistently made between repetitions with the maximum difference between baseline and peak. Statistical significance level was set at $\alpha =$

Table 1 Baseline characteristics of study participants

Characteristics	Total (n = 30)	Male (n = 12)	Female (n = 18)
Age (years)	47.8 (± 5.9)	48.6 (± 6.8)	47.3 (± 5.4)
Height (cm)	174.8 (± 10.2)	184.3 (± 8.5)	168.4 (± 4.9)
Weight (kg)	77.7 (± 15.4)	91.3 (± 12.9)	68.7 (± 9.0)
Lean mass (kg)	33.0 (± 8.2)	41.3 (± 6.0)	27.2 (± 2.9)
Body fat mass (kg)	19.2 (± 6.4)	18.6 (± 6.2)	19.6 (± 6.9)
BMI (kg/m^2)	25.3 (± 3.6)	26.9 (± 3.3)	24.2 (± 3.5)
Resistance training experiences (years)	4.2 (± 4.7)	6.2 (± 5.8)	2.8 (± 3.4)

BMI body mass index

0.05, considering $p < 0.05$ as a significant difference, and all analyses were performed using the statistical software R-Studio version 2023.12.1.

Results

The sample size was calculated a priori using G*power software (version 3.1. Dusseldorf, Germany) for repeated measures ANOVA within-between interaction with statistical power of 0.80, a level of significance of 0.05, and effect size d = 1.2, based on a similar study [28] evaluating AWT across different movement patterns. A minimum of 8 sample size was recommended for the measurements. A total of 30 participants completed the study (12 males, 18 females) with an average age of 47.8 ± 5.9 years, with only these data included in the analyses. Intra-class correlation within all repeated measurements resulted in a coefficient of 0.9 and higher. Repeated measurements were taken for each exercise at 1RM, 5RM, 10RM, and 15RM intensities, both at baseline and peak. Participant's demographics data are presented in Table 1. Four participants were unable to complete the study due to time constraints and one participant dropped out in the familiarization session feeling unable to complete the testing requirements.

Muscle strength test

Statistically significant differences were observed between the loads for both upper ($p < 0.05$) and lower body ($p < 0.05$) and also between sexes ($p < 0.05$). Referring to Table 2, male participants achieved their highest lifting weights during multi-joint exercises for both the lower and upper body. Specifically, the Leg press (150.8 ± 36.9 kg), Romanian deadlift (72.1 ± 16.6 kg), Seated row (97.1 ± 12.2 kg) and Lat pulldown (63.6 ± 10.3 kg), resulted in higher lifting weights compared to single-joint exercises ($p < 0.05$). Similarly, for females, the highest loads were lifted during multi-joint exercises, with the highest values measured in the Horizontal leg press (102.5 ± 19.1 kg), Seated rows (65.3 ± 10.8 kg), and Romanian deadlift (43.4 ± 13.2 kg), compared to single-joint exercises ($p < 0.05$).

Abdominal wall tension during 1RM exercises

The study revealed significant differences in AWT across various REs, showing that the level of tension in the abdominal region varies depending on the exercise type ($p < 0.05$). Sex-based differences were also evident, with greater abdominal wall expansion observed in males compared to females ($p < 0.05$). This was evident in both multi- and single-joint exercises, where males experienced higher increases in AWT.

The exercises focusing on the lower body, such as the Romanian deadlift (Median*, Mdn = 435 g;* interquartile range*; IQR = 182.5)*, Dumbbell front squat *(Mdn = 332.5 g; IQR = 360.5)*, and Horizontal leg press *(Mdn = 284.5 g; IQR = 201)*, exhibited the most pronounced activity in the abdominal wall in the male group, specifically. Only two exercises targeting the upper-body, such as Lat pulldown *(Mdn = 273.5 g; IQR = 184),* Biceps curls with s bar *(Mdn = 201.5 g; IQR = 168)* exceeded 200 g. Then Seated row *(Mdn = 193 g; IQR = 145.5),* Seated peck deck *(Mdn = 161 g; IQR = 116.5)* and Triceps extension *(Mdn = 158 g; IQR = 147.5) exceeded* 100 g. The other exercises targeting the upper body did not exceed the threshold of 100 g see in Fig. 3b and Supplementary material 2.

Similarly, among females, the highest increase in AWT was observed in multi-joint exercises for the lower body, specifically in the Romanian deadlift *(Mdn = 143 g; IQR = 99.5)*, Leg press *(Mdn = 126 g; IQR = 214)*, and Dumbbell front squat *(Mdn = 112.5 g; IQR = 79)*. All other exercises, both for the upper and lower body, were below 100 g see in Fig. 3b and Supplementary material 2.

