Dejan Kernc[1]
Vojko Strojnik [2]
Petra Prevc [2, *]

A NEW DEVICE FOR MEASURING LATERAL ABDOMINAL FORCE

NOVA NAPRAVA ZA MERJENJE LATERALNE ABDOMINALNE SILE

ABSTRACT

A positive relationship between intra-abdominal pressure (IAP) and activation of m. transversus abdominis (TrA) is well established, enabling the non-invasive prediction of IAP from an EMG TrA signal. Since lateral abdominal force (LAF) may also be related to IAP, a new sensor device for measuring LAF was developed to assess IAP. Sixteen participants performed two progressive isometric shoulder flexions to their maximum to induce IAP. The LAF and surface EMG of the TrA muscle were measured. Lateral abdominal force was analysed for reliability and validity regarding the EMG TrA signal. For each individual, correlation coefficients between the EMG TrA and lateral abdominal force sensor (LAFS) signals were significant and ranged from 0.886 to 0.994. In all cases, the EMG TrA signal made a significant contribution (p < 0.001) when predicting the LAFS signal, while the linear prediction of the LAFS signal yielded a small error of estimation. The interclass correlation confirmed consistency between two repetitions. Results provide that the LAFS might estimate IAP in a simple and non-invasive way. The new device also has the potential to detect the start of the increase in IAP before the action, a principle important for lumbar spine protection.

Keywords: intra-abdominal pressure, transversus abdominis, lateral abdominal force, validity, reliability

IZVLEČEK

Pozitivna korelacija med znotrajtrebušnim pritiskom (IAP) in aktivacijo mišice transversus abdominis (TrA) omogoča neinvazivno merjenje IAP preko zaznavanja signala EMG TrA. V članku ugotavljamo povezanost med EMG signalom TrA in lateralno abdominalno silo (LAF), merjeno z novo zasnovano napravo, s pomočjo katere bi lahko enostavno ocenili znotrajtrebušni pritisk. Šestnajst merjencev je izvedlo dve največji hoteni izometrični fleksiji ramena s postopnim naraščanjem sile, da bi povečali IAP. Med nalogo sta bili izmerjeni LAF in površinski EMG mišice TrA. Korelacijski koeficient med signalom senzorja za lateralno abdominalno silo (LAFS) in signalom EMG TrA je bil pri posameznih merjencih med 0.886 in 0.994 in je bil pri vseh statistično značilen (p < 0.001), hkrati pa je bila napaka ocene IAP s pomočjo EMG TrA majhna. Medrazredni korelacijski koeficient je potrdil skladnost dveh ponovitev. Raziskava ugotavlja visoko povezanost med EMG TrA in LAFS, s čimer podpira idejo, da je mogoče iz signala LAFS oceniti IAP na enostaven in neinvaziven način. Nova naprava hkrati predstavlja potencialno možnost zaznavanja začetka povečanja IAP že pred akcijo, ki je pomemben varnostni mehanizem lumbalne hrbtenice.

Ključne besede: znotrajtrebušni pritisk, prečna trebušna mišica, lateralna abdominalna sila, veljavnost, zanesljivost.

[1]RE.AKTIV SPINE, healthcare activities, d.o.o., Ljubljana, Slovenia

[2]Faculty of Sport, University of Ljubljana, Ljubljana, Slovenia

Corresponding author:* Petra Prevc

Faculty of Sport, University of Ljubljana, 1000 Ljubljana, Slovenia
E-mail: petra.prevc@fsp.uni-lj.si

INTRODUCTION

Increased intra-abdominal pressure (IAP) significantly improves lumbar spine stability and protection (Cholewicki et al., 1999; Cholewicki & Reeves, 2004; Hodges et al., 2001). In the present paper, we wish to present a novel method for assessing IAP.

Co-activation of the abdominal muscles is responsible for IAP. Mathematical models show that IAP may reduce spinal load by up to 30 % (Hodges et al., 2001; Stokes et al., 2010; Bojairami & Driscoll, 2022), also during lifting at different loading rates (Murray & Driscoll, 2025). Measuring IAP directly requires a clinical procedure (Lopes et al., 2016; Malbrain, 2009) and, because of its invasiveness (Egger et al., 2014; Moriyama et al., 2014; Tayebi et al., 2021), it is not practical for broad evaluation. Therefore, other less invasive possibilities for assessing IAP behaviour have been developed, e.g. muscle activation. IAP is determined by the combined action of the pelvic floor, diaphragm, intercostal, erector spinae (ES), transversus abdominis (TrA), internal oblique (IO), external oblique (EO) and rectus abdominis (RA) muscles (Goldish et al., 1994; Granata & Marras, 2000; Hodges et al., 2001). Among those, TrA has been shown to be most closely associated with the modulation of IAP (Cresswell et al., 1992; Hodges & Gandevia, 2000; Hodges et al., 2003). Therefore, the activation of TrA may predict changes in IAP.

