Title: The control of respiratory pressures and neuromuscular activation to increase force production in trained martial arts practitioners.

Authors: Sherrilyn Walters[1,2], Ben Hoffman[1,2,3], William MacAskill[1,2], Michael A. Johnson[4], Graham R. Sharpe[4], Dean E. Mills[1,2].

[1]Respiratory and Exercise Physiology Research Group, School of Health and Wellbeing, University of Southern Queensland, Ipswich, Queensland, Australia

[2]Centre for Health Research, Institute for Resilient Regions, University of Southern Queensland, Ipswich, Queensland, Australia

[3]School of Human Movement and Nutrition Sciences, The University of Queensland, Brisbane, Queensland, Australia

[4]Exercise and Health Research Group, Sport, Health and Performance Enhancement (SHAPE) Research Centre, School of Science and Technology, Nottingham Trent University, Nottingham, Nottinghamshire, United Kingdom

Corresponding Author:

Sherrilyn Walters

11 Salisbury Road

Ipswich, QLD, Australia, 4305

Email: sherrilyn.walters@usq.edu.au

Phone: 0431012048

ABSTRACT

Purpose: The mechanisms that explain the ability of trained martial arts practitioners to produce and resist greater forces than untrained individuals to aid combat performance are not fully understood. We investigated whether the greater ability of trained martial arts practitioners to produce and resist forces was associated with an enhanced control of respiratory pressures and neuromuscular activation of the respiratory, abdominal, and pelvic floor musculature.

Methods: Nine trained martial arts practitioners and nine untrained controls were instrumented with skin-surface electromyography (EMG) on the sternocleidomastoid, rectus abdominis, and the group formed by the transverse abdominal and internal oblique muscles ($EMG_{tra/io}$). A multipair oesophageal EMG electrode catheter measured gastric (P_g), transdiaphragmatic (P_{di}), and oesophageal (P_e) pressures and EMG of the crural diaphragm (EMG_{di}). Participants performed Standing Isometric Unilateral Chest Press (1) and Standing Posture Control (2) tasks.

Results: The trained group produced higher forces normalised to body mass$^{2/3}$ (0.033±0.01 vs. 0.025±0.007 N/kg$^{2/3}$ mean force in Task 1), lower P_e, and higher P_{di} in both tasks. Additionally, they produced higher P_g (73±42 vs. 49±19 cmH_2O mean P_g) and $EMG_{tra/io}$ in Task 1 and higher EMG_{di} in Task 2. The onset of P_g with respect to the onset of force production was earlier, and the relative contribution of P_g/P_e and P_{di}/P_e were higher in the trained group in both tasks.

Conclusion: Our findings demonstrate that trained martial arts practitioners utilised a greater contribution of abdominal and diaphragm musculature to chest wall recruitment and higher P_{di} to produce and resist higher forces.

Keywords: Respiratory pressures; respiratory muscles; martial artists; muscular force

DECLARATIONS

Funding: Not applicable.

Conflict of Interest: The authors have no conflicts of interest to declare that are relevant to the content of this article. The results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

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Author Contributions: S.W, B.H. and D.E.M conceptualised and designed the experiments. S.W collected and analysed the data. S.W, W.M, B.H, M.A.J, G.R.S and D.E.M contributed to data interpretation and statistical analysis. S.W, W.M, B.H, M.A.J, G.R.S and D.E.M contributed to revisions of intellectual content. All authors approved the final manuscript.

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Ethics Approval: All study procedures were approved by the University of Southern Queensland Research Ethics Committee, which adheres to the Declaration of Helsinki (USQ HREC ID: H19REA116 (v1)).

Consent to participate: All participants provided written, informed consent prior to participation in the study.

ABBREVIATIONS

P_g – gastric pressure

P_{di} – transdiaphragmatic pressure

P_e – oesophageal pressure

EMG – electromyography

EMG_{scm} – EMG of the sternocleidomastoid

EMG_{ra} – EMG of the rectus abdominis

$EMG_{tra/io}$ – EMG of the group formed by the transverse abdominal and internal oblique