Abdominal wall tension during 5RM exercises

Significant differences ($p < 0.05$) in the changes in AWT were found between sexes, type of exercises and lower and upper-body exercises. Multi-join exercises in male group targeting the lower body, such as Romanian deadlift *(Mdn = 353 g; IQR = 167)*, Dumbbell front squat (*Mdn =* 269 g; *IQR = 327*), and Horizontal leg press *(Mdn = 203.5 g; IQR = 128)* exceed the threshold of 200 g at 5RM. Among the exercises targeting the lower-body, only two Side-lying hip adduction *(Mdn = 81.5 g; IQR = 95.5)* and Standing cable hip adduction *(Mdn = 76 g; IQR = 95.5)* did not exceed the threshold of 100 g. Similarly, for the upper body, the exercises that also remained below this threshold included Seated bicep curls with dumbbells *(Mdn = 85.5 g; IQR = 88.5)*, Seated

Table 2 Muscle Strength Test Results for 15RM, 10RM, 5RM, and 1RM

Exercise	Male[a]				Female[a]			
	15RM (kg)[b]	10RM (kg)[b]	5RM (kg)[b]	1RM (kg)[b]	15RM (kg)[b]	10RM (kg)[b]	5RM (kg)[b]	1RM (kg)[b]
Upper-body and multi-joint RE								
Lat pulldown	38.8 (± 7.5)	45.6 (± 9.1)	53.8 (± 9.5)	63.6 (± 10.3)	21.0 (± 4.1)	24.9 (± 4.3)	29.6 (± 4.9)	35.4 (± 6.1)
Seated rows	52.7 (± 10.4)	66.7 (10.5)	78.8 (± 12.0)	97.1 (± 12.2)	38.2 (± 7.3)	44.7 (± 8.8)	53.6 (± 9.7)	65.3 (± 10.8)
Seated peck deck—elbow extended	26.0 (± 4.2)	31.9 (± 5.7)	38.3 (± 8.4)	46.5 (± 12.5)	8.9 (± 3.0)	11.5 (± 3.3)	14.2 (± 3.7)	18.1 (± 4.9)
Dumbbell chest press—incline 40°- 45°	24.5 (± 8.9)	28.0 (± 9.3)	38.5 (± 11.4)	44.3 (± 11.7)	9.4 (± 2.7)	13.4(± 2.8)	18.7 (± 4.7)	23.0 (± 5.9)
Upper-body and single-joint RE								
Biceps curls with S barbell	17.7 (± 4.7)	22.2 (± 5.4	27.8 (± 6.9	35.8 (± 9.2)	8.97 (± 2.1)	11.6 (± 2.4)	14.3 (± 3.1)	17.1 (± 4.0)
Seated biceps curls with dumbbells	16.8 (± 3.2)	22.3 (± 4.1)	27.8 (± 5.1)	34.6 (± 8.4)	7.0 (± 2.0)	9.8 (± 2.1)	13.0 (± 2.5)	17.4 (± 4.6)
Triceps extensions	33.1 (± 6.0)	41.3(± 9.0)	49.2 (± 12.8)	62.5 (± 18.0)	18.6 (± 4.8)	24.0 (± 5.2)	29.2 (± 6.2)	35.6 (± 8.0)
French press – incline 30°- 40°	15.7 (± 5.2)	20.9 (± 5.1)	26.0 (± 5.6)	32.3 (± 6.7)	8.7 (± 2.9)	11.2 (± 3.4)	14.1 (± 4.1)	17.7 (± 4.7)
Lower-body and multi-joint RE								
Dumbbell front squat	24.3 (6.0)	32.1 (± 6.5)	42.2 (± 8.4)	54.3 (± 10.3)	14.6 (± 5.2)	18.8 (± 6.6)	24.1 (± 8.1)	31.1 (± 11.2)
Horizontal leg press	88.3 (± 19.4)	106.7 (± 24.4)	126.7 (± 30.8)	150.8 (± 36.9)	60.6 (± 13.2)	73.3 (± 13.3)	85.3 (± 14.7)	102.5 (± 19.1)
Romanian deadlift	35.7 (± 9.3)	46.2 (± 11.5)	56.5 (± 12.8)	72.1 (± 16.6)	21.7 (± 8.6)	27.2 (± 10.1)	33.6 (± 10.7)	43.4 (± 13.2)
Side step up with barbell	15.2 (± 4.7)	20.4 (± 6.7)	26.5 (± 8.7)	34.8 (± 11.6)	10.1 (± 3.9)	13.6 (± 4.3)	18.2 (± 5.9)	24.6 (± 7.2)
Lower-body and single-joint RE								
Lying hamstring curls	22.9 (± 6.2)	30.0 (± 6.7)	36.9 (± 9.1)	46.5 (± 9.2)	16.5 (± 5.5)	22.2 (± 6.5)	27.5 (± 7.3)	35.6 (± 8.0)
Standing cable hip abduction with support	10.8 (± 2.0)	15.8 (± 2.0)	20.8 (± 2.0)	30.0 (± 3.0)	8.4 (± 2.6)	12.9 (± 2.5)	17.8 (± 2.6)	24.7 (± 4.0)
Standing cable hip adduction with support	19.6 (± 5.4)	27.1 (± 5.8)	33.8 (± 6.4)	43.8 (± 9.3)	15.0 (± 3.8)	21.1 (± 4.7)	26.7 (± 5.4)	33.1 (± 5.7)
Side-lying hip adduction on an upper cable	23.8 (± 6.1)	32.1 (± 6.2	40.8 (± 7.0)	52.1 (± 7.8)	19.7 (± 5.0	26.1 (± 5.6)	32.1 (± 6.0)	39.5 (± 6.3)

RE resistance exercise, *RM* repetition maximum

[a] Statistically significant differences between sexes $p < 0.05$

[b] Statistically significant differences between loads $p < 0.05$

row *(Mdn = 77.5 g; IQR = 46.5)*, French press *(Mdn = 59.5 g; IQR = 92.5)*, and Chest press *(Mdn = 59 g; IQR = 33)*. However, only one multi-joint exercise for the upper body, the Lat pulldown *(Mdn = 210.5 g; IQR = 255.5)*, showed values above 200 g. see Fig. 4a and Supplementary material 2.

