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Original Research

A Prototype Validation Study of a Digitized Pressure Biofeedback Unit Versus Electromyography During Transverse Abdominis Muscle Activation

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ABSTRACT

Core stability, particularly involving the Transverse Abdominis (TrA) muscle, is essential for lumbar support and is especially relevant for individuals with lower back pain. Traditional Pressure Biofeedback Units (PBUs) are commonly used to monitor TrA activation during core stabilization exercises but these analogue devices have limitations in terms of monitoring usability, often requiring manual readings prone to error. This study aims to develop and test a digitized Pressure Biofeedback Unit (PBU) prototype specifically for monitoring transverse abdominis (TrA) muscle activation, enhancing accuracy and providing real-time digital feedback for clinical and rehabilitation settings. The prototype integrates an Arduino microcontroller and a barometric pressure sensor to capture TrA activation automatically, reducing manual operation. Readings of the PBU prototype were then evaluated by applying loads weighing 1 to 3 kg and compared against the pressure gauge. Six healthy male participants (mean age 24 ÷ 2 years) performed abdominal draw-in manoeuvres at targeted pressures of 50, 60, and 70 mmg, with muscle activation recorded via surface electromyography (EMG) and PBU. Results indicated that the root mean square error (RMSE) of dPBU ranged 0.15 to 0.94mmHg at baseline (i.e. no load) and with loads up to 2kg only, affirming the dPBU's accuracy in detecting TrA activity. Additionally, a positive trend showed between the PBU and EMG measurements with dispersion less than 0.5mmHg across different levels of muscle activity suggests that the PBU could serve as a reliable, user-friendly alternative to EMG biofeedback in core stabilization training, supporting efficient TrA monitoring and activation in clinical rehabilitation.

INTRODUCTION

Core stabilisation exercises are designed to strengthen the core muscles, including the trunk muscles from the diaphragm to the pelvic floor, providing critical dynamic stability to the lumbar spine and improving functional movement (Akuthota & Nadler 2004; McGill 2010). Various core stabilisation exercises engage different core muscles namely the pelvic floor, the rectus abdominis, the internal and external obliques, and, most critically, the transversus abdominis (TrA), the deepest abdominal muscle. Chon et al. (2010) and Moghadam et al. (2019) found that the abdominal drawing-in manoeuvre was more effective at activating the TrA than general core stabilization exercises. A decrease in transversus abdominis muscle activation and delayed onset of contraction with extremity movements were shown to be commonly present in patients with non-specific low back pain (Selkow et al. 2017) and thus essential during the treatment or preventive management of low back pain (Lynders et al. 2019).

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Nonetheless, contraction of the TrA using basic training methods like verbal commands and manual palpation from the physical therapist was likely less effective than a biofeedback application like real-time ultrasound imaging (Lee & Jo 2016). Although contraction of the TrA is improved when real-time ultrasonography is used together with verbal feedback, its high cost limits the use of this method in clinical practice. Alternatively, the use of a pressure biofeedback unit (PBU) has been suggested because it allows the detection of pressure fluctuations inherent to movements in the region of its placement and provides a reliable and practical way to assess and train the stability and control of the lumbar spine and the TrA (Selkow et al. 2017; Grooms et al. 2013). The contraction of TrA activity through abdominal wall pressure changes using a PBU seems as effective as the real-time ultrasound imaging biofeedback (Lee & Jo 2016). The PBU operates on a simple yet effective biomechanical biofeedback that involves measurement of movement, postural control and force.

The PBU consists of a pressure gauge that was calibrated to 2 mmHg interval and has a range between 0 to 200 mmHg and connected to a three chambers-inflatable cuff to monitor pressure alterations that are easily applied in the clinical setting (Giggins et al. 2013; Li et al. 2020). It emerged as a promising tool for providing objective feedback during core stabilization exercises and facilitating effective core muscle activation (Khan et al., 2022; Lee et al. 2024; Yeldan et al.2024). However, underinflation and overinflation of the cuff may impact its effectiveness in detecting subtle muscle contractions. It is advised that during the abdominal draw-in manoeuvre in a prone position, the PBU is placed under the abdomen and inflated to 70mmHg before performing the abdominal draw-in manoeuvre which should result in a pressure decrease of 2-4mmHg. Meanwhile, in the abdominal draw-in manoeuvre that is conducted in a supine-hook lying position, the PBU is placed under the lumbar spine at the height of L3, with the cuff needs to be inflated to 40mmHg (Grooms et al. 2013) before the patient is instructed to perform the abdominal draw-in manoeuvre and increase the pressure in steps of 2-4mmHg. Such subtle changes in the PBU during the intended muscle activation may hardly be monitored due to the analogue pressure readings in a unit of mmHg, shown by the pressure gauge resulting in parallax error that causes lower accuracy and inconsistency.

