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Original Articles

Intra-abdominal pressure correlates with abdominal wall tension during clinical evaluation tests

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ABSTRACT

Background: The abdominal muscles play an important respiratory and stabilization role, and in coordination with other muscles regulate the intra-abdominal pressure stabilizing the spine. The evaluation of postural trunk muscle function is critical in clinical assessments of patients with musculoskeletal pain and dysfunction. This study evaluates the relationship between intra-abdominal pressure measured as anorectal pressure with objective abdominal wall tension recorded by mechanical-pneumatic-electronic sensors.
Methods: In a cross-sectional observational study, thirty-one asymptomatic participants (mean age = 26.77 ± 3.01 years) underwent testing to measure intra-abdominal pressure via anorectal manometry, along with abdominal wall tension measured by sensors attached to a trunk brace (DNS Brace). They were evaluated in five different standing postural-respiratory situations: resting breathing, Valsalva maneuver, Müller's maneuver, instructed breathing, loaded breathing when holding a dumbbell.
Findings: Strong correlations were demonstrated between anorectal manometry and DNS Brace measurements in all scenarios; and DNS Brace values significantly predicted intra-abdominal pressure values for all scenarios: resting breathing ($r = 0.735$, $r^2 = 0.541$, $p < 0.001$), Valsalva maneuver ($r = 0.836$, $r^2 = 0.699$, $p < 0.001$), Müller's maneuver ($r = 0.651$, $r^2 = 0.423$, $p < 0.001$), instructed breathing ($r = 0.708$, $r^2 = 0.501$, $p < 0.001$), and loaded breathing ($r = 0.921$, $r^2 = 0.848$, $p < 0.001$).
Interpretation: Intra-abdominal pressure is strongly correlated with, and predicted by abdominal wall tension monitored above the inguinal ligament and in the area of superior trigonum lumbale. This study demonstrates that intra-abdominal pressure can be evaluated indirectly by monitoring the abdominal wall tension.

1. Introduction

Spinal stability is secured by the bone structures, ligaments, and via coordinated activation between spinal extensors and flexors and all muscles regulating the intra-abdominal pressure (IAP) (Cholewicki and McGill, 1996; Hodges et al., 2005). The diaphragm and pelvic floor form two pistons which push against each other increasing the pressure in the abdominal cavity. Contraction of the abdominal muscles resists lateral movement of the contents within the abdominal cavity (Chaitow et al., 2014; Hodges, 1999). IAP is essentially a hydraulic pressure effective in all directions, stabilizing the torso and reducing axillary compression during activities that increase the demands on spinal stabilization, such as lifting heavy loads (Cobb et al., 2005; Grillner et al., 1978). Hodges et al. has confirmed that an increase in IAP alone without activity of abdominal or back muscles still enhances the stability of the lumbar spine (Hodges et al., 2005).

The amount of IAP can be measured by several different invasive and non-invasive methods. The most accurate is direct laparoscopic measurement using an intra-abdominal catheter (Malbrain et al., 2006). Indirect urethral measurement is considered to be the most frequent and reliable method to monitor IAP; however, this can result in urinary tract infections or urethral injury, therefore, it is not often used in postural function research (Malbrain et al., 2013; Wise et al., 2017).

In rehabilitation medicine, instrumental IAP measurement via rectal

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or gastric probes are mainly used in experimental studies, and are not typically used in routine clinical assessment (Malbrain et al., 2006). Gastric or nasogastric tubes inserted into the stomach provide quite accurate IAP measurements, however, it is quite uncomfortable for patients and an expensive method requiring highly trained personnel (Grillner et al., 1978; Hodges et al., 2005; Wauters et al., 2012). Special catheters or probes inserted into the rectum are used for anorectal measurements. Such pressure sensitive devices convert mechanical signals into electrical signals recorded and displayed on a computer monitor (Pfeifer and Oliveira, 2006). Recently, thin electric probes have become available. Smaller devices lead to fewer artifacts thus offering more exact display and measurement. Small probes are easy to install, temperature resistant, very sensitive to pressure changes and well tolerated by patients, with infrequent side effects (Malbrain et al., 2006; Sugrue et al., 2015). The disadvantage is the high purchase price (Pfeifer and Oliveira, 2006). Such IAP recording has been reported in many studies exploring IAP changes in various postural situations (Kawabata et al., 2010; Sapsford et al., 2013).

IAP measurement has also been combined with simultaneous electromyography or ultrasound assessments of core muscles. However, these methods do not evaluate the global coordination of the trunk muscles but rather local muscle activation. In addition, significant inaccuracies during such recording have been reported (Henry and Westervelt, 2005; Junginger et al., 2010).

In clinical practice, palpation of the abdominal wall tension (AWT), especially in the area above the inguinal ligament and in the upper trigonum lumbale is used to evaluate an individual's ability to regulate their IAP (Kobesova et al., 2020). Available studies suggest that the AWT occurs as a result of increased IAP (Cresswell, 1993; Kumar et al., 2012; Tayebi et al., 2021; van Ramshorst et al., 2011). Different types of sensors have been used to measure the AWT during various postural tasks related to IAP changes (Chen et al., 2015; Malátová et al., 2013, 2008; Novak et al., 2020; van Ramshorst et al., 2011). This study presents simultaneous recording of IAP measured as anorectal pressure and AWT measured via four sensors attached to a trunk brace. In an attempt to further understand the relationship between IAP and outward tension of the abdominal wall, the purpose of this research was to compare anorectal manometry measurements, largely considered the gold standard in ambulatory patients, with abdominal wall outward tension measured by a trunk brace during clinical assessments.

2. Methods

2.1. Participants

Thirty-one asymptomatic volunteers were recruited for the study. Written informed consent was obtained from each participant, and demographic characteristics of the sample including age, weight, height and BMI are shown in Table 1. Exclusion criteria were any symptomatic neurologic, orthopedic, respiratory, internal or musculoskeletal disorder, spine or abdominal surgery, severe trauma during the last year, pregnancy, and history of therapy focusing on IAP training. The study conforms with The Code of Ethics of the World Medical Association and was approved by an Institutional Ethics Committee (Ethics Committee of the University Hospital Motol and 2nd Faculty of Medicine, Charles University in Prague. No.1263.1.15/19; approval date: November 6, 2019). This study adhered to the Helsinki declaration.