In female group, the 100 g threshold was exceeded in leg press *(Mdn = 124 g; IQR = 76.5)*, Dumbbell front squat *(Mdn = 115.5 g; IQR = 104.5)*, which are multi-joint exercises for the lower-body, as well as in the Seated peck deck *(Mdn = 104.5 g; IQR = 74)*, a multi-joint exercise for the upper-body. Surprisingly, the Chest press *(Mdn = 48 g; IQR = 39)* remained below the 50 g threshold see Fig. 4b and Supplementary material 2. Significantly lower increases in AWT were observed in females compared to males ($p < 0.05$), both in multi-joint and single-joint exercises. While both sexes experienced an increase in AWT, males showed a more pronounced and greater abdominal wall expansion.

Abdominal wall tension during 10RM exercises

Significant differences ($p < 0.05$) in the changes in AWT were found between sexes, type of exercises and lower and upper-body exercises. More than 300 g was found in the male group for the Romanian deadlift *(Mdn = 324 g; IQR = 108.5)* and Dumbbell front squat *(Mdn = 316 g; IQR = 360.5)*, both of which are multi-joint exercises targeting the lower body. In contrast, only two exercises: Standing cable hip abduction *(Mdn = 57 g; IQR = 80)* and Side-lying hip adduction *(Mdn = 56 g; IQR = 125.5)* remained below the 100 g threshold. For the upper body, exercises such as Lat pulldown *(Mdn = 183 g; IQR = 181.5)*, Seated peck deck *(Mdn = 178.5 g; IQR = 223.5)*, Bicep curls with an s bar *(Mdn = 113.5 g; IQR = 102)*, and Triceps extensions *(Mdn = 108.5 g; IQR = 110)* exceeded 100 g, while the remaining upper-body exercises had lower values see Fig. 5a and Supplementary material 2.

In the female group, three multi-joint lower-body exercises exceeded the 100 g threshold: Dumbbell front

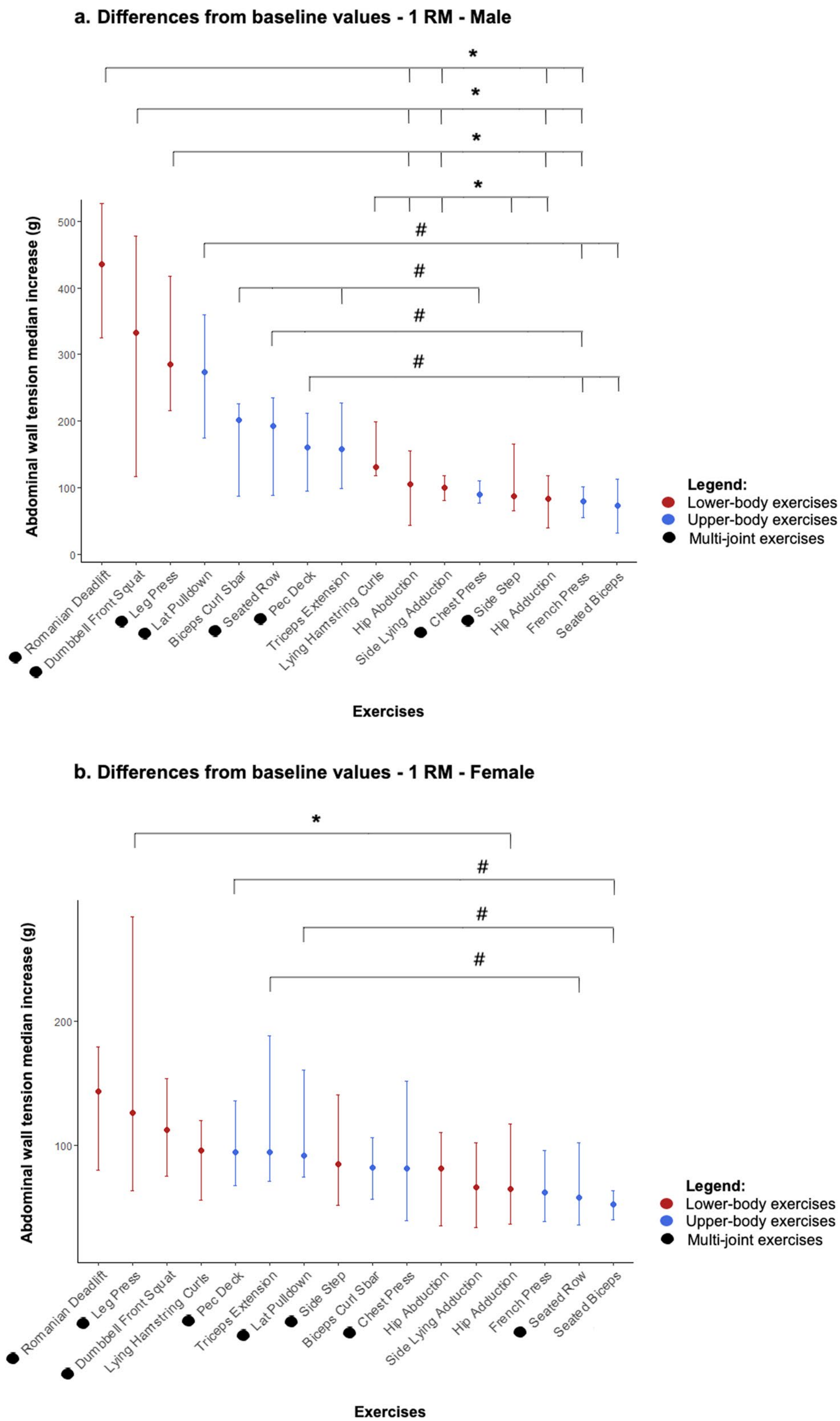

Fig. 3 a. Changes of abdominal wall tension across common resistence exercises during 1RM in male; b. Changes of abdominal wall tension across common resistence exercises during 1RM in female. *Differences were statistically significant between multi-joint lower-body exercise, and lower-body single-joint exercises, $p < 0.05$. #Differences were statistically significant between multi-joint upper-body exercise, and single-joint upper-body exercises, $p < 0.05$