EMG_{di} – EMG of the crural diaphragm

BMI – body mass index

FVC – forced vital capacity

FEV_1 – forced expiratory volume in one second

$P_{e,max}$ – maximum oesophageal pressure

$P_{g,max}$ – maximum gastric pressure

$P_{di,max}$ – maximum transdiaphragmatic pressure

RMS – root mean square

INTRODUCTION

Traditional Chinese martial arts include highly refined and intricate movements and techniques that have been developed specifically to improve performance in combat. Combat in martial arts involves striking, grappling, pushing and intercepting incoming attacks and the ability to produce force and absorb or redirect incoming forces are critical aspects of performance (James et al. 2016). Trained martial arts practitioners produce higher impact forces than untrained individuals (Galpin et al. 2015; Neto et al. 2008; Smith et al. 2000), but the mechanisms that explain the ability of trained martial arts practitioners to produce these greater forces are not fully understood. Putative mechanisms include improved technique, muscular strength and endurance as a result of physical training (James et al. 2018; James et al. 2017; Machado et al. 2010). In addition, the greater ability of trained martial arts practitioners to produce and resist forces to aid combat performance may also be due to enhanced neuromuscular activation and control of the respiratory, abdominal, and pelvic floor musculature leading to higher intra-abdominal pressures (Essendrop et al. 2004; Kawabata et al. 2010). This may result from specialised forms of breath control training found in many traditional martial arts systems.

Qigong, a form of breath control training found in traditional Chinese martial arts, requires practitioners to undertake slow, deep and controlled breathing exercises. These exercises focus on sensation and pressure (traditionally referred to as Qi) in the abdominal and pelvic cavities whilst controlling the pelvic floor musculature and allowing the upper torso to remain relaxed (Chen 2014). This type of training is thought to increase force production during grappling and striking movements, improve core stability (Chen 2014), and may be associated with raised intra-abdominal pressures.

Raising intra-abdominal pressure facilitates support and stabilisation of the trunk (Cholewicki et al. 1999; Stokes et al. 2010) and thereby aids heavy load carrying by stiffening and stabilising the spine and pelvis (Brown and McConnell 2012). However, the relationship between intra-abdominal pressure and force production in humans remains controversial (Essendrop et al. 2004; Hagins et al. 2006; Marras et al. 1985; Marras and Mirka 1996; Tayashiki et al. 2021; Tayashiki et al. 2018). For example, intra-abdominal pressure correlated positively with maximal voluntary isometric hip extension torque (Tayashiki et al. 2021; Tayashiki et al. 2018), but not with maximal voluntary isometric hip flexion or knee extension or flexion (Tayashiki et al. 2018). Hagins et al. (2006) reported that while breath control influenced intra-abdominal pressure, it did not influence isometric trunk extension force. In addition, Marras et al. (1985) observed a delay between the onset of intra-abdominal pressure and the onset of trunk torque production during isometric and isokinetic back extension movements. In a later study, Marras and Mirka (1996) found that intra-abdominal pressure was more strongly related to trunk velocity than to the torque supported by the trunk and concluded that intra-abdominal pressure may be a result of trunk muscle coactivation acting to accelerate the trunk rather than a significant contributor to force or torque production. Taken together, there is still ambiguity concerning the role intra-abdominal pressure plays in generating force in humans.

One approach that may provide better insights into the role of intra-abdominal pressure is to examine populations who have experience in breath control training. Essendrop et al. (2004) reported that trained martial arts practitioners were able to develop high intra-abdominal pressure at sufficient speed to support their lower backs during sudden heavy trunk loading. Individuals, such as martial arts practitioners, who have undertaken specific forms of breath control training may therefore be able to produce and resist greater forces through an increased control of intra-abdominal pressures. This would ultimately aid to improve performance in combat. Furthermore, previous studies did not measure oesophageal pressures, nor did they assess neuromuscular activation of the diaphragm and abdominal musculature. This is important because contraction of the diaphragm and the passive or active contraction of the abdominal wall and pelvic floor muscles are key factors in the control of intra-abdominal pressure and thus may provide insights into the ability of martial arts partitioners to generate high forces (Al-Bilbeisi and McCool 2000; Cresswell et al. 1994; Emerson 1911).

Accordingly, we investigated whether the greater ability of trained martial arts practitioners to produce and resist forces was associated with an enhanced control of respiratory pressures and neuromuscular activation of the respiratory, abdominal, and pelvic floor musculature. To do this, we utilised a multipair oesophageal electrode catheter that included pressure transducers to measure crural diaphragmatic electromyography (EMG_{di}), oesophageal (P_e), gastric (P_g), and therefore transdiaphragmatic (P_{di}) pressure, along with skin-surface EMG of the sternocleidomastoid (EMG_{scm}), rectus abdominis (EMG_{ra}), and the group formed by the transverse abdominal and internal oblique muscles ($EMG_{tra/io}$), which provides a surrogate for pelvic floor activity (Arab and Chehrehrazi 2011). We hypothesised that trained martial arts practitioners would produce and resist greater forces during standing isometric tasks compared to untrained physically active controls, and that this would be associated with higher intra-abdominal pressures and a greater percentage of maximal EMG activity reflecting greater activation.