Table 1
Participant's anthropometric characteristics. $N = 31$, 15 males, 16 females.

	Age (years)	Height (cm)	Weight (kg)	BMI
Mean	21.3	170.5	63.2	24.1
SD	1.6	6.5	7.9	3
Min	19	160	47	17.3
Max	25	185	80	27.6

2.2. DNS Brace

To monitor AWT, a special new device called DNS Brace was used (Fig. 1 – A,C). The DNS abbreviation is derived from the rehabilitation concept called Dynamic Neuromuscular Stabilization (DNS) (Kobesova et al., 2019, 2016). DNS emphasizes the importance of IAP in spinal stabilization and treatment. The diaphragm, pelvic floor and abdominal wall muscles regulate the IAP (Hodges et al., 2007). IAP increases during postural activity (Hodges and Gandevia, 2000), resulting in a contraction and expansion of the abdominal wall due to muscle activity. Abdominal wall expansion and contraction result in pressure that compresses the DNS Brace sensors. The Brace is an original device produced by Ortotika, FN Motol V Úvalu 84, Praha. Four mechanical-pneumatic-electronic sensors are placed on the inner wall of plastic trunk orthosis. Two ventral sensors are located bilaterally above the groin and two sensors are located on the brace parts adhering to laterodorsal sections of the abdominal wall (trigonum lumbale superius). Silicon brace sensors contain the inner air-chamber that is deformed by the abdominal wall pressure. The values recorded in kilopascals (kPa) are transferred via Bluetooth, stored and graphically displayed in a smart-phone device. More details about the brace can be found elsewhere (Jacisko et al., 2020). The brace sensors measure the pressure exerted by the abdominal wall in kilopascals (kPa) (Figs. 2. B, 3. B, 4. B) and transfer the data via Bluetooth to a smart-phone or computer so the data can be statistically processed and graphically displayed.

2.3. High resolution anorectal manometry

The intra-abdominal pressure was measured using the ManoScan™ AR HRM system (Given imaging, 15 Hampshire Street, Mansfield, MA 02048 US). It allows for complex assessment of anorectal pressures (Fig. 1 – B,C). The anorectal probe is equipped with 12 channels each measuring 12 circumferentially located spots thus recording pressures from 144 points simultaneously. The diameter of the probe is 10 mm. The pressure values are measured in mmHg (Figs. 2. A, 3. A, 4. A) and transferred at 0.1 s intervals to a computer, where the data can be further processed. The ManoView™ software color-visualizes the measured pressures. Two distal sensors located behind the anal sphincters in the ampulla of rectum monitor the IAP. The remaining 10 probe sensors record the pressures produced by the sphincters. Before starting the measurement, the probe must always be calibrated to 0 atmospheric pressure and a ManoShield rubber protection must be fitted. The probe records pressure in real time.

2.4. Assessments

The assessment of all participants was performed by the same examiners under similar conditions (time of day, assessment room, temperature). All participants were first informed about the procedure in detail. After calibration, the anorectal probe was inserted into the participant's anus in a side lying position. Then, the participant stood up and the correct location of the probe was ensured. By activating the sphincters, it was verified that the 2 distal sensors are located in the rectal ampulla monitoring the IAP but not the activity of the sphincters (McCarthy, 1982; Pfeifer and Oliveira, 2006; Shafik et al., 1997). Then, DNS Brace was fixed to the participant's trunk and the sensors were calibrated to 0 kPa during the tidal exhalation prior to each measurement. The dorsal sensors were adjusted to be placed bilaterally in the superior trigonum lumbale, bellow the floating ribs, and the ventral sensors were placed bilaterally above the groin at the intersection of the mammilar and bispinal connecting line. Then, the participants were instructed to maintain the upright standing position throughout the whole measurement, avoiding increased spinal kyphosis, lordosis or extremity movements. Five postural tests were performed by each subject and evaluated by DNS Brace and Anorectal manometry simultaneously in the same order. The anorectal pressure and AWT values were