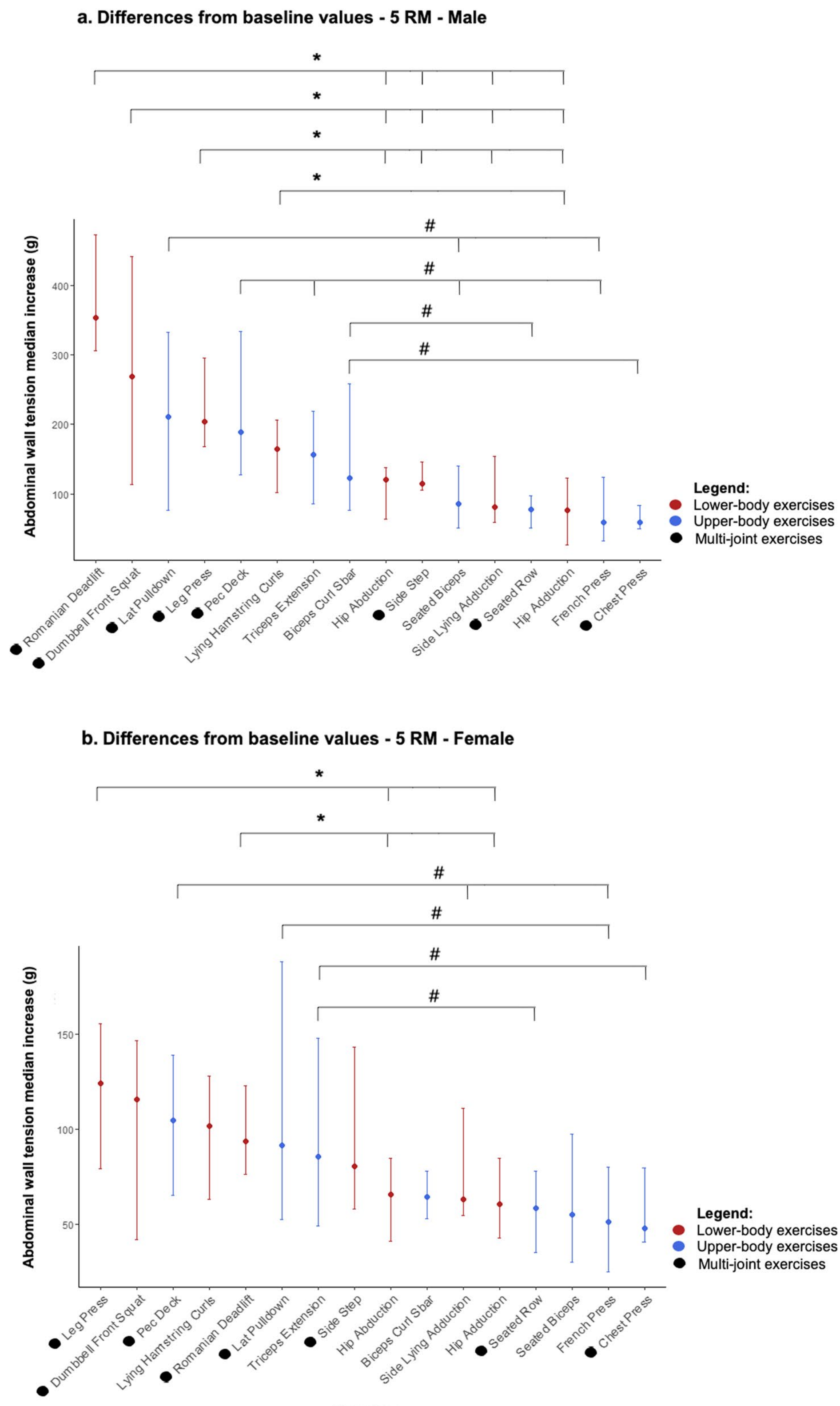

Fig. 4 a. Changes of abdominal wall tension across common resistance exercises during 5RM in male; b. Changes of abdominal wall tension across common resistance exercises during 5RM in female. *Differences were statistically significant between multi-joint lower-body exercise, and lower-body single-joint exercises, $p < 0.05$. #Differences were statistically significant between multi-joint upper-body exercise, and single-joint upper-body exercises, $p < 0.05$