METHODS

Participants

Nine trained martial arts practitioners (6 males and 3 females) and nine controls (6 males and 3 females) who were matched for age, sex, height and body mass participated in the study (Table 1). Participants had normal pulmonary function (Table 1). The exclusion criteria were aged under 18 years or over 60 years; history or current symptoms of cardiopulmonary disease; and contraindications to exercise testing. The trained martial arts practitioners in this study were individuals who had a range of experience in the Chang Hong system of kung fu with a minimum of one year of training (mean = 7.3 ± 7.2 years). All participants took part in an intensive twelve-month training program consisting of daily qigong and basic potency exercises from the traditional Chang Hong system that was completed between 0 and 3 months prior to the current study. This training program was external to the current study and was run by the Chinese Martial Arts and Health Centre Australia, who monitored adherence to the program. Qigong training consists of slow, deep and controlled breathing combined with various arm movements while focusing on sensation and pressure in the dantian (a term describing the area of the pelvic cavity/lower abdomen). Potency exercises consist of performing various isometric movements combined with qigong training and focusing on building and maintaining a feeling of connection from the dantian to the relevant limbs. In relation to the current study, “untrained” refers to participants who have not received training in martial arts. The untrained controls had no martial arts experience but were physically active and engaged in regular sport or exercise training with a weekly activity level that was not different from the trained participants (Table 1). Physical activity was self-reported via the Adult Pre-Exercise Screening System (Exercise & Sports Science Australia, 2021). The self-reported physical activity of the trained participants included all martial arts training, such as participation in the intensive 12-month training program. Regular sport or exercise training and prior participation in martial arts training was determined via a self-administered Lifetime Physical Activity Questionnaire, modified from a questionnaire designed by Chasan-Taber et al. (2002). The questionnaire was modified to include martial arts training, with household activities removed. All study procedures were approved by the University of Southern Queensland Research Ethics Committee, which adheres to the Declaration of Helsinki. All participants provided written, informed consent prior to participation in the study.

Table 1. Participant anthropometrics, physical activity levels and respiratory function. Values are mean ± standard deviation.

	Trained (n = 9)	Control (n = 9)	*P* Value
Age, years	37 ± 12	36 ± 11	0.84
Male / Female	6 / 3	6 / 3	
Height, m	1.76 ± 0.07	1.76 ± 0.09	0.88
Body mass, kg	78.2 ± 18.5	81.6 ± 14.6	0.68
BMI, kg/m^2	25.1 ± 5.0	26.3 ± 3.6	0.56
Self-reported physical activity, MET/min/wk	639 ± 476	324 ± 247	0.10
FVC, L (%predicted)	4.47 ± 0.70 (93 ± 13)	5.09 ± 1.19 (104 ± 13)	0.08
FEV_1, L (%predicted)	3.76 ± 0.63 (95 ± 11)	4.10 ± 0.80 (103 ± 13)	0.16
$P_{e,max}$, cmH_2O	96 ± 40	95 ± 32	0.96
$P_{g,max}$, cmH_2O	173 ± 74	153 ± 58	0.53
$P_{g,max}$, cmH_2O / BMI	6.94 ± 2.67	5.83 ± 2.11	0.34
$P_{di,max}$, cmH_2O	140 ± 48	122 ± 60	0.48

BMI, body mass index; FVC, forced vital capacity; FEV_1, forced expiratory volume in one second; $P_{e,max}$, maximum oesophageal pressure; $P_{g,max}$, maximum gastric pressure; $P_{di,max}$, maximum transdiaphragmatic pressure. Predicted values are from Quanjer et al. (2012).

Experimental design

The study utilised a case controlled cross-sectional design. Participants attended the laboratory on one occasion 4 h postprandially. During the visit, height, body mass, and pulmonary function were initially assessed. Subsequently, participants were familiarised with all other measurements and experimental procedures. Participants were then instrumented with skin-surface EMG and an oesophageal EMG catheter. Participants then undertook maximal respiratory pressure measurements before performing two tasks: A Standing Isometric Unilateral Chest Press task and a Standing Posture Control task. These two tasks involved the participant producing (Standing Isometric Unilateral Chest Press) or resisting (Standing Posture Control) force close to or against the trunk while maintaining a stable body position (Fig. 1). These tasks were chosen because they were simple and could be performed easily by both the trained and control groups. Each task was performed in a way that would reduce the ability of the participant to use their body mass to produce or resist force by leaning due to the strict constraints applied to the posture of the participant during the testing. As we were not interested in examining differences between tasks, and to ensure that the order of tasks was consistent between both groups, the Standing Isometric Unilateral Chest Press task was performed first for each participant. In addition, to minimise the order effect on fatigue, participants rested for 10 min between tasks. We did not observe any decline in force during the tasks, indicating that the order of the tasks had no impact on fatigue.