An attempt to improve the visual feedback of the PBU with digital detection of the TrA muscle activation was achieved using a pressure sensor. However, this pressure sensor was not directly integrated into the PBU. Instead, it was attached separately to the inner side of the lumbar support. Concurrently, one PBU was placed at the front of the TrA muscle and another PBU was placed posteriorly at the lumbopelvic region, with different pressure settings. A decrease in pressure sensor values indicated the amount of TrA muscle activation (Dissanguan et al. 2019) while the two PBUs served to standardize the baseline pressure setting at the anterior and posterior body part before the muscle activation. In this regard, managing multiple devices at a time increases the complexity of the setup and more prone to errors in application and interpretation without proper setup, especially when the valves of both PBU need to be closed manually to stop air leakage (Li et al. 2020). The analogue pressure gauge and manual operation of the PBU were some of the factors that may have contributed to the lack of user-friendliness in the device (Crasto et al. 2019). Consistency of measurement is essential in clinical settings to ensure the results are reliable and valid when comparisons of the patients' performance are made over time or between patients (Mokkink et al. 2010; Kottner & Streiner 2011) which helps clinicians make informed decisions for the treatment plan in the rehabilitation of LBP.

Moreover, assuming constant compressive pressure from the activated muscle to the air-inflatable cuff of PBU during measurement introduces uncertainties. To address these limitations, we propose a new architecture for a digitized pressure biofeedback unit (dPBU) and conduct a laboratory validation followed by a pilot test.

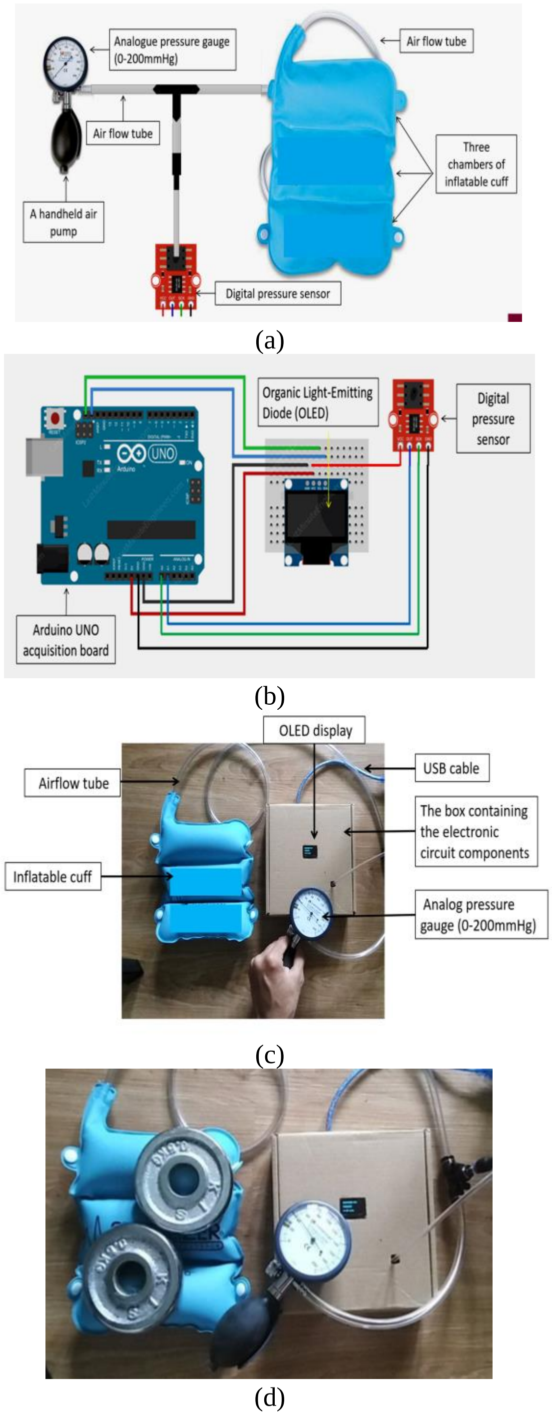

Fig. 1 (a) The connection between the pressure biofeedback unit and the digital pressure sensor (b) The overall circuit used in the designed dPBU prototype (c) The dPBU and its components (d) Standard loads (1kg) applied on the inflatable cuff of dPBU.