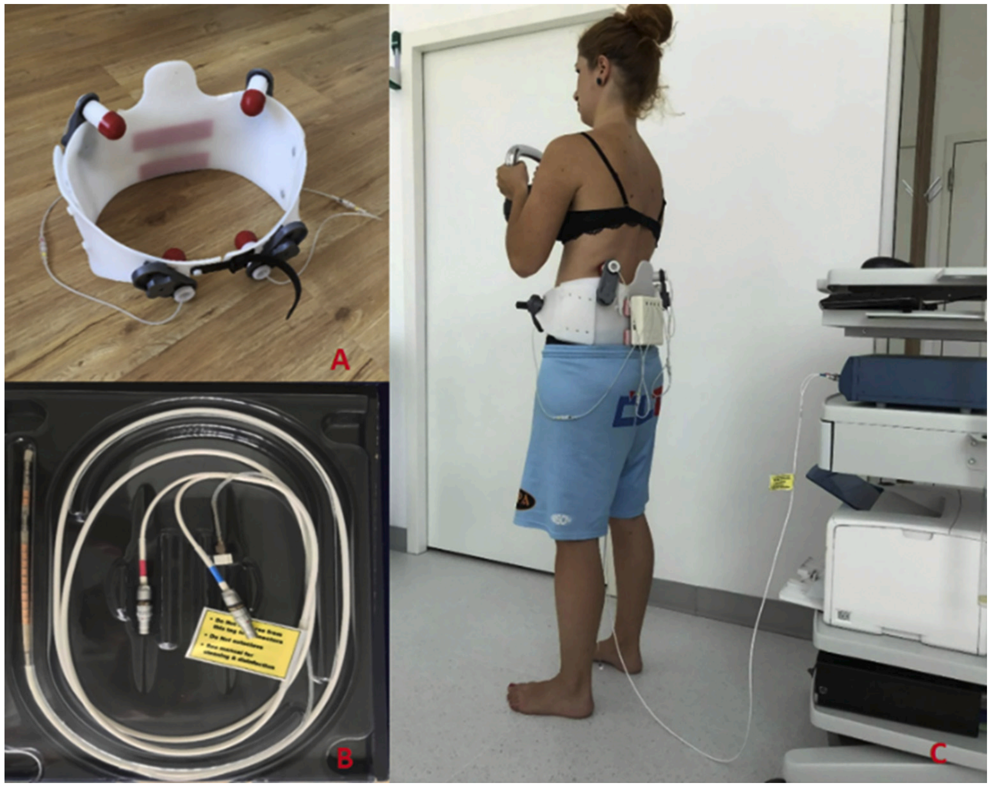

Fig. 1. A: DNS Brace, B: Anorectal probe, C: Participant equipped with DNS Brace and anorectal probe during assessment.

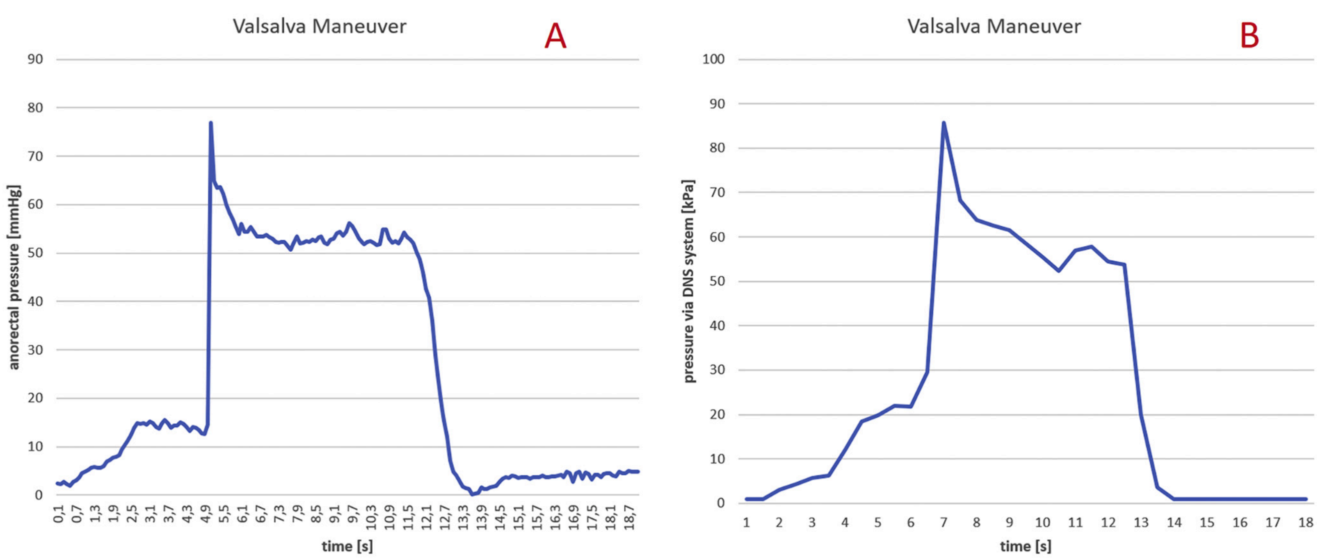

Fig. 2. Example of graphical visualization of the measured pressures (A: anorectal manometry, B: DNS Brace) during Valsalva maneuver scenario. A minor delay in DNS Brace measurement relative to ARM is caused by a minimal delay of AWT relative to IAP and by the fact, that DNS Brace measures AWT in 0.5 s. intervals while ARM measures IAP in 0.1 s intervals. Additionally, brace sensors identify only pressure changes over 1 kPa. These factors may cause negligible inaccuracy. The starting pressure before the maneuver is around 5 mmHg for ARM whereas the DNS system starts from zero and returns to zero after the maneuver. DNS Brace automatically reset to zero starting pressure for user friendly reasons. This has no impact on the results because all indirect measurement techniques are able to monitor the IAP changes rather than estimating the absolute IAP value (Tayebi et al., 2021).

both collected for 10 s during each of the five scenarios, and the average value of each measurement was used for statistical analysis.

The measured scenarios:

1) Resting breathing: The participant was breathing naturally in a standing position.
2) Valsalva maneuver: The participant was forcefully exhaling against closed nostrils and mouth (Talasz et al., 2012, 2011).
3) Müller maneuver: The participant was forcefully inhaling against closed glottis (Mattos Soares et al., 2009).
4) Instructed breathing (The diaphragm test): The participant was expanding the abdominal wall pushing as much as possible against