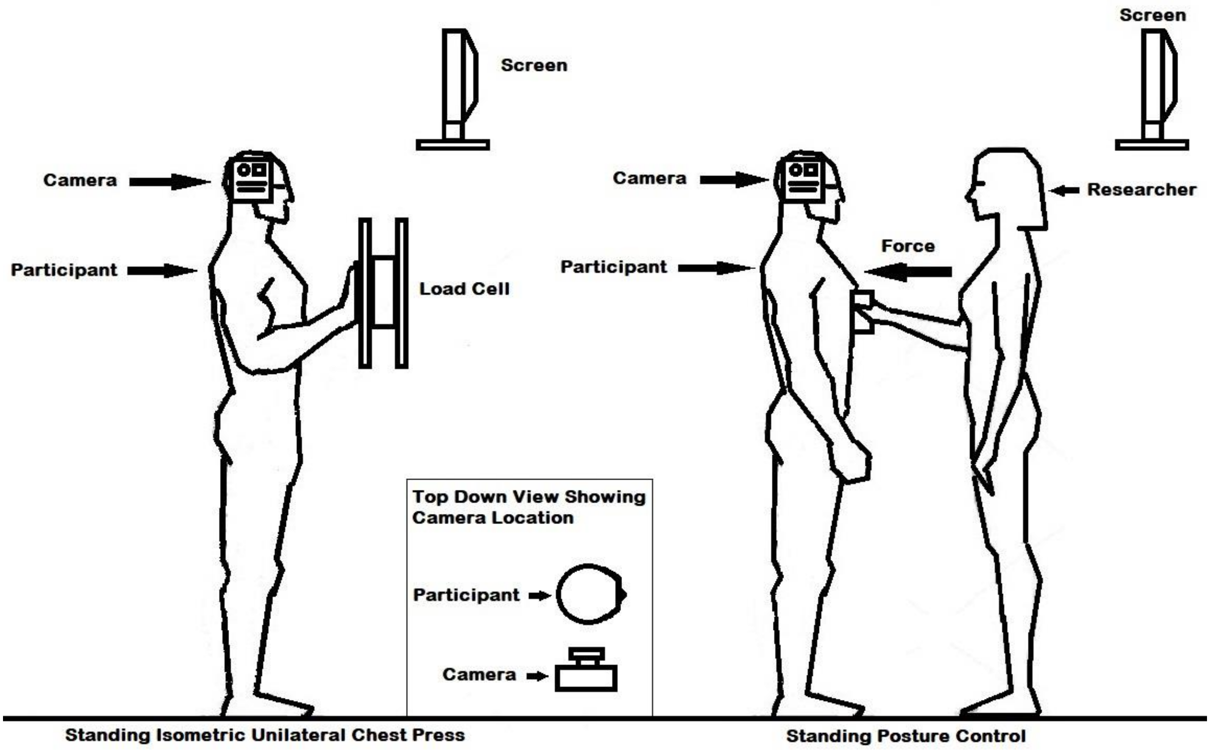

Fig. 1 Schematic representation of the experimental setup for the Standing Isometric Unilateral Chest Press and Standing Posture Control tasks

Pulmonary function and maximal respiratory measurements

Forced vital capacity (FVC) and forced expiratory volume in one second (FEV_1) were assessed according to published guidelines (Miller et al. 2005) using a spirometer (JAEGER® Vyntus; CareFusion, San Diego, CA, USA). Maximal volitional gastric ($P_{g,max}$), oesophageal ($P_{e,max}$), and transdiaphragmatic ($P_{di,max}$) pressures were assessed using maximal static inspiratory and expiratory pressure tests according to published guidelines (American Thoracic Society/European Respiratory Society 2002; Laveneziana et al. 2019). The distal end of a plastic tube (102 mm in length and 76 mm in diameter) was closed and incorporated a 1 mm orifice to prevent glottic closure during efforts, which were initiated from residual volume ($P_{e,max}$ and $P_{di,max}$) or total lung capacity ($P_{g,max}$). All respiratory function manoeuvres were performed whilst standing and sustained for at least 3 s. Repeat efforts separated by 30 s were performed until three serial measures differed by no more than 10% or 10 cmH_2O, whichever was smallest. The highest value recorded was used for subsequent analysis. These maximal pressure manoeuvres were used to determine maximal pressure and EMG responses.

