Original Paper DOI: https://doi.org/10.5114/biolsport.2019.88759

Systematic review of intra-abdominal and intrathoracic pressures initiated by the Valsalva manoeuvre during high-intensity resistance exercises

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ABSTRACT: The Valsalva manoeuvre, intra-abdominal pressure (IAP) and intrathoracic pressure (ITP) play important roles in resistance training and common daily activities. The purpose of this review is to summarize the ITP and IAP responses to resistance exercises and to determine which exercises elicit the highest or lowest body pressure values under high-intensity resistance exercise. The PubMed, Scopus and Web of Science databases were searched until November 1, 2018. A combination of the following search terms was used: Valsalva manoeuvre, hold breath, controlled breathing, controlled breath, abdominal pressure, intrathoracic pressure AND weight training, resistance exercise, power lifting. The search process yielded 1125 studies, of which 16 were accepted according to the selection criteria and methodological quality. The highest IAP was recorded during squats (over 200 mmHg) followed by deadlift, slide row and leg press (161–176 mmHg), and the lowest IAP was found during bench press (79±44 mmHg). The highest ITP was elicited by the leg press, deadlift and box lift (105–130 mmHg), which were higher than during the bench press (95±37 mmHg) and slide row (88±32 mmHg). We recommend the bench press and slide row as exercises useful for beginners and individuals with hypertension. Untrained individuals should not use heavy squats, deadlift, box lift and clean exercises until they have undergone progressive adaptation for lifting high loads resulting in high IAP and ITP. The values of IAP and ITP during high-intensity exercise seem to be determined mutually by the position of the human body and the external load.

CITATION: Blazek D, Stastny P, Maszczyk A, et al. Systematic review of intra-abdominal and intrathoracic pressures initiated by the Valsalva manoeuvre during high-intensity resistance exercises. Biol Sport. 2019;36(4):373–386.

Received: 2019-06-03; Reviewed: 2019-08-08; Re-submitted: 2019-08-28; Accepted: 2019-09-24; Published: 2019-10-17.

Key words:
Valsalva manoeuvre
Exercise prescription
Biomechanics
Exercise safety
Health
Blood pressure
Fitness
Squat

INTRODUCTION

Intrathoracic pressure (ITP), intra-abdominal pressure (IAP) and the Valsalva manoeuvre (VM) play important roles during common life situations through all spectrums of human activity. Increases in ITP and IAP can be initiated by the VM, which is the body technique that increases the tone of the vagus nerve, which decreases the heart rate, changes blood pressure and increases stabilization of the trunk during physical activity [1-3]. The VM can occur unintentionally; it might be constrained or restricted by voluntary breath modifications during low and moderate efforts, but it is unavoidable when the force production exceeds 80% of the one-repetition maximum (1RM) [4, 5]. Therefore, knowledge of the effects of the VM on physiological responses, such as IAP and ITP, should be considered when prescribing physical activities, athletic training and exercise selection in resistance training.

While the variation of moves, athletic performance and body stress all change, IAP, ITP and the VM play the same mechanical roles to increase athletic performance, stabilize the trunk, unload the lumbar spine, and prevent injury [6-8] in addition to increasing the contractility of muscle fibres. One issue is the physiological response to the VM; a previous review [2] stated that the health risks associated with the VM during resistance exercise have not been clearly documented and that the VM alone (not necessarily during resistance exercise) can elicit maximal hemodynamic changes. However, during heavy resistance training (RT) the body is pushed to its limits, and there are cases where the VM might be the cause of the health risk, e.g., VM brain blackout [9], temporary blinding or other vascular brain injuries [10-12]. Although it may appear that the VM is not safe, we must keep in mind that the previously mentioned situations are extreme cases with excessive resistance (whole body overload), and most of the studies that described injuries in connection with the VM were case studies. Conversely, it has been stated that the

VM can protect the body from cerebrovascular damage [13] caused by exercise-induced hypertension (in exercises that induce hypertension) [14] because it affects the cerebral artery blood velocity [15].

The VM causes changes in different body pressures: ITP [9], IAP [2], blood pressure (BP) [5, 16] and cerebrovascular transmural pressure [13, 17]. While ITP and IAP represent the relatively local direct biomechanical effect of the VM, BP represents the physiological effect targeting the whole body. Because different pressure determinations require different methodologies and represent different physiological effects, it is beneficial to review the use of measuring the effect of the VM on IAP and ITP during high-intensity resistance exercise.

In summary, different measurement approaches have been employed to estimate whether the VM causes a health risk or offers protection during standardized resistance training, and a BP response has been clearly described. Conversely, only a small number of mechanical body responses during the VM have been clearly described in previous studies. Currently, there are no guidelines on which exercise can elicit the strongest uncontrolled IAP and ITP response. Therefore, the purpose of this review is to summarize the ITP and IAP responses to resistance exercises and estimate which exercises elicit the highest or lowest body pressure values during high-intensity exercise (over 80% of 1RM) in any population. The summary of current findings should lead to recommendations for the interpretation of IAP and ITP changes in the context of exercise selection for trained and untrained individuals.

MATERIALS AND METHODS

Review process

This study utilized the Preferred Reporting Items for Systematic Reviews (PRISMA), where the protocol was registered in the International Prospective Register of Systematic Reviews (PROSPERO) database under no. CRD42018082240. After identifying potential articles by screening the titles and abstracts, the full text selection was performed according to the exclusion criteria, as well as an eligibility assessment using the "Strengthening the Reporting of Observational Studies in Epidemiology" (STROBE; Supplementary material S1) checklist, which is designed to assess the potential for bias in a study and evaluate the generalizability.