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MATERIALS AND METHOD

The present prototyping study involves innovating the original pressure biofeedback unit (PBU) (Chattanooga Group Inc., LLC Vista, California, USA) into a digitized pressure biofeedback unit (dPBU) using various hardware and software components.

Instrumentation

The key hardware components include an MPS20N0040D-D, a digital barometric pressure sensor to sense and transduce the analogue signal of air pressure into an electrical signal and the Arduino UNO micro-controller board for processing the digital signals from the pressure sensor by reading the input from the sensor and converting it into a digital output that can be displayed on the Organic Light-Emitting Diode (OLED) screen. Meanwhile, the Arduino Integrated Development Environment (IDE) software was used to write and upload the source code to the Arduino UNO board. Arduino IDE worked as the debugging platform for uploading the code from the computer to the processor board that is the Arduino UNO. The hardware components were assembled with the existing pressure biofeedback unit as in Figure 1a. The airflow tube has been modified to have a T-junction so the air pressure can flow into the digital pressure sensor. Then, the electrical signals transduced by the barometric pressure sensor were processed by the microcontroller Arduino UNO to provide the selected output of a real-time digital pressure meter on the OLED screen display (Figure 1b).

The lab validation test for the digitized Pressure Biofeedback Unit (dPBU) measurement was conducted using weights ranging from 1kg to 3kg. The test aimed to assess the effects of different compressive weights on dPBU readings as displayed on the OLED screen, simulating the applied pressure when the digitized PBU is placed on specific body regions for selective muscle activation. The observed dPBU readings and predicted PBU readings from the manual gauge meter were recorded concurrently with 10 repetitions for each weight applied.

Experimental Procedure

Six healthy young adult males, aged 24 ± 2 years old voluntarily participated in this pilot study. They were included as they have no known history of lower back pain, lumbar surgery or neurological conditions affecting the trunk. Informed consent form was obtained from each of them who participated in the present study. Participants were previously instructed to fast for 2 hours before testing (including water) and empty the bladder before the test. Participants were positioned in supine crook lying position on a firm surface, with their hips and knees flexed, feet flat on the floor and arms beside the trunk to ensure that the pelvis is in a neutral position.

Before placing the EMG electrodes, the skin surfaces of targeted abdominal area were properly cleaned with alcohol swab, following the recommendations of ISEK (International Society of Electrophysiology and Kinesiology) and SENIAM (Surface Electromyography for Non-Invasive Assessment of Muscles) for a low impedance between the skin and the electrodes. Electrodes were placed at the center position that was 2 cm cephalic to the pubic bone, just lateral to the midline, and parallel to the superior pubic ramus along either side of the course of the underlying muscle fibers (Lima et al., 2012). Digitized pressure biofeedback unit was placed underneath the lumbar region on the posterior superior iliac spine (PSIS) and inflated to a baseline of 40mmHg before the drawing-in manoeuvre begin. Figure 1d shows the placement of PBU under the subject during the supine crook lying position.

Participants were asked to firstly practice several trials on how to perform drawing-in manoeuvre properly for activation of transverse abdominis (TrA) muscles. The drawing-in manoeuvre was done by slowly draw in the lower abdomen as if they are holding their urine and then draw up their pelvic floor muscle so that it could contract, together with their lower abdomen, while continuing normal breathing. During the drawing-in maneuver, as the individual contracts the deep core muscles (especially the TrA), the abdominal wall is drawn inward, creating an increase in intra-abdominal pressure. This contraction stabilizes the spine and pelvis, which in turn affects the pressure biofeedback unit applied under the lumbar region with the contraction held for 5 seconds to assess the maximum activation of the core muscles while maintaining stability and proper breathing. As the core muscles contract, the participant was asked to slowly and progressively increase the intensity of the contraction to elevate intra-abdominal pressure to reach the first target pressure reading at 50 mmHg through moderate contractions and further increase by 10 mmHg increments to 60 and 70mmHg by engaging the core muscles contraction more intensely. Once the participant understood and able to perform the drawing-in manoeuvre correctly as per instruction during the trial sessions, the recording of surface EMG was started as the participant performed the drawing-in manoeuvre and hold 5 second during the maximum voluntary contraction of the core muscles at targeted pressure of 50, 60, and 70 mmHg (Kim et al. 2015; Van et al., 2006).