Standing Isometric Unilateral Chest Press Task

The Standing Isometric Unilateral Chest Press task required the participant to push with maximum force while maintaining an isometric position against a calibrated load cell sampling at 1 kHz (Boxing Training Kit; Loadstar Sensors, Fremont, CA, USA) fixed to a wall. The output from the load cell was recorded with software (LoadVUE for Boxer Training; Loadstar Sensors, Fremont CA, USA) for live viewing of the force trace and for offline processing. The load cell was affixed to the wall so that the centre of the load cell plate was 1.31 m above the floor of the laboratory. The load cell plate dimensions were 37 cm high and 45 cm wide. The participant was positioned in front of and facing the load cell at a distance that ensured their right palm was in contact with the load cell while their elbow maintained ~110° of flexion. This angle was confirmed using a standard goniometer aligned to the lateral epicondyle of the elbow, the acromion process in the centre of the humerus, and the ulnar styloid. The participant was free to place their arm at a position on the load cell plate that was most comfortable for them, providing they maintained ~110° of elbow flexion. The participant was instructed to apply as much sustained force as possible in a push against the load cell for 10 s without leaning forward, making any rapid 'jerking' movements, and/or pushing themselves away from the load cell (i.e., they were instructed to apply force in a steady and sustained fashion). If a change in position occurred, or if force was not applied steadily, participants were provided with feedback and the task was repeated. Participants were not instructed on how to breathe or recruit musculature during this task. Participants performed the task a minimum of three times with each hand. The data from the load cell was time-aligned with the pressure and EMG data recorded using the data acquisition system (PowerLab 16/35, AD Instruments, Bella Vista, Australia) using a simultaneous signal on both platforms. To achieve this, electrocardiograph electrodes were attached to the plate of the load cell, and prior to each Unilateral Chest Press task the load cell was tapped creating simultaneous responses in both software packages. The coordination of the pressure and EMG data and the load cell data output allowed for time-alignment in subsequent data analysis.

Standing Posture Control Task

During the Standing Posture Control task, the experimenter applied a pushing force against the participant's sternum so that the participant was required to resist while maintaining a fixed stationary position. The participants were instructed to stand fully upright with their feet in line, approximately shoulder width apart, knees slightly bent with arms relaxed by their sides. An experimenter placed a padded block attached to a calibrated handheld grip strength dynamometer (MLT004/ST Grip Force Dynamometer, AD Instruments) on the participant's chest at the centre of the participant's sternum. From this position, the experimenter applied force steadily against the participant's sternum at rate of approximately 7 N/s. The rate of force application was monitored by the experimenter via visual inspection of the force output on LabChart Pro software (AD Instruments). The participant was instructed to resist the increasing force applied by the experimenter for as long as possible until they could no longer hold their stationary position (i.e. the participant stepped backwards). The dynamometer was then immediately removed from the participant's chest. Participants were not instructed on how to breathe or recruit musculature during this task.

Monitoring of body position during tasks

A video camera was positioned perpendicular to the participant to record upper torso and head movements. Movement analysis software (Kinovea, version 0.8.15, www.kinovea.org) was used to draw a vertical line on either side of the participant's upper torso and head on the live video output. The live video output was displayed on a screen in front of the participant. If the participant was observed to be leaning during a task (determined when more than approximately 10% of the participant's head moved outside of the vertical lines), the task was repeated. This ensured that the participant was not leaning into the load cell during the Standing Isometric Unilateral Chest Press and Standing Posture Control tasks. The tasks were repeated with 30 s rest between each repetition until three force measurements were collected that differed by no more than 10%. Most participants only required 3-4 repetitions to achieve consistent results, while some participants improved after the first few repetitions, in which case the measurements were repeated until consistent results were achieved.