Due to the close relationship between IAP and TrA activation, it is possible to predict IAP from an electromyographic (EMG) TrA signal. The EMG TrA signal has primarily been monitored with fine-wire EMG, which requires the insertion of a needle and, because of its invasiveness, it is not practical to use (Cresswell et al., 1994; De Luca, 1997; Hodges & Richardson, 1997). Measuring surface EMG is more practical and cost-effective, but there is an important issue regarding interference from other muscles (De Luca, 1997). It has been demonstrated that surface electrodes located inferior to the anterior superior iliac spine detected activity of the TrA muscle comparable to that represented by fine-wire electrodes (Cholewicki & McGill, 1996). Anatomical fusion of the TrA and IO muscles was observed by Marshall and Murphy (2003) and they concluded that it was impossible to structurally differentiate the two muscles. However, McGill et al. (1996) demonstrated that this site was the best for approximating the function of TrA, based on comparisons with a fine-wire EMG evaluation. An important limitation of surface EMG signal is increased skinfold thickness, which prevents valid EMG signal measurement (Enrique & Milner, 1994; Hug, 2011).

Measurement of IAP is especially interesting in low back pain (LBP), which is a common and recurrent condition with major health and economic implications (Becker et al., 2010; Itz et al., 2013; van Middelkoop et al., 2011). Increased skinfold thickness is not uncommon in LBP patients (Shiri et al., 2010), therefore surface EMG of TrA as a predictor of IAP must be replaced with another non-invasive tool. As IAP acts on the abdominal wall on the lateral side a new sensor device for measuring abdominal lateral force was developed. Due to increased IAP, the lateral abdominal wall pressures on the two horns of device (detailed description in the Methods), which registers this as an increased force between the horns.

The aim of the study was to analyze the repeatability and validity of this device. Since we were unable to measure IAP directly, we estimated it through the EMG TrA signal as such a relationship has been established in other studies (Cresswell et al., 1994). Therefore, we compared the signal from the lateral abdominal force sensor device with the EMG TrA signal.

MATERIALS AND METHODS

Participants

Eight male (mean age 25 ± 5 years; height 1.84 ± 0.05 m; weight 81 kg $\pm$ 5 kg; BMI 24.3 ± 1.7 kg/m2) and eight females (mean age 24 ± 4 years; height 1.69 ± 0.06 m; weight 59 kg $\pm$ 8 kg; BMI 20.4 ± 1.4 kg/m2) physical education students volunteered to participate in the study. The inclusion criterion was low body fat, which was assessed at a supraspinal skinfold site. The results had to be below 10 mm. It was measured at the intersection of a line joining the spinal (front part of the iliac crest) and anterior parts of the axilla and a horizontal line at the level of the iliac crest (Norton & Olds, 1996). Low body fat in participants was needed to obtain valid EMG signals from TrA.

All participants gave their informed consent for the study procedures and were informed with the experimental protocol. The study was conducted according to the Declaration of Helsinki and Committee of the Republic of Slovenia for Medical Ethics issued a consent on its ethical acceptability (document no. 62/03/14).

Electromyographic recordings

The electromyographic (EMG) activity of TrA was detected with a surface EMG on the left and right sides of the abdomen. The skin was carefully prepared by shaving off excess hair, abrading the skin with fine sandpaper to reduce impedance below 5 kΩ (checked with

voltmeter) and cleansing the skin with alcohol. A pair of circular Ag/AgCl surface electrodes (Kendall ARBO, Tyco, Neustadt, Germany) with a contact diameter of 15 mm and centre-to-centre distance of 25 mm were placed in line with the TrA muscle fibres, approximately 2 cm medial and inferior to the anterior superior iliac spine in accordance with Marshall and Murphy (2003). Abdominal electrodes were applied to the participants while standing to eliminate skin movement that might occur while moving from a supine to a vertical position. The EMG signal was collected and amplified using the acquisition system PowerLab 16/35 - ML880/P and displayed with LabChart 8 (both ADInstruments, Bella Vista, Australia).