Literature search

To find articles related to the VM, ITP and IAP during resistance training, a systematic, computerized literature search was conducted on November 1, 2018 in PubMed, Scopus and Web of Science. A combination of the following search terms was used: (Valsalva manoeuvre) OR (hold breath) OR (controlled breathing) OR (abdominal pressure) OR (intrathoracic pressure) AND (weight training) OR (power lifting) OR (resistance training). Only original, full-text articles were eligible, and comments, proceedings, editorials and letters were excluded. Review studies were included to be used for hand searching their reference lists. In addition, a hand search of the reference lists of the included articles was performed (Figure 1).

Literature selection

After identifying potential articles, the titles and abstracts were independently reviewed to select relevant articles for full text screening. The inclusion criteria included reports from objective IAP and ITP measurements performed with the Valsalva manoeuvre during weight lifting (not just performance itself) in different populations. The full texts of relevant articles were analyzed for final inclusion and the eligibility assessment. During the full-text screening, the following exclusion criteria were used: 1) the full text was not available in English, 2) the study contained a poor description of the measurement devices and procedures, and 3) the study did not include a proper resistance exercise task.

Data extraction and processing

The full texts of relevant articles were analyzed to determine inclusion in the final analysis. This full-text screening was performed by three independent reviewers (PS, MP, DB), who also completed the data extraction form (Supplementary material 2, Supplementary material 3), which was designed to record body pressure values during different exercises. If the study contained IAP or ITP measured during resistance exercise at an intensity above 80% of 1RM, the values were further extracted to statistical software (ORIGIN, Version 2018b SR0; OriginLab, Wellesley Hills, MA, USA). The values during high-intensity exercise were compared using Cohen's d effect size to estimate which exercises elicited higher pressure values.

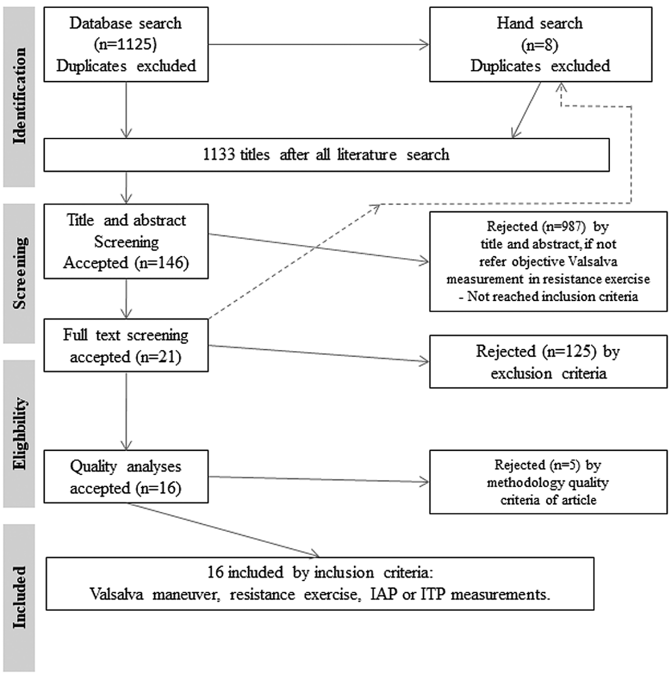

FIG. 1. Review flow chart for articles included in tables.

RESULTS

The database search resulted in 1125 studies after removing the duplicates. The title and abstract screening resulted in 146 accepted papers for full text screening. Finally, 16 studies were included after all the eligibility processes had been completed (Table 1). One study performed the measurement of ITP and IAP simultaneously [18], 8 studies measured IAP by itself [19-26] and 7 studies measured ITP by itself [7, 9, 16, 17, 27-29] (Table 2). From seven studies that measured ITP, 3 of them measured mouth pressure, which is commonly presented as ITP, and two studies [17, 27] used mouth pressure as the exercise intensity measure (instead of the lifted load). Six selected studies performed the simultaneous measurement of blood pressure along with IAP or ITP, and one study associated the ITP and blood pressure values ($p = 0.06$, $r = 0.049$).

A total of 10 exercises from 5 studies were compared regarding their IAP response (Table 3, Figure 2). The highest IAP was measured during squats (over 200 mmHg), followed by deadlift, slide row and leg press (161-176 mmHg), and the lowest IAP was measured during the bench press (79 ± 44 mmHg). Although other studies reported IAP, some of them did not include exercise performance above 80% of 1RM.

In total, seven exercises from three studies were compared in regard to ITP (Table 4), whereas one case study [9] was excluded due to the low sample size ($n = 2$). However, this study [9] reported that clean and jerk exercises were associated with an extremely high IAP (161-261 mmHg) (Figure 2, Table 2). Cohen's comparison showed that the highest ITP was elicited by the leg press, deadlift and box lift (105-130 mmHg), which were higher than the bench press (95 ± 37 mmHg) and slide row (88 ± 32 mmHg) (Table 4).

From 21 studies that fulfilled the search criteria and were previously mentioned, only 16 included intra-abdominal or intrathoracic pressure measurements with precisely described methods and results. There were 7 additional studies that were close to meeting the criteria, and they are mentioned in the discussion below.

DISCUSSION

We considered the final inclusion of 16 studies sufficient to achieve the aim of the study and to compare the IAP and ITP values among six exercises (described further in the exercise selection subchapter). However, the selection process required a great amount of discussion on appropriate resistance exercises and other considerations in terms of measurement technique and the VM, which we describe below. Moreover, our exercise comparison lacks studies performed on a resistance-trained population; therefore we are able to make exercise recommendations with respect to IAP and ITP only for the general population. However, the resistance-trained population is usually healthy and progressively adopted to the physiological and biomechanical demands of those exercises.