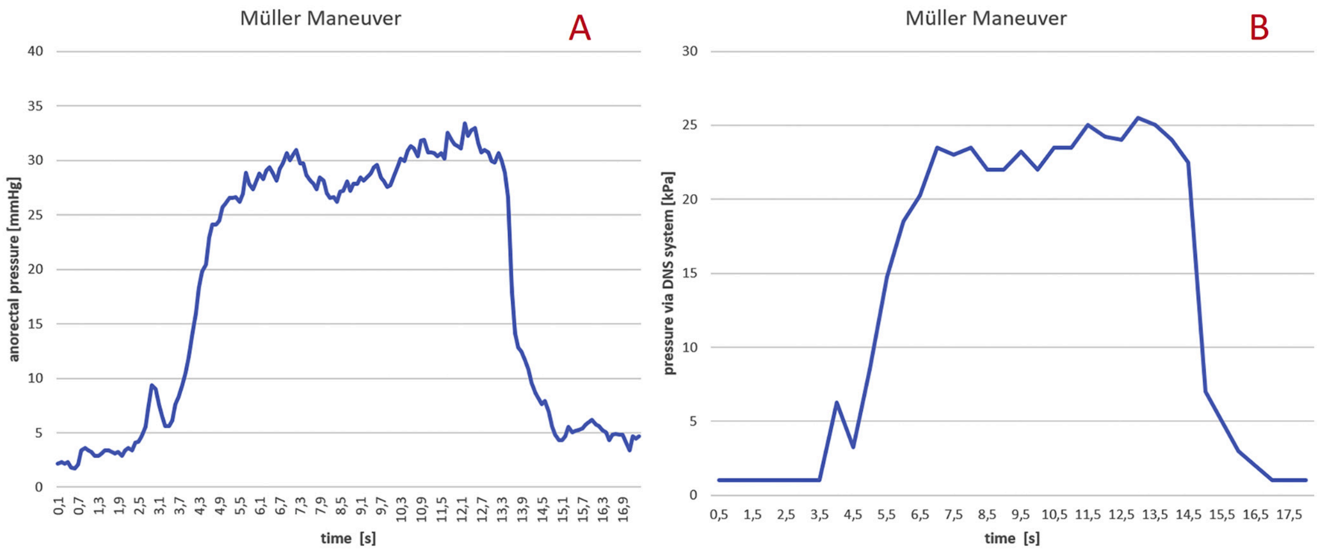

Fig. 3. Example of graphical visualization of the measured pressures (A: anorectal manometry, B: DNS Brace) during Müller maneuver scenario.

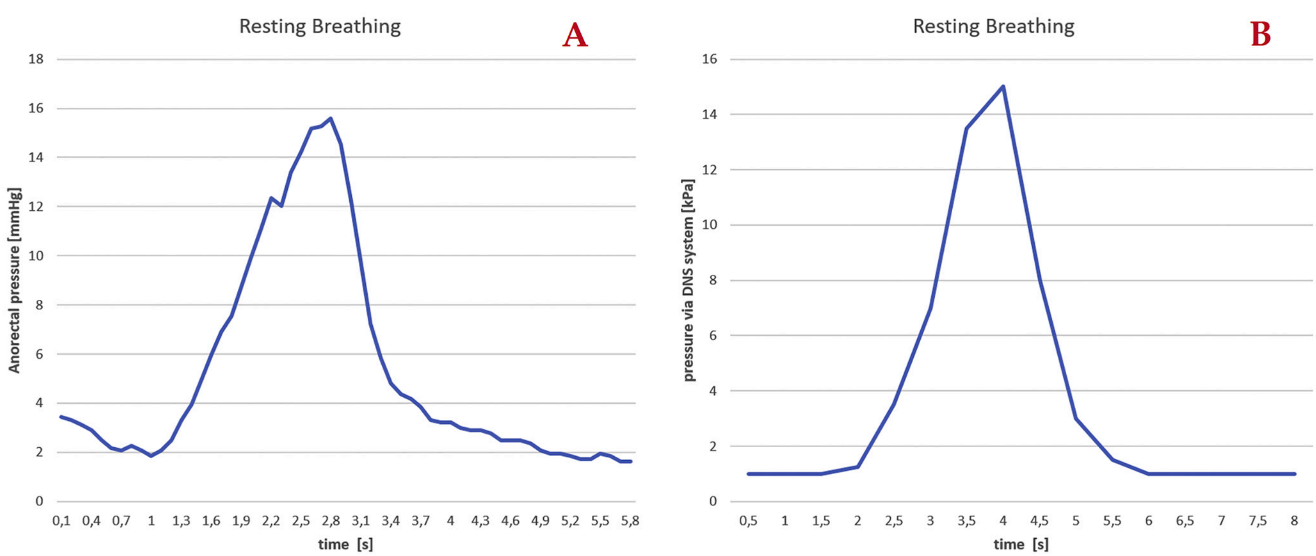

Fig. 4. Example of graphical visualization of the measured pressures (A: anorectal manometry, B: DNS Brace) during resting breathing scenario.

all four sensors both during inhalation and exhalation (Kobesova et al., 2020).

5) Holding a load of 20% of participant's body weight in hands in front of the trunk - loaded breathing (Fig. 1C).

2.5. Statistical analysis

Data analyses were conducted using the Statistical Package for the Social Sciences *v27.0 for Mac (IMBCorp, Armonk, NY).*. Pearson's correlations and linear regression tests were used to assess the relationship between the 10-s mean anorectal manometry values and DNS Brace values under all five scenarios. Statistical significance was determined a priori at $p < 0.05$, and power analyses revealed in order to achieve a power of 0.80, 29 subjects were needed to identify a large effect size of 0.50 for Pearson's correlations, and 26 subjects were needed to achieve a large effect size of 0.35 for linear regression analyses. The strength of correlations were interpreted as weak (< 0.30), moderate (0.30–0.50), or strong (> 0.50), and the strength of regression predictions were interpreted as weak (< 0.02), moderate (0.15–0.35) or strong (> 0.35) as reported by Cohen, 1988 (Cohen, 1988).

3. Results

Preliminary analyses showed linear relationships, with no outliers as assessed by scatterplots, but not all variables were normally distributed, as assessed by Shapiro-Wilk's test ($p < 0.05$). Data are mean ± standard deviation unless otherwise stated. Pearson's correlations demonstrated strong statistically significant positive relationships between anorectal manometry pressures and DNS Brace pressures, under all five scenarios: resting breathing: $r(31) = 0.735$, $p < 0.001$; Valsalva maneuver: $r(31) = 0.836$, $p < 0.001$; Müller's maneuver: $r(31) = 0.651$, $p < 0.001$; instructed breathing: $r(31) = 0.708$, $p < 0.001$; and loaded breathing: $r(31) = 0.921$, $p < 0.001$ (Table 2). Simple linear regression models established that anorectal manometry pressure could significantly be predicted from the DNS Brace values under all five scenarios: resting breathing: $F(1, 29) = 34.14$, $p < 0.001$; Valsalva maneuver: $F(1, 29) = 67.42$, $p < 0.001$; Müller's maneuver: $F(1, 29) = 21.29$, $p < 0.001$; instructed breathing: $F(1, 29) = 29.14$, $p < 0.001$; and loaded breathing: $F(1, 29) = 161.2$, $p < 0.001$ (Figs 5 - 9). Table 3 depicts all results from regression analyses.