Lateral Abdominal Force Sensor (LAFS)

A lateral abdominal force sensor (LAFS) was used to estimate IAP. A custom-made measuring device was »U-shaped« with a built-in force sensor (model 5930, Sensy, Jumet, Belgium). Two horns were attached perpendicularly to a bar with a force sensor, while one horn was mobile to adjust the distance between the horns. Two side fixations were applied to prevent movement of the adjustable horn. The force sensor signal was collected with the acquisition system PowerLab 16/35 - ML880/P and displayed with LabChart 8 (both ADInstruments, Bella Vista, Australia).

Measurement procedure

The LAFS was adjusted across the waist in line with the umbilicus. The measurements were conducted with the same pre-tension of the LAFS (10N) to reduce tissue compliance. The point of body fixation to the horn was kept the same to control the force lever. The LAFS was held in a horizontal position during the measurement. Participants were standing upright and holding a bar with extended arms held in front of the body at shoulder level (Fig. 1). The participants were instructed to progressively increase isometric shoulder flexion by increasing pulling force in 2–4 seconds, retain maximal force for 3 seconds and progressively decrease in 2–4 seconds. The pulling force was monitored with an additional force sensor mounted on the rope that was pulled. Two repetitions were conducted.
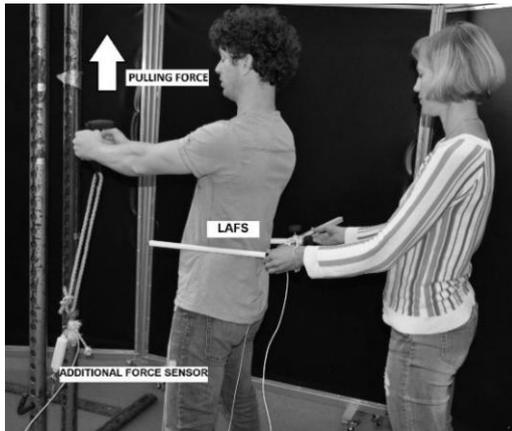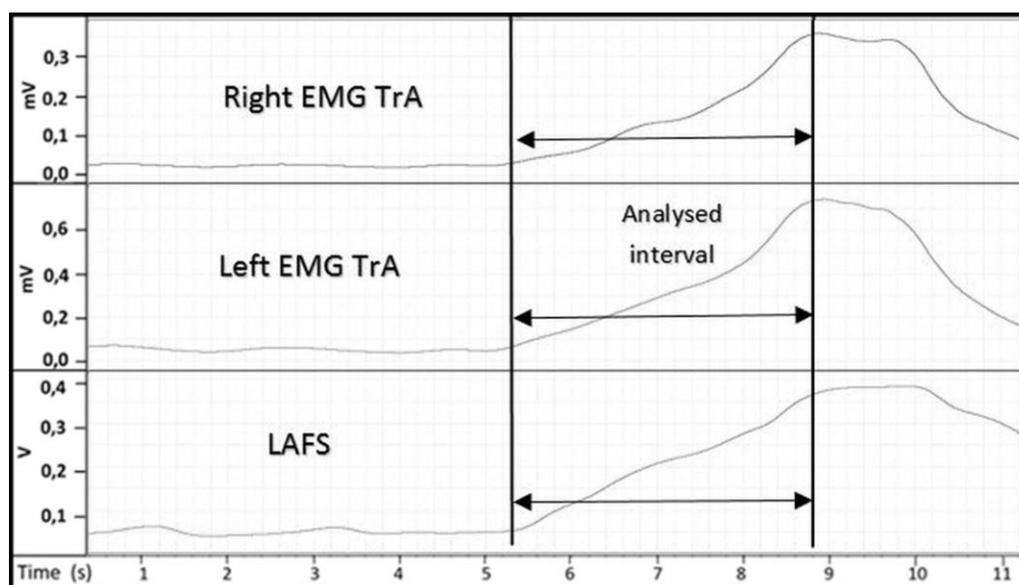
Notes. LAFS – lateral abdominal force sensor.

Figure 1. Position of the lateral abdominal force sensor adjustment during the measurement.