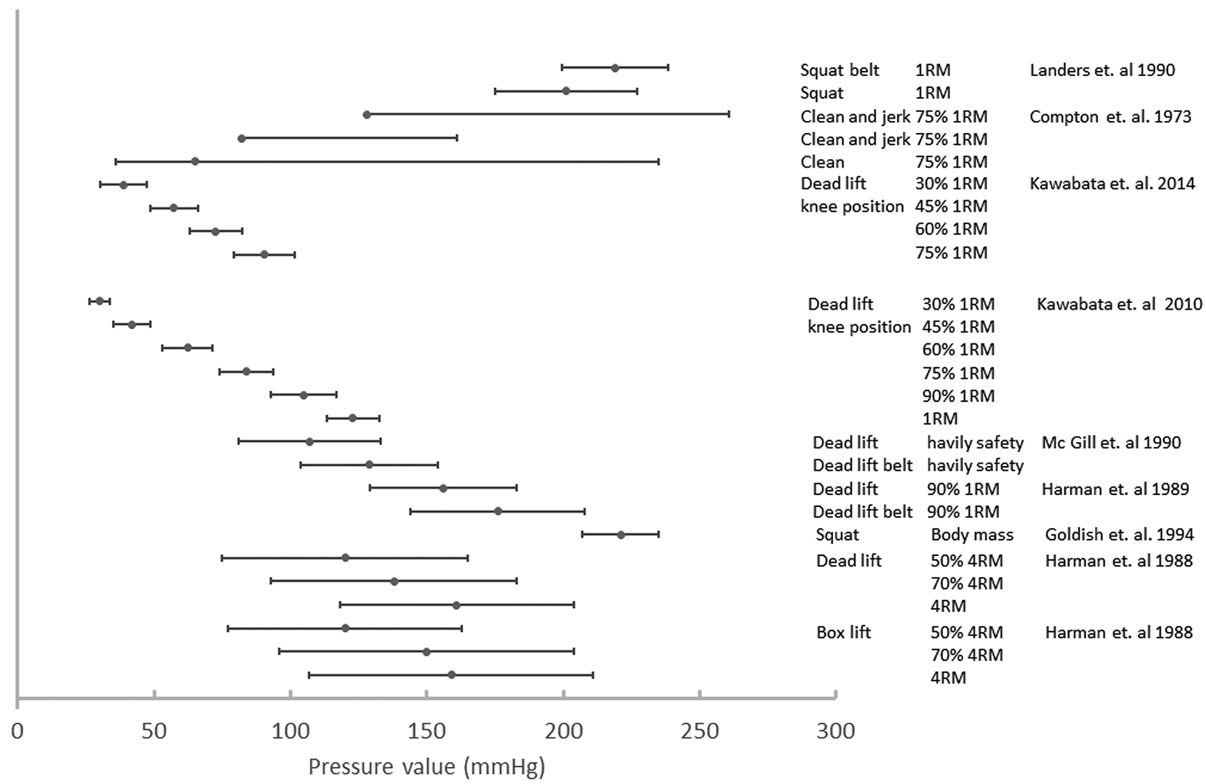

FIG. 2. Differences in intra-abdominal pressures during different resistance exercises. Values are mean and standard deviation.

TABLE 1. Basic characteristics of included studies measuring intra-abdominal or intrathoracic pressure during resistance exercises using the Valsalva manoeuvre

Author	Participants (mean ± standard deviation)	Type of resistance exercise	Results
Haykowsky, Taylor, Teo, Quinney and Humen [28]	5 healthy resistance-trained males, age 27.6 ± 2.9 years, height 175.5 ±7.3 cm, body mass 79.2 ± 6.4 kg	Leg press	Leg press exercise performed with a brief Valsalva manoeuvre is not associated with an alteration in left ventricular systolic wall stress or left ventricular systolic function in healthy young men.
MacDougall, Tuxen, Sale, Moroz and Sutton [16]	5 healthy experienced male bodybuilders (22-28 years)	Single-arm curls, overhead press, double/single-leg press	Weight-lifting exercises combined with the Valsalva manoeuvre produced an extreme elevation in blood pressure.
Niewiadomski et al. [27]	12 healthy young males, age 23.9 ± 4. Height 180 ± 6, body mass 84 ± 16 kg.	knee extension	Valsalva manoeuvre increased peak systolic and peak diastolic pressure.
Cobb et al. [26]	10 male and 10 female healthy young adults, age 27 18-30 years, BMI 18.4 –31.9 $kg \cdot m^{-2}$	13 different tasks, including bench-pressing 25 pounds and arm curling 10 pounds	From 13 measured tasks, the highest intra-abdominal pressures occurred during coughing and jumping.
Harman, Frykman, Clagett and Kraemer [18]	11 males, age 25.2 ± 6.6 years, height 183 ± 5 cm, body mass 83 ± 9.3 kg	Deadlift, leg press, bench press	IAP and ITP rose significantly with the amount of weight lifted. The highest rise was before and the peak was after the weight was lifted.
Lentini, McKelvie, McCartney, Tomlinson and MacDougal [29]	5 healthy males, age 23 ±1.5 years, height 181 ± 8.4 cm, body mass 92 ± 21 kg	Leg press	Rapid changes in cardiac volumes, contractility, and pressure occurred during weight lifting and were related to different phases of the lift.
Lander, Simonton and Giacobbe [20]	6 skilled adult males	Squats	Few differences were observed between using belts of different types. These data suggest that a weight belt can aid in supporting the trunk by increasing IAP.
McGill, Norman and Sharratt [21]	6 subjects, age 25.7 ± 71.7 years, height 177 ± 7 cm, body mass 74.8 ± 8.6 kg	Squat and lifts	The muscle activity and IAP during short duration lifting tasks made it difficult to justify the prescription of abdominal belts for workers.
Adams et al. [7]	41 healthy volunteers, 19 males and 22 females, age 38 ± 12 years, height 170 ± 8 cm, body mass 82 ± 18 kg	Bench press	Patients withstood much more force on the sternum by sneezing than during standard low and moderate intensity bench press, meaning they can perform more activities than they are currently allowed.
Niewiadomski et al. [17]	20 normotensive, pre-hypertensive or moderately hypertensive, otherwise healthy males, age 56 ± 5.4 (range, 46-69) years, height 178 ± 5.6 cm, body mass 86 ± 17 kg	Knee extension	Transmural pressure declined, dependent mainly on ITP pressure developed during a brief Valsalva manoeuvre. Resting blood pressure did not influence the effect of a brief VM on transmural pressure.