Respiratory neuromuscular responses: Pressures and EMG

EMG_{di} was assessed using a bespoke multipair oesophageal electrode catheter (Gaeltec Devices Ltd., Dunvegan, Isle of Sky, UK). The catheter comprised a 100 cm silicon shaft (2.7 mm diameter) containing nine silver electrodes spaced 1 mm apart. P_e and P_g were measured simultaneously using two independent pressure transducers integrated within the catheter spaced 22.8 cm apart and positioned proximally and distally to the electrodes. The transducers were calibrated over the physiological range by placing the catheter within a sealed, air-filled tube to which positive and negative pressures were applied using a glass syringe filled with 2 ml of air. The calibration tube was connected to a handheld respiratory pressure meter (MicroRPM, Care Fusion, Basingstoke, UK) and the voltage outputs of each pressure transducer were calibrated against reference pressures. The catheter was positioned using the method described by Luo et al. (2001). Following local anaesthesia with Co-Phenylcaine Forte Spray (ENT Technologies Pty Ltd., Hawthorne, Australia), the catheter was passed peri-nasally into the stomach until a positive deflection in P_g and a negative deflection in P_e were observed during repeated sniffs. The catheter was then repositioned based on the strength of EMG_{di} recorded simultaneously from different pairs of electrodes and was then secured in place. EMG_{scm}, EMG_{ra}, and $EMG_{tra/io}$ were assessed with pairs of bipolar skin-surface electrodes (Ambu WhiteSensor 40713, Ambu Australia, Warriewood, Australia) after carefully shaving (if required), cleaning and abrading the skin. The electrodes were 2 cm in diameter and the inter-electrode distance (the distance from the centre of one electrode to the centre of another electrode) was 2 cm. As the transverse abdominal and internal oblique muscles have been shown to co-contract with pelvic floor contraction, the $EMG_{tra/io}$ site was chosen as a surrogate for pelvic floor activity (Arab and Chehrehrazi 2011). The positions of the surface electrodes were as follows: EMG_{scm}, placed at the midpoint along the longitudinal axis of the sternocleidomastoid muscle between the mastoid process and the medial clavicle (Segizbaeva et al. 2013); EMG_{ra}, 2 cm superior and 2-4 cm lateral to the umbilicus on the left-hand side of the torso (Neumann and Gill 2002); and for $EMG_{tra/io}$, 2 cm proximal to the midpoint on the line between the anterior superior iliac spine and the pubic symphysis on the left hand side of the torso (Neumann and Gill 2002).

Data capture and analysis

Raw data were sampled continuously using a 16-channel analogue-to-digital data acquisition system (PowerLab 16/35; AD Instruments) at 200, 1000 and 2000 Hz for pressure, force and EMG, respectively. Force data from the Standing Isometric Unilateral Chest Press task were analysed with Excel (Microsoft Office 365; Microsoft Corporation, Redmond, WA, USA). All other data were recorded and analysed using LabChart Pro software package (AD Instruments). Although participants had been instructed to apply as much sustained force as possible without leaning forward, making any rapid 'jerking' movements, and/or pushing themselves away from the load cell, some instances of these movements did still occur during the testing procedures. The force data was thus visually inspected for momentary data spikes associated with non-sustained force production and all spikes greater than 50% of the mean force produced by that participant in that particular task were removed. The onset of effort was determined automatically in Excel using the method described by Chavda et al. (2020), which utilises a threshold for force onset based on 5 x the standard deviation of the baseline force measurement prior to the pushing onset (i.e., while the participant's hand was resting on the force plate prior to commencing a manoeuvre). For the Standing Posture Control task, the rate of force development was calculated as the average rate of force development between the onset of force and the maximum resistive force. In addition, the total impulse for each Standing Posture Control task was calculated as the integral of the force-time graph for the duration of each Standing Posture Control task using the following equation [1]:

$$I = \int_{t_0}^{t_f} F \, dt \qquad [1]$$

Where I is the impulse, t_0 is the time at the start of the task, t_f is the time at the end of the task, and F is the force.

Force was normalised to body mass$^{2/3}$ while factoring in allometric scaling (F_A) through the use of the equation [2] (Jaric 2002):

$$F_A = \frac{F}{m^{2/3}} \qquad [2]$$

Where *F* is the absolute force produced by the participant and *m* is the mass of the participant. Normalisation of force to body mass$^{2/3}$ corrects for any within-group differences in body mass and was used in order to assess force production independently of body size due to the direct effect of body size on the amount of force that each participant was able to produce or resist. Muscle force has been found to be proportional to body mass$^{2/3}$ (Jaric 2002; Vanderburgh et al. 1995). EMG data were high-pass filtered at 80 Hz and notch-filtered at 50 Hz (Li et al. 2011). Raw EMG data were converted to root mean square data using a time constant of 100 ms and a moving window. All EMG data were expressed as a percentage of the maximum EMG activity recorded during a maximal inspiratory or expiratory pressure manoeuvre (%max). The onset of P_g was calculated automatically in LabChart Pro software (AD Instruments) using a threshold value of 5 x the standard deviation of resting P_g. Resting P_g was determined as the average P_g during a 10 s resting period to account for variations in P_g during quiet breathing. The onset time for P_g in relation to the onset time for force was compared between the two groups. P_{di} was calculated online by subtracting P_e from P_g. Extreme outliers due to artefacts, including breath holding or peristalsis, were removed. In order to compare the two groups of participants in terms of the relative contribution of P_g/P_e (reflecting the pattern of abdominal to chest wall muscle recruitment) and the relative contribution of P_{di}/P_e (pattern of diaphragm to chest wall muscle recruitment), the differences between the pressures for each recruitment pattern type were determined. These differences were calculated as the percentage of the difference between the two pressures divided by the mean of the two pressure values, using equations [3] and [4] and based on previous work by Brown et al. (2014) and Nava et al. (1993):