Data analysis

The PowerLab 16/35 - ML880/P multi-channel data acquisition system and LabChart 8 (both ADInstruments, Bella Vista, Australia) were used to sample and store data at 1000 Hz (Durkin & Callaghan, 2005). The same program was used for the analysis. The LAFS signal was low-pass filtered with a triangular (Bartlett) window (window width 201 data points). The raw EMG signal was first high-pass filtered with a cut-off frequency of 10 Hz, then rectified and low-pass filtered with a triangular (Bartlett) window (window width 1001 data points).

For all three signals (right and left EMG TrA and LAFS signals), the analysed interval started when the last of the three signals began to rise and ended when the first of the three signals reached a plateau (Fig. 2). A filter time lag was added to the time points to avoid a filter (signal smoothing) time shift. The analysis intervals were 2–4 seconds long.

Minimum and maximum signals' amplitudes of the analysed interval were obtained for signal normalization (min-max interval). The interval was divided into 20 subintervals and mean signal amplitude for each subinterval was calculated. These means were normalized to the min-max intervals for each signal and used for further processing. In addition, the difference between the start of the LAFS signal rise and the start of EMG TrA signal was established.

Notes. EMG TrA – electromyographic signal of m. transversus abdominis; LAFS –lateral abdominal force sensor signal.

Figure 2. Time envelope of the right and left electromyographic signal of m. transversus abdominis and lateral abdominal force sensor signal.

Statistical analysis

All statistical analyses were preformed using the SPSS® 20.0 for Windows (IBM Co., Armonk, NY, USA). To determine the LAFS' validity, Pearson's correlation coefficient between the LAFS signal and EMG TrA signal was calculated. A simple linear regression model was used to compute the relationship between the LAFS signal and the EMG TrA signal for each individual. Repeatability (test-retest) of the slope of the regression line predicting the LAFS signal from the EMG TrA signal (between two repetitions) was examined with the Wilcoxon signed-rank test and interclass correlation coefficient (ICC). The same procedure was employed for the LAFS signal delay regarding the EMG signal. The level of significance was set at a two-sided alpha error of 5%.

RESULTS

Validity of the LAFS

For each individual, the relationship between the EMG TrA signal and the LAFS signal was calculated (Table 1); for the right side of the abdomen for the first repetition, correlation coefficients ranged from 0.905 to 0.994 and for the second from 0.886 to 0.994 (all p < 0.001). Statistically significant correlation coefficients were also observed for the left EMG TrA signal

and the LAFS signal; for the first repetition the correlation ranged from 0.892 to 0.994 and for the second repetition from 0.921 to 0.998 (all $p < 0.001$).

Table 1. Correlation coefficient between the lateral abdominal force sensor signal and electromyographic signal of m. transversus abdominis on the right and left side of the abdomen for the first and second repetitions.

	N	Median	Min	Max
Right EMG TrA_1	16	0.975	0.905	0.994
Right EMG TrA_2	16	0.979	0.886	0.994
Left EMG TrA_1	16	0.984	0.892	0.994
Left EMG TrA_2	16	0.988	0.921	0.998

Notes. EMG – electromyographic signal; TrA – m. transversus abdominis; _1 – first repetition; _2 – second repetition.

A simple linear regression was calculated (on normalised data) for each participant to predict the LAFS signal based on the EMG TrA signal (Table 2). The median value of the slope (gradient) of the regression line based on the right EMG TrA signal was 1.057 (St. Err. 0.058) for the first and 1.038 (St. Err. 0.047) for the second repetition. Meanwhile, the median values for the left EMG TrA signal were 0.987 (St. Err. 0.041) and 0.979 (St. Err. 0.040), respectively. In all cases, the EMG TrA signal made a statistically significant contribution ($p < 0.001$) when predicting the LAFS signal.

Table 2. Unstandardised regression coefficients and standard errors for the electromyographic signal of m. transversus abdominis on the left and right side of the abdomen for the first and second repetitions.

	N	k			SE		
		Median	Min	Max	Median	Min	Max
EMG Right TrA_1	16	1.057	0.843	1.275	0.058	0.030	0.134
EMG Right TrA_2	16	1.038	0.829	1.167	0.047	0.020	0.139
EMG Left TrA_1	16	0.987	0.825	1.342	0.041	0.020	0.156
EMG Left TrA_2	16	0.979	0.867	1.166	0.040	0.010	0.091

Notes. k – unstandardized regression coefficient; SE – standard error; EMG – electromyographic signal; TrA – m. transversus abdominis; _1 – first repetition; _2 – second repetition.