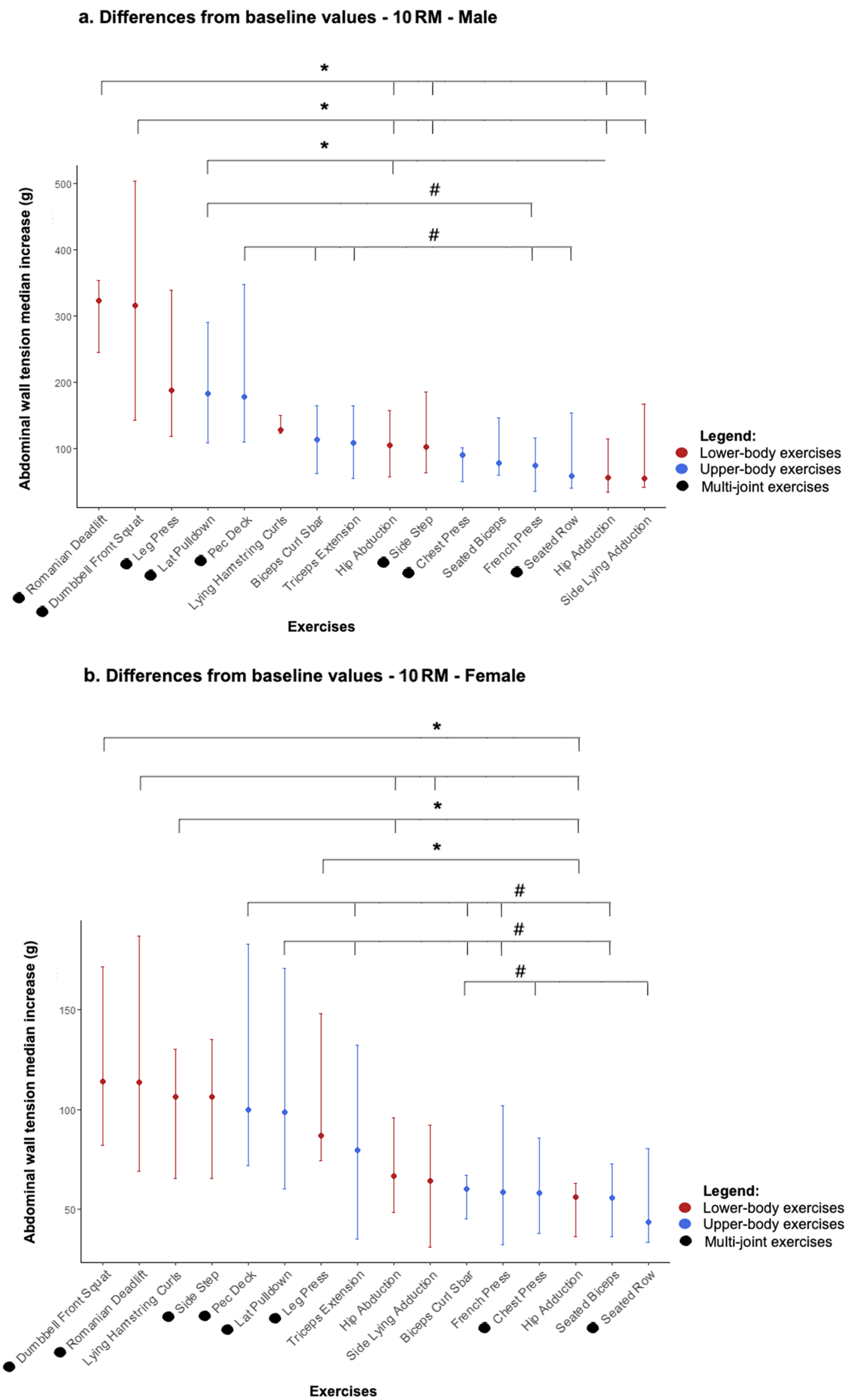

Fig. 5 a. Changes of abdominal wall tension across common resistence exercises during 10RM in male; b. Changes of abdominal wall tension across common resistence exercises during 10RM in female. *Differences were statistically significant between multi-joint lower-body exercise, and lower-body single-joint exercises, $p < 0.05$. #Differences were statistically significant between multi-joint upper-body exercise, and single-joint upper-body exercises, $p < 0.05$

squat (Mdn =114 g; IQR =89.5), Romanian deadlift (Mdn =113.5 g; IQR =118), and Side steps (Mdn =106.5 g; IQR =69.5). Additionally, the single-joint lower-body exercise, Lying hamstrings curls (Mdn =106.5 g; IQR =65), also surpassed this threshold. Among upper-body exercises, only the multi-joint Seatec peck deck (Mdn =100 g; IQR =112.5) exceeded 100 g, while the Seated row (Mdn =43.5 g; IQR =47) remained below 50 g see Fig. 5b and Supplementary material 2. Both males and females showed an increase in AWT, but the expansion was significantly greater in males than in females ($p < 0.05$). This difference was observed in both multi-joint and single-joint exercises, with females showing notably lower increases in AWT.

Abdominal wall tension during 15RM exercises

Significant differences ($p < 0.05$) in the changes in AWT were found between type of exercises and lower and upper-body exercises. In the male group, the Dumbbell front squat *(Mdn = 339 g; IQR = 183.5)* showed an increase of over 300 g, while the Romanian deadlift *(Mdn = 279 g; IQR = 138.5)* exceeded 200 g. The multi-joint exercise Leg press *(Mdn = 112.5 g; IQR = 83.5)* and single-joint exercise Lying hamstring curls *(Mdn = 100 g; IQR = 93.5)* surpassed 100 g, which are targeting the lower-body. In contrast, other single-joint exercises for the lower-body remained below 100 g. Among upper-body exercises, only the multi-joint Seated peck deck *(Mdn = 105 g; IQR = 154)* exceeded 100 g, while Bicep curls with s bar *(Mdn = 47 g; IQR = 110)*, Chest press *(Mdn = 43 g; IQR = 31)*, and Seated bicep curls with dumbbells *(Mdn = 30.5 g; IQR = 55.5)* were below 50 g see Fig. 6a and Supplementary material 2.