$$P_g/P_e\ (\%) = \frac{2(P_g - P_e)}{P_g + P_e} * 100 \qquad [3]$$

$$P_{di}/P_e\ (\%) = \frac{2(P_{di} - P_e)}{P_{di} + P_e} * 100 \qquad [4]$$

Maximum values were recorded for the force and pressure measurements, and their corresponding time values were recorded for each Standing Isometric Unilateral Chest Press and Standing Posture Control task. Mean values for the force and pressure measurements were also calculated during each task. In addition, to obtain the values at peak force, the mean pressure and EMG measurements were calculated over a 1 s time period when peak force was achieved. Artefacts were visually inspected and manually removed from pressure and EMG data. For the Standing Isometric Unilateral Chest Press task, the data from the left and right-hand efforts were combined when comparing values between groups.

Statistical analysis

Statistical analysis was performed using SPSS for Windows (IBM, Chicago, IL, USA). Within-day reliability of the repeated force and neuromuscular measurements for the Standing Isometric Unilateral Chest Press and Standing Posture Control tasks were assessed using the intraclass correlation coefficient (ICC). Normality of the data was confirmed using the Shapiro-Wilk test. Between-group data were analysed using independent t-tests. Statistical significance was set at $P < 0.05$. Effect sizes are given as Cohen's *d* (Cohen, 1988) and interpreted as trivial (≤ 0.19), small ($0.2 \leq 0.49$), medium ($0.5 \leq 0.79$) and large (≥ 0.8) (Cohen, 1988). All values are presented as means ± standard deviation.

RESULTS

Participant groups

There were no between-group differences in participant anthropometrics and respiratory function (Table 1). Fig. 2 shows representative data sets from the Standing Posture Control task for a trained and control participant who were both male, aged 45 years with a body mass index of 27 and 30 kg/m^{-2}, height of 1.78 and 1.75 m, and body mass of 87 and 91 kg, respectively. The data shown in Fig. 2 is from a single Standing Posture Control task, with the plots starting at the beginning of the application of force and ending when the force application ended.

Task reliability

There were no systematic differences in the repeated pressure, force and EMG measurements. Within-day, between-trial reliability coefficients in the Standing Isometric Unilateral Chest Press task for pressure, force and EMG were 0.68, 0.97, and 0.77 for trained, and 0.53, 0.94, and 0.78 for control participants, respectively. Within-day, between-trial reliability coefficients in the Standing Posture Control task for pressure, force and EMG were 0.87, 0.95, 0.92 for trained and 0.72, 0.81, 0.82 for control participants, respectively. These values are indicative of moderate to excellent reliability.