Table 2
Correlations between Intra-Anal Manometer and DNS Brace Pressures. Values are Mean [Standard Deviation].

Condition	Manometric probe pressure	DNS Brace pressure	Pearson r	Sig
1-Resting Breathing	22.73 [12.38]	20.34 [11.68]	0.735	< 0.001*
2-Valsalva Maneuver	47.20 [27.09]	35.93 [20.19]	0.836	< 0.001*
3-Müller's Maneuver	35.92 [24.96]	20.87 [10.45]	0.651	< 0.001*
4-Instructed Breathing	34.72 [17.45]	26.57 [15.05]	0.708	< 0.001*
5-Loaded Breathing	36.35 [21.46]	30.97 [25.86]	0.921	< 0.001*

Note: DNS = Dynamic neuromuscular stabilization.
* Statistically significant correlation ($P < 0.01$).

4. Discussion

4.1. IAP measurement methods

Currently, various methods to measure the IAP are available. It can be monitored directly via sensors located intraperitoneally or in the inferior caval vein. Intra-vesical, intra-gastric intra-anal or intra-vaginal recording allow to measure the IAP indirectly (Malbrain et al., 2006; Wise et al., 2017). This study utilized intra-anal, i.e. measurement using anorectal manometry, which has been determined the safest and easiest method of assessment (Malbrain et al., 2013, 2006). Other methods posed different challenges, such as intra-vesical catheters may cause urinal infection and urethral trauma, intra-gastric measurement is uncomfortable for participants, and intra-vaginal measurement would exclude male participants. The intra-anal pressure measurement is a reliable way to monitor the IAP, although it does not match with the IAP as accurately as the intra-vesical pressure (Wise et al., 2017). There are only a few inconveniences of intra-anal pressure monitoring such as the presence of residual faeces, incorrect insertion of the probe and participant's embarrassment (Bhatia and Bergman, 1986; Pfeifer and Oliveira, 2006).

In a clinical practice, practitioners often palpate the abdominal wall assuming it to be a non-invasive and indirect way of IAP evaluation. The abdominal wall expands with the IAP increase (van Ramshorst et al., 2011). Palpation can be performed in the area above the inguinal ligament and in the superior lumbar triangle (Kobesova et al., 2020). Poor activation in these specific areas of the abdominal wall are commonly found in individuals with low back pain (LBP) (Frank et al., 2013; Kobesova et al., 2016). The same trunk sections were previously assessed by other researchers when evaluating abdominal wall activity in relation to IAP regulation (Kumar et al., 2012; Malátová et al., 2013; Novak et al., 2020). Therefore, the sensors are placed on the DNS Brace in the parts adhering to the abdominal wall above the inguinal ligaments and in the superior lumbar triangles. Here, only the attachments of the flat abdominal muscles are located and therefore the abdominal wall is easily accessible (Grevious et al., 2006).

Our in vivo correlations between IAP and AWT in asymptomatic individuals are in line with the study by Ramshorst et al. previously performed on corpses. Ramshorst used a special dynamometer to monitor AWT resulting from IAP changes in corpses, in which the IAP was changed artificially by insufflation (van Ramshorst et al., 2011). Ramshorst's study reports that AWT reflects the IAP. The findings from this study demonstrate significant correlations between the natural IAP regulation and AWT in all five measured scenarios with Pearson's coefficient ranging 0.651 to 0.921 which indicates strong correlations, with the ability to predict the IAP from the measured tension values.

4.2. Changes in IAP in response to respiration and postural load

The findings of the current study support prior experiments reported by Davis (Davis, 1959) and Cholewicki (Cholewicki et al., 1999), confirming that IAP increases with progressing demands on postural stability. The IAP increase results in the proportional activation of the abdominal wall which can be objectively monitored by the sensors or subjectively palpated in the area above the inguinal ligament and in the superior lumbar triangle. In other words, these results confirm that subjective palpation of the abdominal wall is an indirect evaluation of IAP.

Breathing has been shown to considerably influence IAP, trunk stability and movement (Bradley and Esformes, 2014). In this study, inhalation during resting breathing caused only slight increases in the

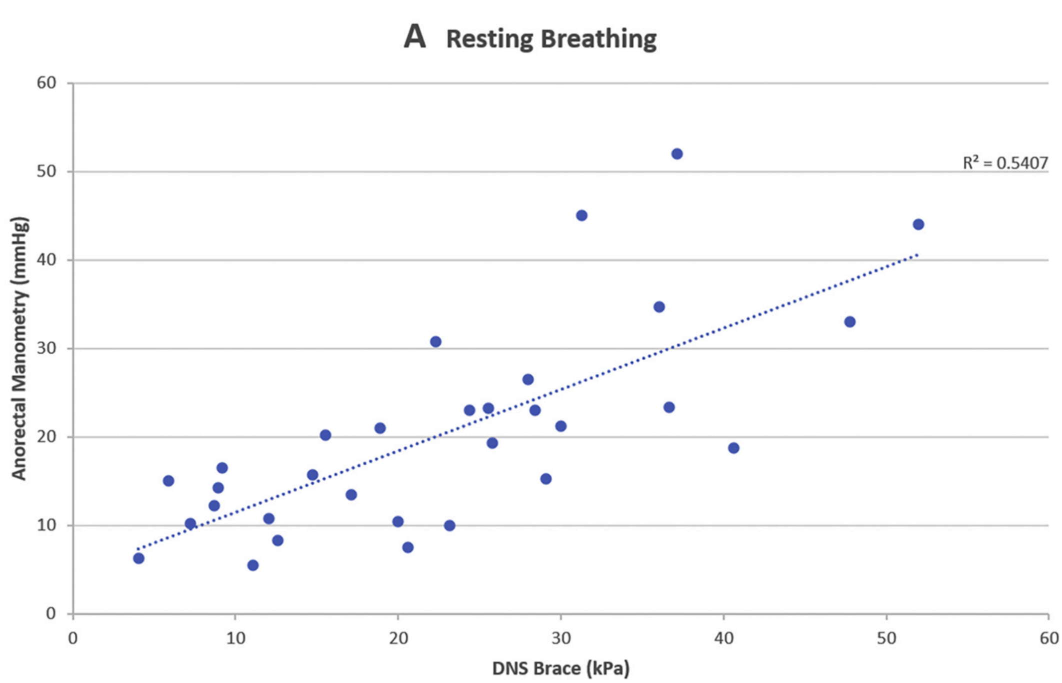

Fig. 5. Simple linear regression analysis of anorectal manometry values (mmHg) and DNS Brace values (kPa) measured during resting breathing.