TABLE 1. Continue

Author	Participants (mean ± standard deviation)	Type of resistance exercise	Results
Kawabata, Shima and Nishizono [22]	11 healthy males, age 23 (range, 20-24) years, height 173 (range, 161-182) cm, body mass 66.4 (range, 57-77.5) kg	Deadlift from knee position	Preparative pre-lifting behaviours altered intra-abdominal pressure and breathing and were coordinated by the magnitude of the lifted load. These behaviours appear to be functionally important for dynamic lifting.
Kawavata, Shima, Hamada, Nakamura and Nishizono [23]	10 highly trained males, age 22 (range, 20-21) years, height 172 ± 7 cm, body mass 76 ± 13 kg 11 healthy males, age 22 (range, 20-24) years, height 173 ± 7 cm, body mass 173 ± 7 kg	Deadlift from knee position	Spontaneous breath volume and IAP development were coupled with an increased lifting effort, and strong abdominal muscles can modify IAP development and inspiratory behaviour during lifting.
Harman, Rosenstein, Frykman and Nigro [19]	9 subjects, age 28.2 ± 6.6 years	Deadlift	Using a belt during a deadlift can lead to increased IAP.
Goldish, Quast, Blow and Kuskowski [24]	8 normally trained subjects, age 32-61 years	Sits, flexions, stands, rotations, squats	The greatest IAP from the included positions was measured during squatting.
Cholewicky, Ivancic and Radebold [25]	9 untrained males, 1 untrained female, age 28 ± 4 years, height 177 ± 7 cm, body mass 78 ± 14 kg	Isometric trunk flexion, extension and lateral bending	The spine stability was greater when increased IAP was applied. The motor control strategy used to increase IAP during steady state, physical exertion was not to reduce the spinal compression force, but rather to increase the rigidity of the ribcage and stability of the lumbar spine.
Compton, Hill and Sinclare [9]	2 national representative body mass lifters, age 30 and 21 years, height 159 and 185 cm, body mass 68 and 132 kg, max performance 140 and 185 kg clean and jerk	One repetition of 75% RM clean and jerk	Weight-lifters' blackout can be attributed to the reduced cardiac output and cerebral blood flow associated with the VM.

Legend: IAP = intra-abdominal pressure, ITP = intrathoracic pressure.

TABLE 2. Intensity and body pressure values during different exercises and using different measurement methods

Author	Type of exercise	Intensity of exercise	Pressure measurement method	Measured values
MacDougall, Tuxen, Sale, Moroz and Sutton [16]	Single arm curls, overhead press, leg press	To failure at 80, 90, 95, and 100% of 1RM	MP: through open glottis expiring against column of Hg BP: brachial artery catheter	MP: single arm curls, overhead press, leg press 30-50 mmHg average not exceeding 70 mmHg, VM alone 130 ± 11 mmHg BP: VM from 135 ± 5/90 ± 3 to 190 ± 8 / 170 ± 8 mmHg, leg press 480/350 mmHg, 350 mmHg during exercise, below 50 mmHg immediately after
Niewiadomski et al. [27]	Knee extension	15 RM	MP: pressure sensor on mouthpiece BP: non-invasive	MP: knee extension 54.8 ± 16.2 mmHg, knee flexion 55.5 ± 15.5 mmHg, VM alone 54.6 ± 15.8 mmHg BP: 360 mmHg 191±25 /94 ± 12 mmHg
Niewiadomski [17]	Knee extension	6 sets x 6 repetitions with weight not higher than 15 RM	MP: pressure sensor on mouthpiece BP: non-invasive	Measured exact values as MP: 10, 20 and 40 mmHg No association of MP with BP or transmural pressure BP: 160 - 205 ± 28_4 mmHg
Lentini, McKelvie, McCartney, Tomlinson and MacDougal [29]	Leg press	95% of 1RM	ITP: intra-oesophageal catheter BP: intra-arterial catheter, right brachial artery	ITP: leg press 57.8 ± 24 mmHg during experiment up to 184 mmHg BP: 269 ±21 / 183 ± 18 mmHg, eccentric phase 207 ± 23 mmHg Association between BP and ITP ($p = 0.06$, $r = 0.049$)
Adams et al. [7]	Bench press	12x40% and 10x70% of 1RM	ITP: balloon-tipped catheter in nostril and oesophageal catheter	ITP: bench press (40, 70, and 100% of 1RM) 33.4 ± 16.0, 49.4 ± 24.2, and 68.9 ± 34.6 kg, respectively, on a median sternotomy closure derived from ITP
Haykowsky, Taylor, Teo, Quinney and Human [28]	Leg press	Baseline, 80, 90 and 100% of 1RM	Pressure-tipped catheter in the mid-oesophagus	ITP: leg press 80% of 1RM, 111.7 ± 20.2 mmHg; 95% of 1RM, 112.2 ± 21.1 mmHg; 100% of 1RM, 111.0 ± 21.3 mmHg BP: 80% 297.0 ± 10.7/ 226.0 ± 11.5, 95% 307.3 ± 20.6/238.0 ± 16.3, 100% 290.2 ± 24.0/ 220.6 ±16.5
Compton, Hill and Sinclare [9]	Clean and jerk	75% of 1RM, every time to failure, (90 and 150 kg)	ITP: oesophageal balloon catheter system, one in the oesophagus and one in the stomach	ITP peak subject 1: clean 256-261 mmHg, jerk 172-235 mmHg ITP peak subject 1: clean 161 mmHg, jerk 161 mmHg
Harman, Frykman, Clagett and Kraemer [18]	Deadlift, leg press, bench press	50, 75 and 100% of each subject's four-RM	Millar model SPC 350 Mikro-Tip catheter	Peak IAP and ITP for exercises at 50, 75 and 100% of 4 RM: Dead lift: IAP 120 ± 45, 138 ± 45, 161 ± 43; ITP 65 ± 18, 90 ± 26, 105 ± 33 mmHg Box lift: IAP 120 ± 43, 150 ± 54, 159 ± 52; ITP: 71 ± 23, 86 ±21, 111 ± 19 mmHg Slide row: IAP 96±30, 132±40, 164 ±39; ITP: 57±33, 73±39, 88±32 mmHg Leg press: IAP 35±24, 94±46, 161±55; ITP: 45±15, 74±27, 130±28 mmHg Bench press: IAP 42±17, 46±22, 79±44; ITP: 53±15, 67±21, 95±37 mmHg