In the female group, the dumbbell front squat *(Mdn = 111.5 g; IQR = 82)* and Romanian deadlift *(Mdn = 110.5 g; IQR = 112.5)* were the only exercises to surpass 100 g, with the lowest values found for Standing cable hip adduction *(Mdn = 46.5 g; IQR = 37.5)*, Seated row *(Mdn = 43.5 g; IQR = 45.5)*, and Seated bicep curls with dumbbells *(Mdn = 43 g; IQR = 16)*, all below 50 g see Fig. 6b and Supplementary material 2.

Discussion

This study evaluated the impact of sixteen REs commonly used in the gym and their different training intensities on acute AWT values in healthy adult men and women experienced in resistance training. The study found significant differences ($p < 0.05$) in AWT changes based on exercise type especially multi-joint exercises for the lower-body, such as the Romanian deadlift, Dumbbell front squat, and Leg press, producing the highest increases in AWT. Key findings also showed that at both maximum intensity (1RM) and submaximal intensities (5RM and 10RM), AWT increased significantly from baseline to peak in both sexes ($p < 0.05$). However, at 15RM, no statistically significant differences were observed between men and women across the REs, suggesting that at lower intensities, AWT changes similarly in both sexes.

Using maximal resistance intensities at 1RM led in our study to the highest increases in AWT values compared to submaximal resistances. Our results are consistent with previous research by Kawabata et al. [8, 9], who found heightened IAP during deadlifts at various knee positions across intensities from 30 to 100% of 1RM, and by Harman et al. [7], who observed similar trends across deadlifts, leg presses, box lifts, slide rows, and bench presses at intensities ranging from 15 to 4RM. However, our study encompasses various REs, highlighting its comprehensive nature. Therefore, beginners should initiate training with lower resistance levels, gradually increasing intensity as adaptation occurs. Neglecting a systematic approach to resistance training may lead to adverse outcomes, such as abdominal wall hernia [49] or even blackout [14], making it essential to understand the impact of training intensities to mitigate these risks. As intensity increases, particularly at maximal effort (e.g., 1RM), AWT rises proportionally, playing a crucial role in spinal stabilization by enhancing trunk rigidity and load distribution [21]. However, its protective function is only effective when combined with proper technique, sufficient recovery, and gradual progression. Poor mechanics, excessive fatigue, or sudden increases in intensities may still elevate the risk of injury [50] despite higher AWT. Conversely, lower intensities (e.g., 15RM) generate less AWT, making them more suitable for beginners or individuals recovering from injury. A well-structured, progressive training approach is therefore essential gradually increasing intensity while ensuring optimal biomechanics [40]. Additionally, sex-related physiological differences may influence AWT responses, highlighting the need for individualized training strategies to optimize trunk stability and performance across various loading conditions.

Our study accounted for sex differences in AWT and found a significant increase from baseline to peak values at both maximal (1RM) and submaximal (5RM and 10RM) intensities across both males and females ($p < 0.05$). Notably, AWT increases were higher in males than in females, which may be attributed to distinct demands placed on respiratory and stabilizing muscles. At lower intensities, the reduced AWT increase could reflect a decreased need for deep or forceful breathing, minimizing disparities in abdominal engagement between sexes. Physiological factors likely influence these findings: females typically show greater thoracic movement, while males display more abdominal excursion during respiration [51]. Moreover, females tend to engage