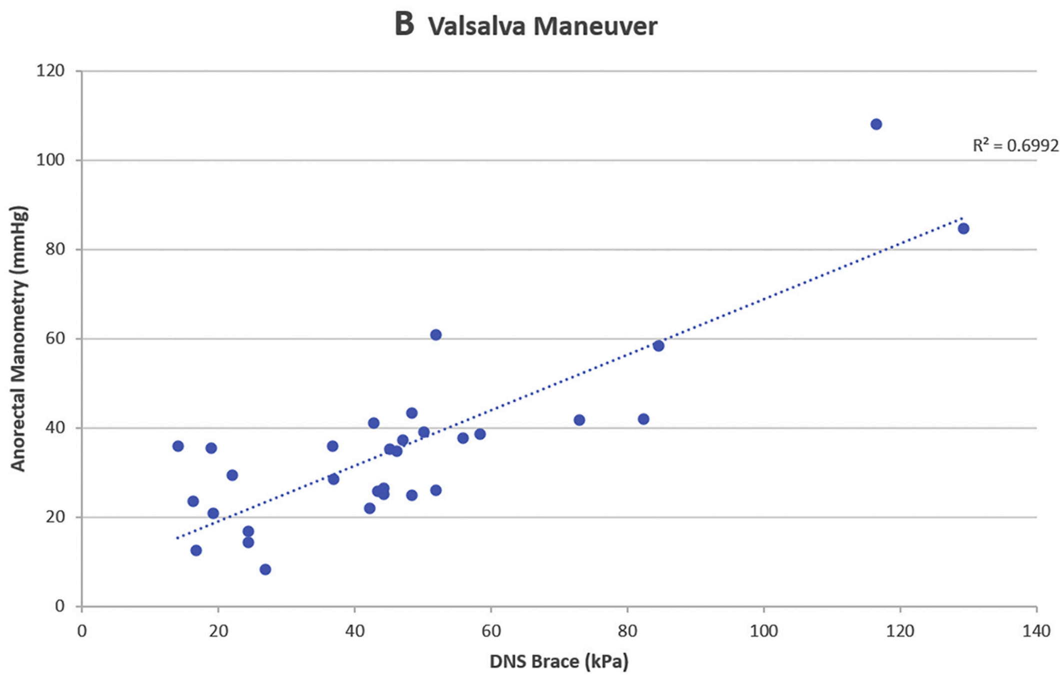

Fig. 6. Simple linear regression analysis of anorectal manometry values (mmHg) and DNS Brace values (kPa) measured during Valsalva maneuver.

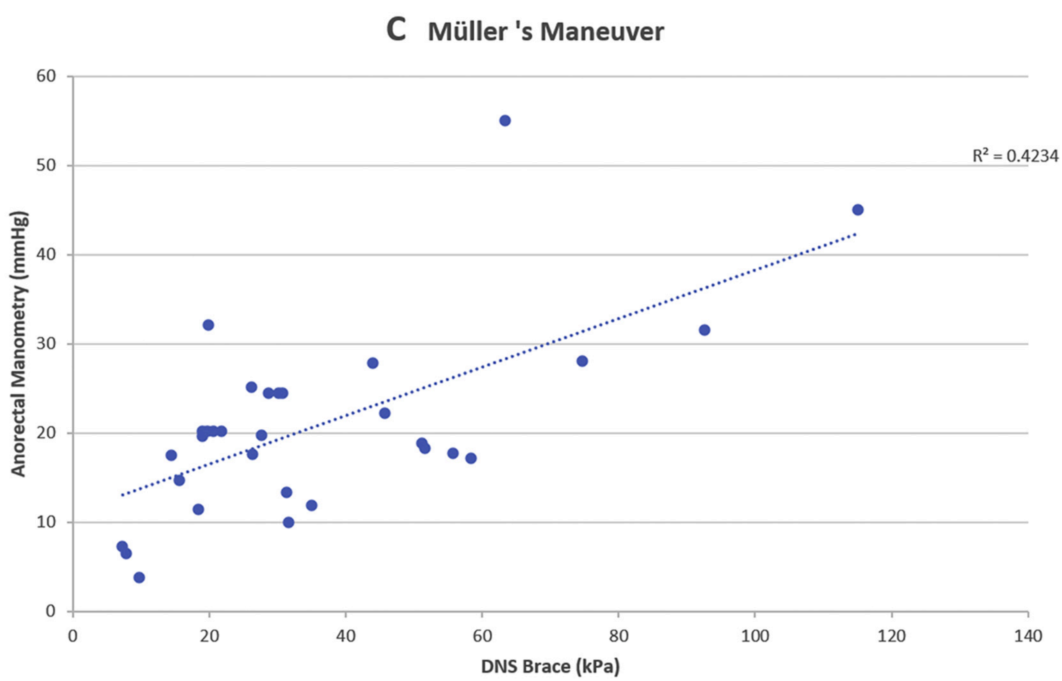

Fig. 7. Simple linear regression analysis of anorectal manometry values (mmHg) and DNS Brace values (kPa) measured during Müller maneuver.