In addition to individual comparisons, a concurrent comparison of all individuals was performed. A significant relationship was found ($r = 0.949$, $p < 0.001$, $F(1.334) = 3025.63$, and standard error 0.017). The predicted LAFS signal was equal to $2.446 + 0.96$ x the right EMG

TrA signal. A significant relationship was found for the left TrA as well ($r = 0.952$, $p < 0.001$, $F(1.334) = 3226.73$, and standard error 0.016). The predicted LAFS signal was equal to 4.393 + 0.919 x the left EMG TrA signal.

Repeatability of the relationship between the LAFS and EMG TrA signals

When we checked the repeatability of the regression line slopes using non-normalised data, we found no significant difference between the two repetitions when the right EMG of the TrA muscle was used as a predictor ($z = -0.213$, $p = 0.831$); further, the interclass correlation confirmed the consistency of two repetitions (overall α 0.820 (N=2), $p < 0.001$). In a similar way, the same was observed with the left EMG TrA ($z = -0.355$, $p = 0.723$ and overall α 0.898 (N=2), $p < 0.001$).

With normalised data the Cronbach alpha values were lower than with non-normalised data (right EMG TrA overall α 0.576 (N=2), $p < 0.054$; left EMG TrA overall α 0.368 (N=2), $p < 0.193$) as well as differences in regression line slopes between the measurements (right EMG TrA $z=-1.112$, $p = 0.266$; left EMG TrA $z = 0.310$, $p = 0.757$).

Repeatability of the delay between the LAFS and EMG TrA signals

The start of the LAFS signal compared to the right EMG TrA signal (Table 3) did not significantly differ between two repetitions ($z = -1.474$, $p = 0.140$); moreover, the interclass correlation confirmed the consistency of two repetitions (overall α 0.759 (N=2), $p = 0.005$). On the left side, the start of the LAFS signal compared to the left EMG TrA signal did not significantly differ between two repetitions ($z = -0.336$, $p = 0.737$), and consistency between two repetitions (overall α 0.832 (N=2), $p < 0.001$) was also high.

Table 3. Delay between the lateral abdominal force sensor signal and electromyographic signal of m. transversus abdominis on the right and left side of the abdomen for the first and second repetitions.

	N	Median (s)	Min (s)	Max (s)
EMG Right TrA_1	16	0.023	0.164	-0.217
EMG Right TrA_2	16	0.000	0.051	-0.254
EMG Left TrA_1	16	0.024	0.101	-0.279
EMG Left TrA_2	16	0.025	0.091	-0.298

Notes. Values are in seconds. EMG – electromyographic signal; TrA – m. transversus abdominis; _1 – first repetition; _2 – second repetition.

DISCUSSION

A new device for non-invasively estimating IAP by measuring lateral abdominal force was tested for its reliability and validity. The LAFS device was considered valid if there was a close relationship between the LAFS and EMG TrA signals. In all cases, a high and significant correlation between the EMG TrA and LAFS signals was found; furthermore, the linear prediction of the LAFS signal yielded a small error of estimation. The interclass correlation confirmed consistency between two repetitions.

For practical use, the LAFS measurement should be reliable because it provides confidence and statistical power to the results. The present study showed high agreement between the first and second measurements for the left and right sides of the abdomen. The repeatability of the measurements was higher with the originally measured data than with the normalised data. The reason for this outcome was the big differences in values of the original data among the participants. These differences mainly stem from the EMG signal since the conditions for acquiring the EMG signal differed significantly among the participants and prevented any direct comparison of them. With the normalised data, different EMG measurement conditions were excluded, causing the repeatability to decrease slightly. This was due to the much smaller differences among the participants after the normalisation. However, it is important to note that the standard error of the regression estimate was small. Based on this, we estimate that the reliability and consistency are sufficient for the practical use of LAFS.

It was assumed that an increase in IAP leads to stiffening of the lateral abdominal wall which can be monitored as a change in the lateral abdominal force. With a small pretension of the LAFS device on the lateral abdominal wall during a relaxed stance, the lateral abdominal wall gave in to the pretension force and made it possible to measure the pressure on the lateral horns. We were unable to directly measure IAP and relate it to the LAFS signal. Instead, we used the EMG TrA signal as it is closely associated with IAP behaviour (Bartelink, 1957; Cresswell et al., 1992; Cresswell et al., 1994; Hodges & Gandevia, 2000; Hodges et al., 2003). The results showed there is a high linear relationship between the LAFS and EMG TrA signals with a small standard error. Although IAP was assessed indirectly, it is possible to assume that the LAFS signal provides a reasonable estimate of the IAP. Together with the good repeatability and consistency of the measurements, the LAFS may represent a new noninvasive approach to assessing IAP from lateral abdominal force.