TABLE 2. Continue

Author	Type of exercise	Intensity of exercise	Pressure measurement method	Measured values
Harman, Rosenstein, Frykman and Nigro [19]	Deadlift	1x 90% RM	Catheter transducer	Peak IAP: 156 ± 27 mmHg without belt, 175.5 ± 32 mmHg with belt
Lander, Simonton and Giacobbe [20]	Squats	70, 80, and 90% of 1RM in increasing order	Balloon catheter in rectum	Peak IAP: 219 ± 19.5 mmHg with belt and 201 ± 26 mmHg for 1RM with and without belt
McGill, Norman and Sharratt [21]	Deadlifts (machine)	72.7-90.9 kg	Millar pressure catheter placed into stomach via nasoesophageal pathway	Peak IAP: 107±26 129 ±25 mmHg with and without belt, respectively
Kawabata, Shima and Nishizono [22]	Deadlift from knee position	30, 45, 60, and 75% of isometric maximal lifting effort	Intrarectal pressure transducer	Peak IAP: 36.8 ± 8.4, 57.3 ± 8.8, 72.7 ± 9.6 and 90.3 ± 11.2 mmHg, respectively, at 30, 45, 60, and 75% of isometric maximum
Kawavata, Shima, Hamada, Nakamura and Nishizono [23]	Deadlift from knee position	30, 45, 60, 75, 90, and 100% of isometric maximal lifting effort	Intrarectal pressure transducer	Peak IAP trained: 30 ± 4, 42 ± 7, 62 ± 9, 84 ± 10, 105 ±12 and 123 ± 10 mmHg, respectively, at 30, 45, 60, 75, 90 and 100% of isometric maximum Peak IAP untrained: 20 ± 2.2, 36 ± 6, 48 ± 6, 70 ± 9, 96 ±12 and 106 ± 16 mmHg, respectively, at 30, 45, 60, 75, 90 and 100% of isometric maximum
Goldish, Quast, Blow and Kuskowski [24]	VM in standing, sitting and other rotated positions and during bodyweight squats	3 seconds in each position	Pressure-sensitive radio capsule	Peak IAP during squats 221.44 ± 14 SE mmHg VM standing 215 ± 17 SE, VM sitting 215 ± 13 SE
Cholewicky, Ivancic and Radebold [25]	Isometric trunk flexion, extension and lateral bending	0, 40 and 80% of their maximal IAP while co-contracting muscles	Transducer (Micro-tip MPC500, Millar Instr., Texas) inserted into the stomach via the nasoesophageal pathway	Peak IAP during flexion 26.2+-9.6
Cobb et al. [26]	13 different tasks	3 repetitions every task, e.g., bench-pressing 23 kg, arm curling 4.5 kg	Urinary bladder catheter	Peak IAP during 23 kg bench press 7.4 ± 7.3 mmHg Jumping 171 ± 48, min/max 43/252 mmHg Arm curl 25.5 ± 6 mmHg

Legend: RM = repetition maximum, BP = blood pressure, MP = mouth pressure, ITP = intrathoracic pressure, IAP = intra-abdominal pressure, 1 kPa = 7.500617 mmHg, 1 mmHg = 0.133322 kPa [30].

TABLE 3. Differences by Cohen's d between intra-abdominal pressures during resistance exercises performed at an intensity above 80% of 1-repetition maximum

Exercise	1	2	3	4	5	6	7	8	9	10	IAP (mmHg)	Lifted load (N)
1 Squat belt [20]											219 ± 19.5	1590–1764
2 Squat [20]	0.78										201 ± 26	1590–1764
3 Deadlift knee position [23]	6.2	3.9									123 ± 10	1295 ± 228
4 Deadlift knee position [22]	7.9	5.6	3.1								90 ± 11	1000, 792-1222
5 Deadlift belt [19]	1.6	0.86	2.23	3.59							176 ± 32	1403 ± 265
6 Deadlift [19]	2.6	1.69	1.6	3.2	0.32						156 ± 27	1404 ± 265
7 Deadlift [18]	1.7	1.34	1.2	2.26	0.39	0.13					161 ± 43	1171 ± 225
8 Box lift [18]	1.5	1.02	0.96	1.84	0.39	0.07	0.04				159 ± 52	439 ± 114
9 Slide row [18]	1.8	1.11	1.44	2.58	0.33	0.23	0.07	0.11			164 ± 39	870 ± 115
10 Leg press [18]	1.4	0.93	0.96	1.79	0.33	0.11	0	0.04	0.06		161 ± 55	1520 ± 282
11 Bench press [18]	4.11	3.38	1.38	0.17	2.52	2.1	1.88	1.66	2.04	1.65	79 ± 44	760 ± 233

Legend: IAP = intra-abdominal pressure. The reported values represent the highest measured value in each reported study.