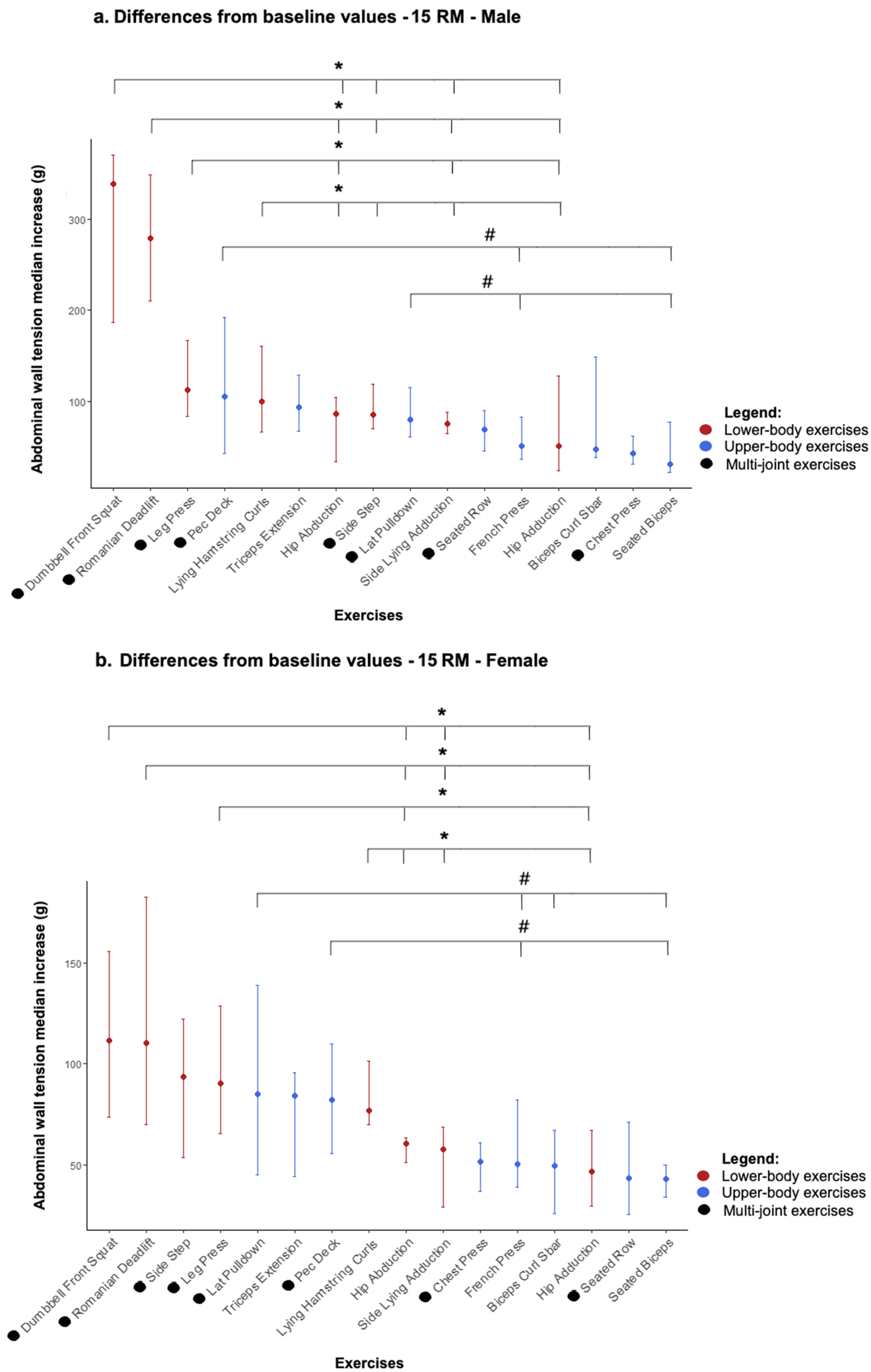

Fig. 6 a. Changes of abdominal wall tension across common resistence exercises during 15RM in male; b. Changes of abdominal wall tension across common resistence exercises during 15RM in female. *Differences were statistically significant between multi-joint lower-body exercise, and lower-body single-joint exercises, $p < 0.05$. #Differences were statistically significant between multi-joint upper-body exercise, and single-joint upper-body exercises, $p < 0.05$

the diaphragm, scalene, and sternocleidomastoid muscles more during exertion, which could result in reduced activation of the abdominal wall and thus contribute to the AWT differences [52]. This is further compounded by the generally lower resistance lifted. Overall, these results highlight sex differences in AWT changes.

An important finding of our study was that AWT is significantly influenced by the specific muscle groups targeted during exercises. At 5RM, 10RM, and 15RM, significant differences were observed in AWT increases between lower- and upper-body exercises ($p < 0.05$). However, at 1RM, no significant difference in AWT increase was found across targeted muscle groups. Our results showed that multi-joint exercises for the lower-body, such as the Romanian deadlift, dumbbell front squat, and leg press, result in the highest increase in AWT. In the lower positions of these movements, the compressed organs and diaphragm exert pressure on the abdominal wall, necessitating careful management to prevent abdominal protrusion [53] and creating optimal conditions for the synergistic engagement of all muscles involved [54]. Failure to appropriately engage the abdominal wall may result in undue leverage transfer onto the paravertebral muscles [55]. These results are similar to those found in a systematic review by Blazek et al. [10] which revealed that squats or exercises incorporating a squatting task (e.g., deadlift, leg press, clean and jerk) exhibit the highest increase in IAP, compare to bench press [7]. However, it is essential to also reference additional studies that observed significant differences between exercises performed in a standing, hanging, seated, and supine position [28, 56], as demonstrated in our study as well. AWT is most prominently engaged during exercises requiring enhanced trunk stabilization, particularly when the body must contend with gravity and vertical load position, stabilizing more during standing than sitting and supine position [56], perceived as a passive body position. This is especially evident in squatting REs, where support of both lower limbs is required. Moreover, when body position is further combined with the Valsalva maneuver under high resistance, the resulting increase in pressure becomes especially pronounced. For this reason, we should respect the selection of exercises and intensities tailored to each individual to achieve the best possible outcome, whether in the form of improving athletic performance or preventing sports-related injuries. During RE, the priority is placed on spinal stability, aiming to achieve proper body alignment and maintain a consistent breathing pattern for each exercise [8, 10, 57]. This approach is motivated by the desire to achieve optimal adaptations in body structures, ultimately enhancing overall stability while minimizing the potential risk of injury [21, 57]. It is worth noting that these practices not only represent an effective training regimen but also a strategy for preventing potential future complications associated with exercise [58].

Given the study results, it would be beneficial to compare untrained individuals with the outcomes of this study, which included healthy men with resistance training experience of 6.2 (± 5.8) years and women with 2.8 (± 3.4) years of experience. Furthermore, it is essential to consider respiratory rhythm more extensively and to further compare differences not only between trained and untrained individuals but also between those experiencing pain, as the values of AWT for individual exercises may differ compared to healthy individuals without pain. This could be also valuable in rehabilitation conditions. Finally, it's important to compare different variations of exercises to find significant differences between free weights and cable machine exercises, and to consider the ROM.