IAP. During exhalation, the AWT and the IAP returned to the basic value. This physiological fluctuation of IAP is normal within the respiratory cycle. Permanent excessive resting IAP would cause organ function failure (Cobb et al., 2005; De Waele et al., 2011; Smit et al., 2016). In this study, the largest increase in the IAP was noted during the Valsalva maneuver. Perhaps this is due to the fact that the muscles of the torso do not have to perform a respiratory function during the Valsalva when the air is not flowing out of the body, the intra-thoracic pressure increases and the cranial displacement of the diaphragm is smaller than with a normal exhalation (Talasz et al., 2012, 2011). During the Müller maneuver, the intra-thoracic pressure is significantly reduced, the diaphragm descends towards the abdominal cavity but no air flows into the lungs (Kushida, 2013). In our study, Pearson's correlation coefficient was the smallest in this scenario (0.651) which was also the most difficult task for the participants to understand and perform. The instructed breathing represents the Diaphragm Test according to DNS concept. The participants voluntarily expand the abdominal wall towards all four sensors, keeping the abdominal cavity pressurized during the entire respiratory cycle (Kobesova et al., 2020). With this scenario, the participant must be able to combine the respiratory and postural functions of the diaphragm, which is a frequent problem in clinical practice (Kawabata et al., 2010; Shirley et al., 2003). It is speculated that

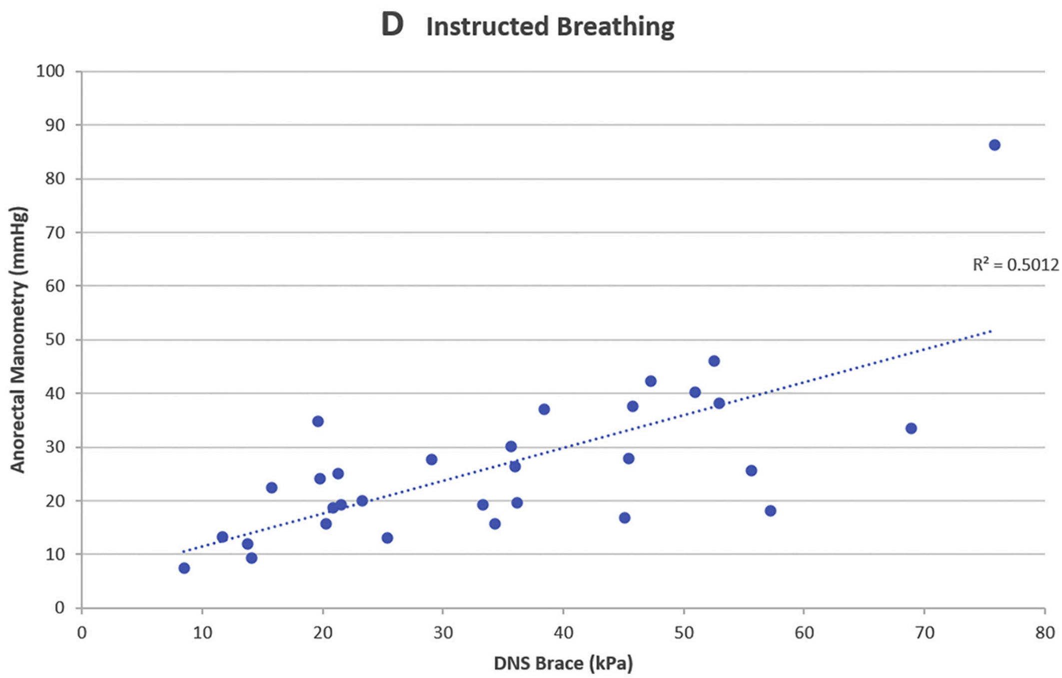

Fig. 8. Simple linear regression analysis of anorectal manometry values (mmHg) and DNS Brace values (kPa) measured during instructed breathing.

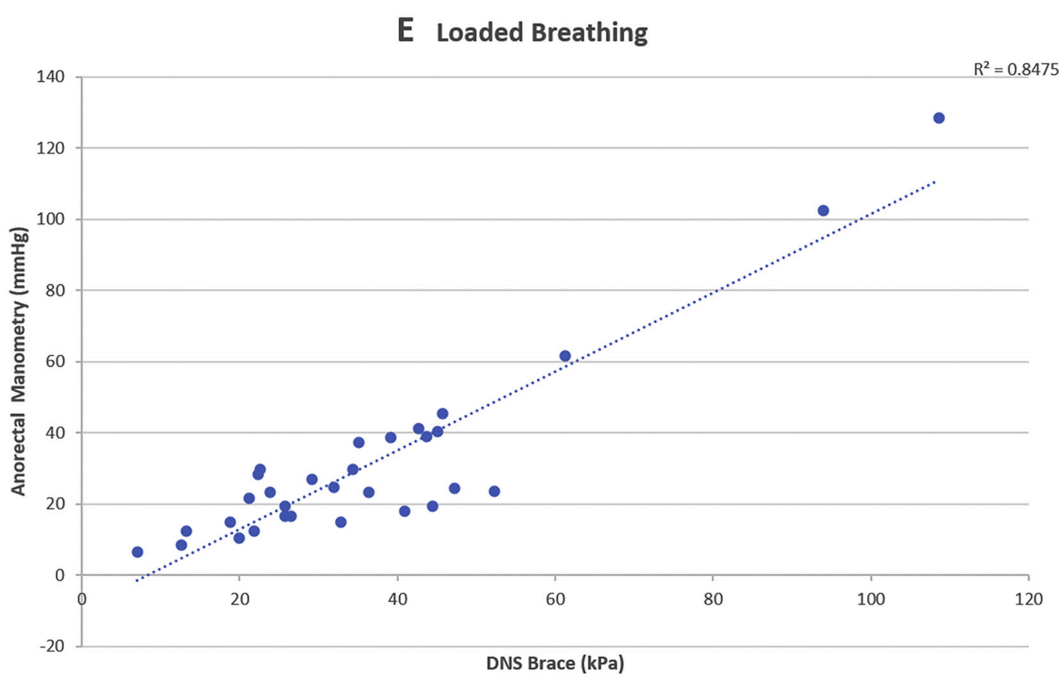

Fig. 9. Simple linear regression analysis of anorectal manometry values (mmHg) and DNS Brace values (kPa) measured during loaded breathing.