TABLE 4. Differences by Cohen's d between intrathoracic pressures during resistance exercises performed at an intensity above 80% of 1-repetition maximum

Exercise	1	2	3	4	5	6	ITP (mmHg)	Lifted load
1 Leg press [28]							111 ± 21	420 ± 118 kg
2 Deadlift [18]	0.21						105 ± 33	1171 ± 225 N
3 Box lift [18]	0	0.22					111 ± 19	439 ± 114 N
4 Slide row [18]	0.84	0.52	0.87				88 ± 32	870 ± 115 N
5 Leg press [18]	0.77	0.81	0.79	1.39			130 ± 28	1520 ± 282 N
6 Bench press [18]	0.53	0.29	0.57	0.2	1.07		95 ± 37	760 ± 233 N
7 Leg press [29]	2.35	1.6	2.44	1.06	2.76	1.19	185, 58± 24 mean	NR

Legend: ITP = intrathoracic pressure, NR = not reported. The reported values represent the highest measured value in each reported study.

Exercise selection by IAP and ITP

The main finding of this study is that IAP and ITP are strongly associated with exercise selection and not solely dependent on the lifted load [25]. Squats, or exercises that include a squatting task (e.g., clean and jerk), were associated with the highest IAP and ITP, which corresponds to practical experiences where the squatting technique includes an intensive VM effort. Since invoking the VM and the elevation of IAP and ITP play protective roles during squatting [3, 13], this pressure elevation seems to be beneficial in a healthy population. However, when resistance training is applied, all practitioners should apply a progressive approach in exercise selection and lifted load [31, 32]. In this manner, squatting exercises are the most difficult in terms of exercise technique [33] and allow high external loads to be lifted [34]. Therefore, regarding the progressivity of exercise selection (from easier to more difficult), we recommend considering not only the exercise technique [35] and lifted load [22, 23] but also the exercise effect on body pressures; for example, high-intensity squats should be incorporated in resistance training programmes after mastering less challenging exercise tasks. Thus, high loaded squats should be recommended only in a resistance-trained population.

The deadlift, slide row and leg press are exercises that elicit a lower IAP than squats (161-176 mmHg); therefore, their application in a resistance training programme for non-resistance-trained people is seemingly safer than squats. However, this is not true for the deadlift, as this exercise technique is considered very advanced and the shear forces in the lower back might be similar to those during squatting [20]. On the other hand, leg press and slide row exercises are easy to perform for a non-trained population; thus, their implementation should be safe in any case, and especially since both exercises showed lower ITP than IAP (Tables 3 and 4). The lowest ITP and IAP values were found during the bench press, and regarding BP, the leg press and slide row might be safely used even in a hypertensive population [36, 37].

Our conclusion about the progressivity of resistance exercises and loads is especially important in populations with high blood pressure or cardiovascular disease, where even body weight squats might be considered as high-intensity exercise. For this population, resistance training is highly recommended to improve their health [38]; however, exercise selection is typically provided without consideration of ITP and IAP responses.

The IAP or ITP differences between exercises might be explained by body and load positions, as the body position during squats coupled with an external load on the scapula elicited the highest IAP, and a supine body position (bench press) required the lowest IAP and ITP [26]. The deadlift exercise has a similar movement pattern to squats with the ability to lift a similar load, with the difference being that the lifted load is carried in tightened upper limbs. Thus, the position of the lifted bar with the absence of vertical forces from the bar acting on the lifter's trunk might be the reason for the lower IAP values observed with the deadlift compared to squats. Although the bench press has been found to have lower values than squats and deadlifts, the bar position above the chest might explain why the bench press was the only exercise that elicited higher ITP values than IAP values [18].

Consideration of non-included studies

Some studies were not included in the review, but were still somehow related to IAP, ITP and the VM. These studies met most of the criteria, but there was still some obstacle that prevented their inclusion in the main list. A study by Essendrop and Schibye [39] measured IAP pressure during sudden back loads, which should imitate judo techniques. Since sudden loads are uncommon in resistance training, the study was excluded. Another study by Essendrop et al. [40] measured IAP during an uphill/incline test, which does not correspond to resistance training, although this task has a high anaerobic requirement. A study by Daggfeldt [8] was very important to the present topic; however, we considered their methods as a study model instead of a measurement. Studies by Cresswell et al. [41], Williams and Lind [42] and Nachemson et al. [43] were excluded because they included isometric exercises (isometric trunk flexion, isometric extension, isometric hand grip and isometric uphill/incline static test) where only a voluntary VM might be applied.

Although 16 studies fulfilled all inclusion and exclusion criteria, many studies did not contain the desired exercise intensity condition; therefore, we summarized them in Tables 3 and 4 but not in the comparison part of the article. Another limitation of studies included in Tables 3 and 4 is in absolute lifted load being reported instead of relative lifted load, which is due to reported values in original studies.