It has been shown that IAP should precede action to be able to prevent lumbar spine loading (Cholewicki & McGill, 1996; Murray & Driscoll, 2025). In most studies, the start of the rise in IAP has been connected to the rise of activation of the TrA muscle (Daggfeldt & Thorstensson, 2003; Hodges et al., 2003; Hodges & Richardson, 1997). Since the LAFS measures a mechanical event and the EMG TrA an electrical one, there should be a delay between them. We therefore analysed the time delay between the start of the TrA activation and the start of the LAFS signal. There are two reasons for this delay. One is an electro-mechanical delay (EMD) (Cavanagh & Komi, 1979) and the other a need for IAP to start rising before the action to have a protective effect on the lumbar spine. EMD values between 20–120 ms have been reported (Norman & Komi, 1979; Viitasalo & Komi, 1981) with high variability for the same muscle (Vos et al., 1990). For a protective effect, TrA activation should occur 30–100 ms before the prime mover (Hodges & Richardson, 1997). In the present study, median delays between the EMG TrA and LAFS signals were between 0–25 ms, which is within the above proposed values. However, the differences in minimal and maximal values were much greater. In some participants, the LAFS signal started already before the EMG TrA signal, which seems illogical from the above perspective. One possible explanation could be the number of muscles involved in control of IAP (Cholewicki et al., 1999) where TrA might not be the first muscle involved in the production of IAP or of lateral abdominal force. This raises a question about the use of the delay between TrA (Hodges & Richardson, 1997) and the prime mover, assuming that the EMG TrA signal mimics the IAP (Daggfeldt & Thorstensson, 2003; Hodges & Gandevia, 2000).

Limitations and Future Research Directions

Due to nature of EMG measurement, which requires low skinfold thickness, we had to confirm the relationship between TrA activation and LAF on participants with low body fat. We are aware that low abdominal fat is not typical for LBP patients (Shiri et al., 2010), which present a possible limitation of our study. We assume that LAF could be detected also in individuals with increased abdominal skinfold thickness, which has to be confirmed in further studies.

CONCLUSION

In conclusion, the present results provide compelling evidence that the LAFS might estimate IAP in a simple and non-invasive way in participants with low skinfold thickness. At the present, the LAFS device does not support the estimation of absolute IAP values but the percentage of the greatest value during the normalization procedure. The new device also has a

potential to detect the start of an increase in IAP before the action describing the 'stabilisation-action' principle important for lumbar spine protection. This may have clinical importance in assessing and learning how to use IAP in low back pain patients, but remains to be clarified in LBP patients with increased body fat.

Acknowledgments

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

REFERENCES

Bartelink, D. (1957). The role of abdominal pressure in relieving the pressure on the lumbar intervertebral discs. *Bone & Joint Journal, 39*(4), 718-725. https://doi.org/10.1302/0301-620X.39B4.718

Becker, A., Held, H., Redaelli, M., Strauch, K., Chenot, J. F., Leonhardt, C., . . . Donner-Banzhoff, N. (2010). Low back pain in primary care: costs of care and prediction of future health care utilization. *Spine (Phila Pa 1976), 35*(18), 1714-1720. https://doi.org/10.1097/BRS.0b013e3181cd656f

Bojairami, I. E., & Driscoll, M. (2022). Coordination Between Trunk Muscles, Thoracolumbar Fascia, and Intra-Abdominal Pressure Toward Static Spine Stability. *Spine, 47*(9), E423–E431. https://doi.org/10.1097/BRS.0000000000004223

Cavanagh, P. R., & Komi, P. V. (1979). Electromechanical delay in human skeletal muscle under concentric and eccentric contractions. *European journal of applied physiology and occupational physiology, 42*(3), 159-163. https://doi.org/10.1007/BF00431022

Cholewicki, J., Juluru, K., & McGill, S. M. (1999). Intra-abdominal pressure mechanism for stabilizing the lumbar spine. *Journal of biomechanics, 32*(1), 13-17. https://doi.org/10.1016/S0021-9290(98)00129-8