Data Acquisition and Analysis

The real-time data on pressure changes from the dPBU were generated through Excel CSV Data Streamer. Data Streamer is a two-way data transfer tool for Excel, allowing live data to be streamed from a microcontroller into Excel and enabling data to be sent back to the microcontroller. When the barometric pressure sensor has been connected to the microcontroller, a custom Excel workbook for the sensor was opened, and real-time data began streaming. Root means squared errors (RMSE) values were calculated based on a following formula to evaluate the accuracy of dPBU.

$$\text{RMSE} = \sqrt{[\textstyle\sum_{x=1}^{10}(predicted_{\chi} - observed_{\chi})^2/10]}$$

Meanwhile, EMG data was recorded using a portable electromyograph (PLUX Wireless Biosignals SA, Portugal) with a sampling frequency of 1,000 Hz as set in OpenSignals software. The data logger was connected to the computer via Bluetooth, transmitting the signal frequency to the software. The software filtered the received signal and processed the frequency graph, from which the amplitude of muscle activity was extracted. Average value of muscle electrical activity over a period during isometric contraction of TrA was calculated by averaging EMG signals from 3 trials (AEMG) while maximum voluntary isometric contractions (MVIC) of the TrA is the highest level of muscle activity recorded during a maximal effort contraction throughout the 5s contraction hold. Based on these 2 variables, %MVIC was computed as the mean of the AEMG divided by the MVIC and then multiplied by 100. Next, the correlation between the digitized PBU measurements and the

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EMG data (Meldrum et al., 2003; Fuente et al., 2020) was evaluated by the trend of the graph obtained.

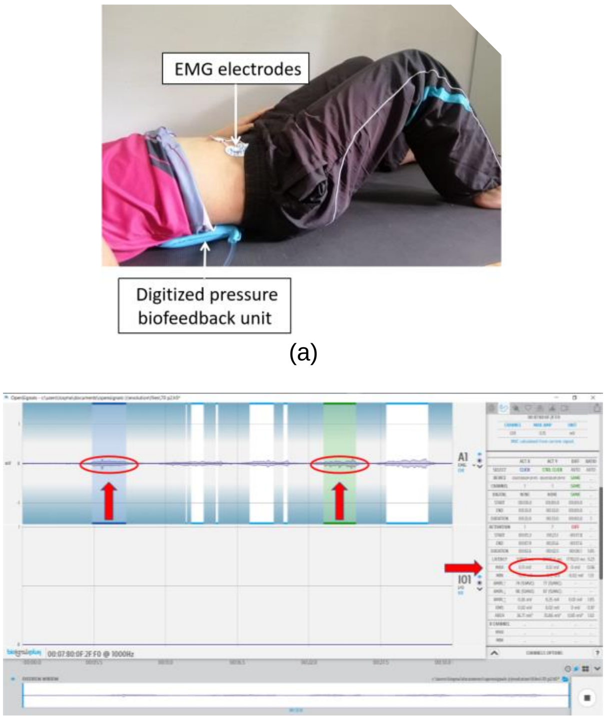

Fig. 2 (a) Placement of dPBU and wireless EMG on the participant in supine crook lying (b) Electromyography signals (indicated in red arrows above) during the abdominal draw-in manoeuvre exercise.

RESULTS AND DISCUSSION

The average of the squared difference between the observed and predicted pressure values over 10 repeated trials when load of various weights applied on the cuff of dPBU is shown in Table 1. The root mean square errors (RMSE) between the observed and predicted pressure values was found to range between 0.15 to 1.18mmHg from light to heavier weight of compressive loads. In biofeedback applications, RMSE values under 1.0mmHg are often considered reasonable as the goal is often to guide general movement or pressure changes rather than provide high-precision measurements. The 3kg loads applied onto the dPBU showed a RMSE >1.0mmHg possibly due to small leaks or redistribution of air within the inflatable cuff of dPBU under a heavier load. Meanwhile, a higher baseline error (0.94mmHg) found is likely due to sensor noise, offset and calibration drift (Zou et al. 2023) but when a small load is added, a more stable output and lower RMSE is profound. In studies focused on physical therapy tools, values around this range are commonly reported and accepted when offering feedback on muscle activation or joint movement (Giggins, et al. 2013). Additionally, exact numerical values in therapeutic settings are less critical than trends and changes over time.