Measurement techniques to determine intra-abdominal and intrathoracic pressure

Several methods were used for measuring IAP and ITP in the mentioned review studies. There was not a single measurement that was identical with another among the different author's studies. ITP was mainly measured using a pressure recorder inserted via the nostril into the oesophagus [7], or as mouth pressure [16, 17, 27]. IAP was mostly measured in the gastric system (stomach) via the nostril [21] but also via the rectum [20] or urinary bladder [26]. Thus, correlation and comparison studies may be required to prove differences or similarities between different measurement procedures. For example, ITP is correlated with blood pressure [29], and mouth pressure is usually used as a representative value of ITP [5, 17]; therefore, a direct association study should be performed in the future.

This review also included studies that used mouth pressure as the parameter of exercise intensity [17, 27], which is the reverse approach to our suggestion. Although a voluntary VM in a sitting position results in the highest IAP and ITP [2], which can elicit 100% of the individual pressure abilities, people mostly use the VM without noticing and cannot focus on both the exercise task and pressure values at the same time [44]. Therefore, the use of mouth pressure as the intensity parameter seems to be much less applicable than the standardized 1RM in regard to maximal voluntary effort. Therefore, future studies should not use mouth pressure or other pressures as the intensity scale. The VM during high-intensity exercise cannot be performed with the elevation of only one pressure (ITP or IAP); however, changes in these pressures are not linear and are based on load position and the exercise performed. Since only one study simultaneously measured ITP and IAP, which differed between exercises [18], these pressures should be further compared in the future.

General effect of the VM during high-intensity effort

The VM decreases cerebral blood flow velocity by 21-52% based on individual adaptation to this manoeuvre [12]. Furthermore, the VM might strengthen breathing muscles [24, 45], especially when using external resistance, which leads to increasing the speed of breathing muscles [45, 46] but also in normal breathing conditions [24, 45-47]. Several studies have focused on blood pressure (BP) measurement and using the VM without external weight. These studies demonstrate that the VM leads to significantly increased BP and do not recommend its use by people with hypertension [48-50]. However, other studies have attempted to warn against free breathing, stating that it can lead to hyperventilation and is associated with negative consequences, even for healthy individuals [15, 50]. When weight lifting and using the VM, there is a significant increase in systolic, diastolic, intracranial and cerebrovascular pressure [13, 48, 49, 51]. An increase in intraocular pressure often leads to the rupture of peripheral capillaries, which may cause blood to spill into the eye. This condition is not dangerous for healthy individuals [16, 52]. However, in extraordinary situations, using a high-intensity VM during weight lifting may lead to eye damage or blindness. During leg extensions when using the VM and a weight lifting belt, intra-muscular pressure on the erector spinae is increased, which leads to stabilization of the spine, in addition to overall trunk stabilization [4, 53]. During chest press and leg press exercises with average weight, there is a minimal difference between BP and heart rate (HR) while holding the breath compared to controlled breathing variations [54]. When using the VM compared to concentric exhaling and inhaling, a very similar HR and BP were measured. Only during the VM was the BP response much stronger [55]. During chest press exercises with middle weight hold breathing and free breathing, there were no blood pressure or HR changes measured. This result is an indication that during heavy weight lifting, it is unnatural to hold the breath completely [56].

Studies agree that increased IAP and ITP lead to greater stabilization of the trunk and greater intramuscular pressure on the erector spinae and abdominal muscles, which allows a greater magnitude of resistance to be overcome [6, 25]. Some studies deny that strengthening the abdominal muscles affects the IAP generated during exercise in healthy participants and those with low back pain [57, 58], while another study proved that weakened abdominal muscles negatively affect the maximum generated IAP [41]. A study by Lander [20] also showed that using a weight lifting belt leads to increased IAP and can be used for injury prevention; however, it is not recommended for long-term usage [21]. High-intensity VM carries a risk for people with hypertension and cerebrovertebral anomalies [13]. For global populations, the risks are very low, and for trained populations, the risks are even lower, due to body adaptation.

CONCLUSIONS

Regardless of participants' training level, the highest IAP was measured during squats followed by deadlift, slide row and leg press, and the lowest IAP was measured during the bench press (79 ± 44 mmHg). The highest ITP values were elicited by the leg press, deadlift and box lift, which were higher than values measured during the bench press (95 ± 37 mmHg) and slide row (88 ± 32 mmHg). Therefore, we can recommend the bench press and slide row as exercise useful for beginners and individuals with hypertension. Untrained individuals should not use heavy squats, deadlift, box lift and clean exercises until they have undergone progressive adaptation for lifting high loads resulting in high IAP and ITP.

The methods of non-invasive measurements of IAP, ITP and the VM have not been sufficiently established while applying muscle force during RT. More studies are required to standardize the measurement procedures for IAP, ITP and the VM during RT. There is currently no agreement as to whether the VM is safe for the global population, although a high percentage of articles state that it is safe. Most of the studies were related to the standard VM, where the air pressure is stopped by a closed glottis. However, resistance training typically uses a modified VM, where the glottis works as a piston that leads to releasing pressured air; therefore, the physiological results may vary with the use of the standard VM. The high IAP and ITP initiated by the VM during high-intensity exercise seem to be determined by body and external load positions; the body position during squats coupled with an external load on the scapula elicited the highest IAP, and a supine body position required the lowest IAP and ITP. Increasing the load or intensity causes an increase in IAP and ITP, which is associated with an increase in systolic blood pressure; however, a higher load does not necessary mean a higher IAP or ITP between exercises. The current research does not sufficiently recognize whether the VM occurs unintentionally (naturally, during exercises with 80% or more of one-repetition maximum) or purposely, by controlled breathing. Therefore, future studies should recognize the effects of constrained and natural types of the VM.

Acknowledgement: This study has been supported by the UNCE/HUM/032 grant, GACR project GA19-12150S, SVV 260466 and by a grant from the Ministry of Science and Higher Education of Poland (NRSA4 040 54).