Cholewicki, J., & McGill, S. M. (1996). Mechanical stability of the in vivo lumbar spine: implications for injury and chronic low back pain. *Clinical biomechanics (Bristol, Avon), 11*(1), 1-15. https://doi.org/10.1016/0268-0033(95)00035-6

Cholewicki, J., & Reeves, N. P. (2004). All abdominal muscles must be considered when evaluating the intra-abdominal pressure contribution to trunk extensor moment and spinal loading. *Journal of biomechanics, 37*(6), 953-954. https://doi.org/10.1016/j.jbiomech.2003.09.021

Cresswell, A. G., Grundström, H., & Thorstensson, A. (1992). Observations on intra-abdominal pressure and patterns of abdominal intra-muscular activity in man. *Acta Physiologica, 144*(4), 409-418. https://doi.org/10.1111/j.1748-1716.1992.tb09314.x

Cresswell, A. G., Oddsson, L, & Thorstensson, A. (1994). The influence of sudden perturbations on trunk muscle activity and intra-abdominal pressure while standing. *Experimental Brain Research, 98*(2), 336-341. https://doi.org/10.1007/BF00228421

Daggfeldt, K., & Thorstensson, A. (2003). The mechanics of back-extensor torque production about the lumbar spine. *Journal of Biomechanics, 36*(6), 815-825. https://doi.org/10.1016/s0021-9290(03)00015-0

De Luca, C. J. (1997). The use of surface electromyography in biomechanics. *Journal of Applied Biomechanics, 13*, 135-163. https://doi.org/10.1123/jab.13.2.135

Durkin, J. L., & Callaghan, J. P. (2005). Effects of minimum sampling rate and signal reconstruction on surface electromyographic signals. *Journal of Electromyography and Kinesiology, 15*(5), 474-481. https://doi.org/10.1016/j.jelekin.2005.02.003

Egger, M. J., Hamad, N. M., Hitchcock, R. W., Coleman, T. J., Shaw, J. M., Hsu, Y., & Nygaard, I. E. (2014). Reproducibility of intra-abdominal pressure measured during physical activities via a wireless vaginal transducer. *Female pelvic medicine & reconstructive surgery, 21*(3), 164-169. https://doi.org/10.1097/SPV.0000000000000167

Enrique, J, & Milner, T. E. (1994). The effects of skinfold thickness on the selectivity of surface EMG. *Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section, 93*(2), 91-99. https://doi.org/10.1016/0168-5597(94)90071-X

Goldish, G. D., Quast, J. E., Blow, J. J., & Kuskowski, M. A. (1994). Postural effects on intra-abdominal pressure during Valsalva maneuver. *Archives of physical medicine and rehabilitation, 75*(3), 324-327. https://doi.org/10.1016/0003-9993(94)90037-X

Granata, K. P., & Marras, W. S. (2000). Cost-benefit of muscle cocontraction in protecting against spinal instability. *Spine (Phila Pa 1976), 25*(11), 1398-1404. https://doi.org/10.1097/00007632-200006010-00012

Hodges, P. W., Cresswell, A. G., Daggfeldt, K., & Thorstensson, A. (2001). In vivo measurement of the effect of intra-abdominal pressure on the human spine. *Journal of biomechanics, 34*(3), 347-353. https://doi.org/10.1016/s0021-9290(00)00206-2

Hodges, P. W., & Gandevia, S. C. (2000). Changes in intra-abdominal pressure during postural and respiratory activation of the human diaphragm. *Journal of applied physiology (Bethesda, Md. : 1985), 89*(3), 967-976. https://doi.org/10.1152/jappl.2000.89.3.967

Hodges, P., Holm, A. K., Holm, S., Ekström, L., Cresswell, A., Hansson, T., & Thorstensson, A. (2003). Intervertebral stiffness of the spine is increased by evoked contraction of transversus abdominis and the diaphragm: in vivo porcine studies. *Spine, 28*(23), 2594-2601. https://doi.org/10.1097/01.BRS.0000096676.14323.25

Hodges, P. W., & Richardson, C. A. (1997). Feedforward contraction of transversus abdominis is not influenced by the direction of arm movement. *Experimental Brain Research, 114*(2), 362-370. https://doi.org/10.1007/PL00005644

Hug, F. (2011). Can muscle coordination be precisely studied by surface electromyography? *Journal of electromyography and kinesiology, 21*(1), 1-12. https://doi.org/10.1016/j.jelekin.2010.08.009