The results show that this dPBU could be a reliable, easy-to-use tool for monitoring TrA activation, particularly for patients needing core stabilization in rehabilitation. With a strong positive correlation between dPBU and EMG ($r = 0.905$, $p < 0.05$), this device is ready for clinical use to support low back pain patients, especially given the convenience of automated data recording (Jones, 2005; Lee & Jo, 2016). Unlike traditional analog PBUs, the digital model streamlines the process by removing the need for manual data entry, improving efficiency for clinicians (Godfrey et al., 2018). Although we had a small sample size, our findings align with previous research supporting the benefits of digital feedback in rehabilitation (Moghadam et al., 2019; Kim & Ryu, 2016; Dunai et al., 2014). There was a lower energy consumption overall and stable data transmission with the existing wired system of dPBU but some portability restriction was as expected and cumbersome when the person moved or changed positions.

Table 1 Root Mean Squared Errors (RMSE) in the dPBU that was tested under various weight loads.

Weight of load (kg)	Average [Predicted – Observed pressure value]^2 (mmHg)	RMSE (mmHg)
0	0.889	0.94
1	0.022	0.15
2	0.032	0.18
3	1.394	1.18

The data obtained from the experiment is presented in Table 2 below. There is no muscle activity performed (i.e. MVIC equal to 0) when the dPBU cuff is set at mean 40.9 mmHg to serve as a baseline. As the dPBU reading reached 50.2 mmHg, the associated mean MVIC is 32.9mV across the participants. The general upward trend illustrated in Figure 2 indicates a positive correlation between dPBU and MVIC. As dPBU values increase, MVIC values also tend to increase. This suggests that a higher value in dPBU40 is associated with a higher value in MVIC40. Although the barometric pressure sensor (MPS20N0040D-D) is often utilized in various projects and applications due to its affordability and simplicity,it lacks advanced features like environmental robustness compared to premium sensors and thus limited adoption in health industries. Moreover, there are still some room for improvement in source coding to make the barometric pressure sensor to be more accurate.

Table 2 Descriptive analysis of mean pressure values and standard deviations from digitized pressure biofeedback unit (dPBU) and mean percentage Maximum Voluntary Isometric Contraction (MVIC%) at targeted pressures of 40, 50, 60 and 70 mmHg.

Targeted pressures/ Variables	dPBU (mmHg)	MVIC (%)
40mmHg	40.9 ± 0.02	0 ± 0
50mmHg	50.2 ± 0.02	32.9 ± 8.59
60mmHg	60.9 ± 0.49	43.4 ± 6.95
70mmHg	70.6 ± 0.43	73.5 ± 12.03

With only 6 data points, the statistical correlation analysis was however not conducted to avoid the risk of misinterpretation. Nevertheless, descriptive data analysis in Table 2 still provides valuable insights for our further study with a larger sample size. As the trend was observed in a small sample, it could justify a larger study to confirm the trend's validity. Future research could expand on these results by including larger populations and also adding wireless system to

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support cloud-based data storage and remote monitoring (Ometov et al., 2021; Kim et al., 2015).

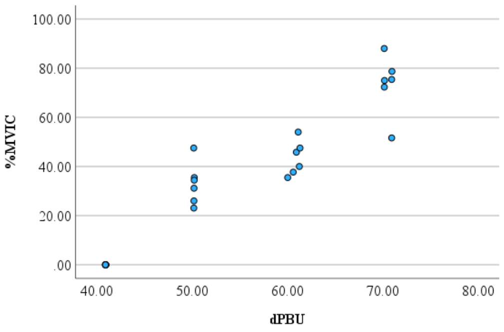

Fig. 3 Pressure readings obtained from dPBU versus Percentage of MVIC from EMG

CONCLUSION

The Digitized Pressure Biofeedback Unit (dPBU) was successfully developed by integrating a barometric pressure sensor, which outputs data via an OLED display and in a real-time Excel data streaming format with minimum error difference. Additionally, the data upward trend indicate a positive correlation between dPBU and MVIC. Thus, the digitized PBU potentially used to monitor the isometric exercises for core muscles mainly the TrA at various target pressures digitally with capability of automatic recording of the data into Excel Data Streamer format. The dPBU is potentially applied in exercise rehabilitation as a user-friendly monitoring tool of isometric exercise training with automatic data recording.

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