individuals unable to do so maybe in a greater risk of developing LBP in the future (Ostwal and Wani, 2014; O'Sullivan and Beales, 2007). During the last scenario, the participants were holding a barbell of a weight corresponding with 20% of body weight. This situation caused less IAP increase than the Valsalva maneuver but more than resting and instructed breathing and Müller maneuver. Other studies also report significant increases in abdominal muscle activity monitored by EMG (Ershad et al., 2009; Mesquita Montes et al., 2017) and in the IAP monitored by anorectal probe (Hodges et al., 2005; Tayashiki et al., 2015) during posturally challenging situations. With normal resting breathing, a decrease in the IAP during exhalation occurs. However, there is only slight pressure fluctuation within the respiratory cycle with postural loading when the IAP must be reflexively maintained on a higher level throughout the whole respiratory cycle. In this test, the correlation between the values obtained from the manometry and from the DNS Brace sensors was the strongest (Pearson $r = 0.921$). When holding a load, the stabilization strategy is purely reflexive, i.e. involuntary, and therefore diagnostically valuable in determining possible risks associated with poor trunk stabilization.

Table 3
Summary of Simple Regression Analyses for Predicting Intra-Anal Manometer Pressure using DNS Brace Pressure ($n = 31$).

Condition	*B*	*SE B*	R^2	Adjusted R^2	95% CI	Effect Size (f^2)
1-Resting Breathing	0.78	0.13	0.54	0.53	0.51, 1.05	1.18
2-Valsalva Maneuver	1.12	0.14	0.70	0.69	0.84, 1.40	2.32
3-Müller's Maneuver	1.55	0.34	0.42	0.40	0.87, 2.24	0.73
4-Instructed Breathing	0.82	0.15	0.50	0.48	0.51, 1.13	1.00
5-Loaded Breathing	0.76	0.06	0.85	0.84	0.64, 0.89	5.58

Note: DNS = Dynamic neuromuscular stabilization.
R^2 = R square: proportion of variance explained by model in sample.
Adjusted R^2: proportion of variance explained by model in population.

4.3. Methods to measure abdominal wall tension and abdominal wall activation

The DNS Brace helps to assess both voluntary control and reflex postural activation. It can be used as a feedback tool to train abdominal wall activation and the IAP fluctuations. The DNS Brace can be fixed to the trunk keeping all four sensors in stable contact with the abdominal wall thus allowing evaluation in various body positions. Future studies need to identify the AWT in other postural situations. Other devices like a pressure Biofeedback Unit (Lima et al., 2011) and muscle dynamometry (Malátová et al., 2013), designed to measure or train trunk muscles and lumbopelvic stability may not allow such positional variability. Electromyography (Marshall and Murphy, 2010) or ultrasound (Amerijckx et al., 2020) analyze mainly local activation of the abdominal muscles. The information from the four DNS Brace sensors monitor more global co-activation of all abdominal muscles. Based on the strong correlations identified with the DNS Brace and anorectal manometry it can be concluded that the DNS Brace presents a new simple and non-invasive method to evaluate IAP indirectly. The DNS Brace may prove to be useful in physical rehabilitation medicine and research to monitor AWT in response to postural-respiratory demands, and may help to objectivize therapeutic effects, while also providing biofeedback during self-treatment. In the ideal condition, the DNS system is able to track IAP fluctuations and not measure absolute values of IAP, and therefore would not be suitable for IAP monitoring at intensive care units.

4.4. Study limitations

This study has several limitations. An average value from the four DNS Brace sensors was calculated and used for statistical analysis. Therefore, possible asymmetric tension of the abdominal could not be taken into account. The current version of the DNS Brace is not commercially available, but sensors working on a similar principle called Ohm Track (Novak et al., 2020) can be purchased and used in a similar way. DNS Brace cannot be applied to any participants with very narrow or extremely wide waistlines, therefore a different version of the DNS Brace is needed to increase the variability in testing individuals with different corset circumferences. While BMI seems to have no impact on indirect IAP measurements (Chen et al., 2015), the thickness of the abdominal fat layer may play a role. The relationship between the AWT changes measured by the brace sensors and subcutaneous fat thickness measured by a caliper can be explored in future studies. The research was performed on 31 asymptomatic and rather young individuals. Further studies should investigate larger cohorts of individuals comprised of both asymptomatic and LBP or other musculoskeletal problems.

5. Conclusions

This study established strong correlations between IAP measured as the anorectal pressure through high resolution manometry with AWT measured by the DNS Brace. Such manometry values could be predicted through the measurement of AWT. Strong correlations were identified during various breathing modifications and also during postural stabilization situations when holding a load. It was confirmed that with progressing demands on postural stability, the IAP increases in a direct correlation with proportional tension of the abdominal wall. The AWT was identified by four DNS Brace sensors located above inguinal ligaments and in the upper lumbar triangle bilaterally. For clinical applications, subjective palpation may be an effective indirect evaluation of intra-abdominal pressure.

Credit authorship contribution statement

Jakub Novak: Conceptualization, Project administration, Methodology, Investigation, Data curation, Writing - original draft. **Jakub Jacisko:** Conceptualization, Methodology, Investigation. **Andrew Busch**: Data curation, Software, Writing - review & editing. **Pavel Cerny:** Conceptualization, Interpretation and analysis of data. **Martin Stribrny:** Conceptualization, Methodology, Investigation. **Martina Kovari:** Supervision, Writing - review & editing. **Patricie Podskalska:** Project administration, Data curation. **Pavel Kolar:** Conceptualization. **Alena Kobesova**: Conceptualization, Supervision, Writing - review & editing, Funding acquisition.

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Declarations of Competing Interest

None.

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