Study limitations

This study has some limitations. The findings are based on healthy, trained individuals, which limits their applicability to untrained populations or those with different training backgrounds. Variability in participants'years of experience and specific RT modalities may have influenced AWT responses, potentially affecting the consistency of the results. Additionally, while exercise execution and breathing patterns were standardized as much as possible, minor individual variations could still impact AWT measurements. Another limitation is the use of a single measurement device (OHMbelt) for AWT assessment, which, although validated and correlated with IAP [3], requires further research to confirm its reliability across diverse populations and REs. Finally, despite strict adherence to the study protocol—including controlled rest intervals, range of motion, and supervision—other physiological factors, such as muscle fatigue or inter-individual differences in neuromuscular control, may have influenced the results. However, all participants were selected based on their health status and thoroughly familiarized with the study protocol, ensuring a high level of compliance. Future studies should explore these factors, particularly in different training populations and across a broader spectrum of REs and intensities.

Practical considerations

For trained individuals, exercises performed at higher intensities (> 75% 1RM) with lower repetitions (< 10) are effective for strength progression, particularly by enhancing core engagement and stability through increased AWT. The level of AWT is a key indicator of core activation during exercise, with higher AWT reflecting greater muscle engagement. This contributes not only to improved performance but also to a reduced risk of injury. When designing training programs, it is essential to consider various parameters such as exercise intensity, volume, rest intervals, and exercise selection. AWT plays an integral role in this process, serving as a tool to assess and adjust core engagement. Monitoring AWT allows trainers to ensure that the core is properly activated, particularly in high-intensity and multi-joint exercises like deadlifts, squats, and overhead presses. These exercises place substantial demands on core stability, and inadequate core activation can compromise performance and increase injury risk.

The choice of exercises significantly impacts core activation levels. Multi-joint exercises, due to their complexity and higher load, generally require more abdominal activation than single-joint exercises, which place less stress on the core. By understanding how AWT fluctuates across different exercises, trainers can better tailor programs to meet individual needs, ensuring the core is optimally engaged to support both performance and safety. While AWT is especially important for advanced athletes, it is equally valuable for beginners. Monitoring AWT during lower-intensity exercises ensures that the core is sufficiently engaged from the start, reducing the risk of injury as the individual progresses to higher intensities. In this way, AWT provides crucial feedback that allows for more informed decisions regarding exercise prescription, facilitating a balanced and safe approach to training for individuals at all levels.

Conclusions

This study highlights the significant impact of resistance exercise type and intensity on acute abdominal wall tension in healthy adults experienced in resistance training. Our findings reveal that multi-joint lower-body exercises, including the Romanian deadlift, Dumbbell front squat, and Leg press, lead to progressively higher abdominal wall tension values as exercise intensity increases. The greatest increases in AWT were observed during maximal (1RM) loads, followed by submaximal (5RM, 10RM) loads. These multi-joint lower-body exercises generated higher abdominal wall tension compared to both single-joint lower-body and upper-body exercises, highlighting the role of exercise complexity and intensity in influencing abdominal wall tension responses. In contrast, the differences between single-joint and multi-joint upper-body exercises were less pronounced. Individual variability played a more significant role in these exercises, making it challenging to draw definitive conclusions. Additionally, significant sex differences were observed, with males exhibiting higher abdominal wall tension increases, potentially due to differences in breathing mechanics and a higher total training volume. The results also emphasize the importance of exercise selection, body position, and intensity in influencing abdominal wall tension and improving trunk stabilization. These factors are critical for understanding abdominal wall tension responses and optimizing resistance training outcomes.

In conclusion, our findings support the need for a personalized approach to resistance training that considers exercise selection, intensity, sex-specific adaptations, and the complexity of abdominal wall tension responses. By incorporating these elements, training programs can be optimized to enhance performance and minimize injury risk.

Abbreviations

AWT	Abdominal Wall Tension
BMI	Body Mass Index
DNS	Dynamic Neuromuscular Stabilization
HR	Heart Rate
IQR	Interquartile Range
IAP	Intraabdominal Pressure
MDN	Median
RM	Repetition Maximum
REs	Resistance Exercises
RT	Resistance Training
VM	Valsalva Maneuver

Supplementary Information

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Supplementary Material 1.

Supplementary Material 2.

Supplementary Material 3.

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The results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation. We also would like to acknowledge the study participants.

Authors' contributions
RJ and PS contributed to the conceptualization, methodology, writing (original draft preparation, and editing), supervision, investigation and data collection, and project administration; DK contributed to the methodology, statistical analysis, writing (editing); TV participated in concept evaluation, methodology and writing (editing). JN, AK, MK and AB contributed to the methodology, and writing (editing). All authors have read and approved the final version of the manuscript, and agree with the order of presentation of the authors.

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Data availability
Our study adheres to the journal's data sharing policy. All data supporting our findings are available upon request.

Declarations

Ethics approval and consent to participate
The study was received approval from the Ethics Committee of the Faculty of Physical Education and Sport at Charles University (protocol number 242/2018). Informed consent to participate was obtained from all participants involved in the study. Each participant was fully informed about the study's purpose, procedures, potential risks, and their right to withdraw at any time without consequence. Written informed consent was obtained from all individual participants included in the study prior to their participation.

Consent for publication
Consent for publication was obtained from the individual depicted in Fig. 1 using the official Consent for Publication form provided by the journal. The completed form is included in the supplementary materials.

Competing interests
The authors declare no competing interests.

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