Itz, C. J., Geurts, J. W., van Kleef, M., & Nelemans, P. (2013). Clinical course of non-specific low back pain: A systematic review of prospective cohort studies set in primary care. *European journal of pain (London, England), 17*(1), 5-15. https://doi.org/10.1002/j.1532-2149.2012.00170.x

Lopes, A. M., Nunes, A., Niza, M. MRE, & Dourado, A. (2016). Intra-abdominal Pressure is Influenced by Body Position? *American Journal of Clinical Medicine Research, 4*(1), 11-18. https://doi.org/10.1007/s00134-009-1445-0

Malbrain, Manu LNG. (2009). Different techniques to measure intra-abdominal pressure (IAP): time for a critical re-appraisal. *Applied Physiology in Intensive Care Medicine* (pp. 143-157): Springer. https://doi.org/10.1007/978-3-642-28233-1_2

Marshall, P, & Murphy, B. (2003). The validity and reliability of surface EMG to assess the neuromuscular response of the abdominal muscles to rapid limb movement. *Journal of Electromyography and Kinesiology, 13*(5), 477-489. https://doi.org/10.1016/S1050-6411(03)00027-0

McGill, S., Juker, D., & Kropf, P. (1996). Appropriately placed surface EMG electrodes reflect deep muscle activity (psoas, quadratus lumborum, abdominal wall) in the lumbar spine. *Journal of biomechanics, 29*(11), 1503-1507. https://doi.org/10.1016/0021-9290(96)84547-7

Moriyama, S, Ogita, F, Huang, Z, Kurobe, K, Nagira, A, Tanaka, T, . . . Hirano, Y. (2014). Intra-abdominal pressure during swimming. *International journal of sports medicine, 35*(02), 159-163. https://doi.org/10.1055/s-0033-1349136

Murray, S. A., & Driscoll, M. (2025). Finite element investigation of the intrinsic stiffness contribution of intra-abdominal pressure in a transient spine and trunk model. *Computers in biology and medicine, 196(Pt A)*, 110549. https://doi.org/10.1016/j.compbiomed.2025.110549

Norman, R. W., & Komi, P. V. (1979). Electromechanical delay in skeletal muscle under normal movement conditions. *Acta physiologica Scandinavica, 106*(3), 241-248. https://doi.org/10.1111/j.1748-1716.1979.tb06394.x

Norton, K., & Olds, T. (1996). *Anthropometrica: a textbook of body measurement for sports and health courses.* UNSW press.

Shiri, R., Karppinen, J., Leino-Arjas, P., Solovieva, S., & Viikari-Juntura, E. (2010). The association between obesity and low back pain: a meta-analysis. *American Journal of Epidemiology, 171*(2), 135-154. https://doi.org/10.1093/aje/kwp356

Stokes, I. A., Gardner-Morse, M. G., & Henry, S. M. (2010). Intra-abdominal pressure and abdominal wall muscular function: Spinal unloading mechanism. *Clinical biomechanics (Bristol, Avon), 25*(9), 859-866. https://doi.org/10.1016/j.clinbiomech.2010.06.018

Tayebi, S., Gutierrez, A., Mohout, I., Smets, E., Wise, R., Stiens, J., & Malbrain, M. L. N. G. (2021). A concise overview of non-invasive intra-abdominal pressure measurement techniques: from bench to bedside. *Journal of clinical monitoring and computing, 35*(1), 51–70. https://doi.org/10.1007/s10877-020-00561-4

van Middelkoop, M., Rubinstein, S. M., Kuijpers, T., Verhagen, A. P., Ostelo, R., Koes, B. W., & van Tulder, M. W. (2011). A systematic review on the effectiveness of physical and rehabilitation interventions for chronic non-specific low back pain. *European spine journal, 20*(1), 19-39. https://doi.org/10.1007/s00586-010-1518-3

Viitasalo, J. T., & Komi, P. V. (1981). Interrelationships between electromyographic, mechanical, muscle structure and reflex time measurements in man. *Acta Physiologica Scandinavica, 111*(1), 97-103. https://doi.org/10.1111/j.1748-1716.1981.tb06710.x

Vos, E. J., Mullender, M. G., & van Ingen Schenau, G. J. (1990). Electromechanical delay in the vastus lateralis muscle during dynamic isometric contractions. *European journal of applied physiology and occupational physiology, 60*(6), 467-471. https://doi.org/10.1007/BF00705038