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S1 Table. The modified STROBE checklist, Von Elm et al., 2007 [1].

	n	Description
• *TITLE /* • *ABSTRACT*	1	Indicate the study's design with a commonly used term in the title or the abstract. Provide in the abstract an informative and balanced summary of what was done and what was found including intraabdominal, intrathoracic pressure or Valsalva maneuver.
• *INTRODUCTION*	2	Explain the scientific background and rationale for the investigation being reported in introduction.
•	3	State specific objectives, including any pre-specified hypotheses in introduction.
• *METHODS*	4	Present key elements of study design early in the paper such as in "Methods".
•	5	Describe the setting, locations, and relevant dates, including periods of recruitment, follow-up, and data collection. Describe methods of follow-up.
• *Participants*	6	Participant eligibility criteria, and the sources and methods of selection of participants. Give matching criteria of participants, strength training experience.
• *Test methods*	7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable.
•	8	For each variable of interest, give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group.
•	9	Describe any efforts to address potential sources of bias.
•	10	Explain how the study size was arrived at.
•	11	Explain how intraabdominal, intrathoracic pressure data were acquisitioned and handled in the analyses. If applicable, describe which groupings were chosen, and why.
•	12	Describe all statistical methods, including those used to control for confounding. Describe any methods used to examine subgroups and interactions. If applicable, describe analytical methods taking account of sampling strategy. Describe any sensitivity analyses.
• *RESULTS*	13	Report the numbers of individuals at each stage of the study, completing follow-up, and analysed in results. Indicate the number of participants with missing data for each variable of interest. Explain how missing data were addressed.
•	14	Report numbers of outcome events or summary measures.
• *Test results*	15	Give unadjusted estimates of intraabdominal, intrathoracic pressure or Valsalva maneuver outcome and, if applicable, their precision (e.g., 95% confidence intervals). Make clear which confounders were adjusted for and why they were included in main results.
•	16	Report other analyses done—e.g., analyses of subgroups and interactions, and sensitivity analyses. Other analyses.
• *Discussion*	17	Summarise key results with reference to study objectives in discussion.
•	18	Discuss limitations of the study, taking into account sources of potential bias or imprecision. Discuss both direction and magnitude of any potential bias.
•	19	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence.
	20	Discuss the generalisability (external validity) of the study results.

1. Von Elm E, Altman DG, Egger M, Pocock SJ, Gøtzsche PC, Vandenbroucke JP. The Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) Statement: Guidelines for reporting observational studies. Prev Med. 2007;45(4):247-51. doi: http://dx.doi.org/10.1016/j.ypmed.2007.08.012.

S2 Table. Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) checklist.

Item	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Haykowski 2001	Y	N	N	Y	Y	N	Y	Y	N	Y	Y	Y	N	Y	Y	N	Y	Y	Y	Y
Brennecke, Guimaraes et al. 2009	Y	N	Y	Y	N	N*	N	N	N	Y	N	N	N	N	Y	Y	Y	N	N	N
Niewiadomski, Pilis et al. 2012	Y	Y	Y	Y	Y*	N*	Y	Y	N	Y	Y	Y	Y*	Y	Y	Y	Y	Y	Y	Y
Cobb, Burns et al. 2005	Y	Y	Y	N	Y*	Y	Y	N	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y
McCaw and Friday 1994	Y	N	N	Y	Y*	Y	Y	Y	N	Y	Y	Y	N	Y	Y	N	Y	Y	N	Y
Martorelli, Martorelli et al. 2014	Y	N	N	Y	Y*	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Lander, Simonton et al. 1990	Y	Y	Y	Y	Y*	N	Y	Y	N	Y	Y	Y	N	Y	Y	Y	Y	N	N	Y
McGill, Norman et al. 1990	Y	Y	Y	Y	N	N	Y	Y	N	Y	Y	N	N	Y	Y	Y	Y	N	Y	Y
Adams, Schmid et al. 2014	Y	Y	Y	Y	Y*	Y	Y	Y	N	Y	Y	Y	Y	Y	N	N	Y	Y	Y	Y
Niewiadomski, Pilis et al. 2014	Y	Y	Y	Y	Y*	N	Y	N	N	Y	Y	Y	Y	Y	Y	N	N	Y	Y	Y
Kawabata, Shima et al. 2014	Y	Y	Y	Y	Y*	Y	Y	Y	N	Y	Y	Y	N	Y	Y	N	Y	Y	Y	Y
Kawabata 2010 et. Al	Y	Y	Y	Y	Y*	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	N	N	Y
Harman, Rosenstein et al. 1989	Y	Y	Y	Y	Y*	Y	Y	Y	N	Y	N	Y	Y	Y	Y	N	Y	Y	Y	Y
Goldish, Quast et al. 1994	Y	Y	Y	Y	N	N*	Y	Y	N	N	Y	Y	Y	Y	N	N	Y	N	Y	Y
Cholewicki, Ivancic et al. 2002	Y	Y	Y	Y	N	N*	Y	Y	N	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	N
Compton, Hill et al. 1973	N	Y	Y	Y	Y*	Y	N	Y	N	Y	N	N	N	Y	N	N	N	Y	N	Y

Legend:Y-criteria filled, N-criteria not filled Y*-most of the criteria filled, N*-most of the criteria non-filled

Data extraction form

Reviewer.. Date..........................

Author... Journal.......................

Study method

Cross sectional Intervention RCT

Other:

Study aim:____

____

Participants

n = ...settings (age, height, weight,other):

population:

Closer population description::

Measurement details

Type of pressure measured:..

Peak pressure measured:...

Type of exercise:...

Intensity of 1 RM:..

Additional comments:

Authors conclusions:

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____

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Reviewer decision:

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