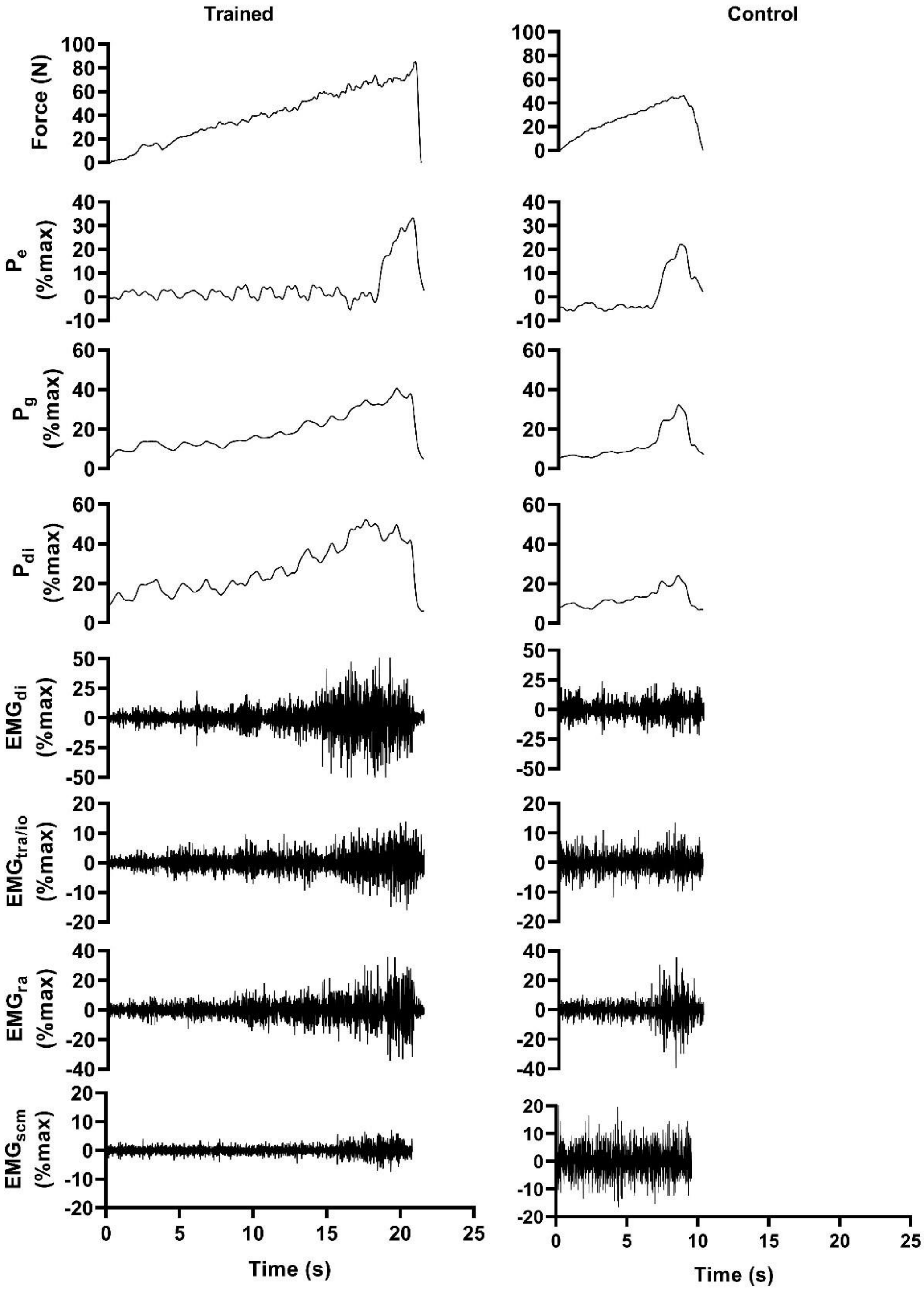

Fig. 2 Representative examples from the Standing Posture Control task for a trained (left panels) and control (right panels) participant. P_e, oesophageal pressure; P_g, gastric pressure; P_{di}, transdiaphragmatic pressure; EMG_{di}, crural diaphragm EMG; $EMG_{tra/io}$ transverse abdominis/internal oblique EMG; EMG_{ra}, rectus abdominis EMG; EMG_{scm}, sternocleidomastoid EMG

Force production

For the Standing Isometric Unilateral Chest Press task, the mean and peak force were not different between the trained (66.5 ± 28.1 and 95.1 ± 41.9 N) and control (56.0 ± 17.1 and 76.5 ± 22.8 N) groups (*P* = 0.18 and 0.11, *d* = 0.45 and 0.55). However, when normalised for body mass$^{2/3}$, the mean (*P* = 0.01, *d* = 0.91) and peak forces produced (*P* = 0.006, *d* = 0.99) were higher for the trained group than the control group with large effect sizes (Fig. 3). For the Standing Posture Control task, the rate of force development was compared between groups to ensure that the experimenter pushed against all participants in a similar manner. There were no differences in the rate of force development between the trained (7.24 ± 1.6 N/s) and control (7.97 ± 1.55 N/s) groups (*P* = 0.4, *d* = 0.47). The mean and peak forces applied were not different between the trained (39.9 ± 12.0 and 65.5 ± 22.1 N) and control (31.6 ± 9.06 and 53.6 ± 16.8 N) groups (*P* = 0.12, *d* = 0.76; and *P* = 0.21, *d* = 0.61) with medium effect sizes. When normalised for body mass$^{2/3}$, the mean (*P* = 0.01, *d* = 1.35) and peak (*P* = 0.02, *d* = 1.29) forces were higher for the trained compared to the control group with large effect sizes (Fig. 3). The total impulse was higher for the trained (323 ± 37.5 N/s) group than for the control (265 ± 25.3 N/s) group with large effect sizes (*P* = 0.04, *d* = 0.89).

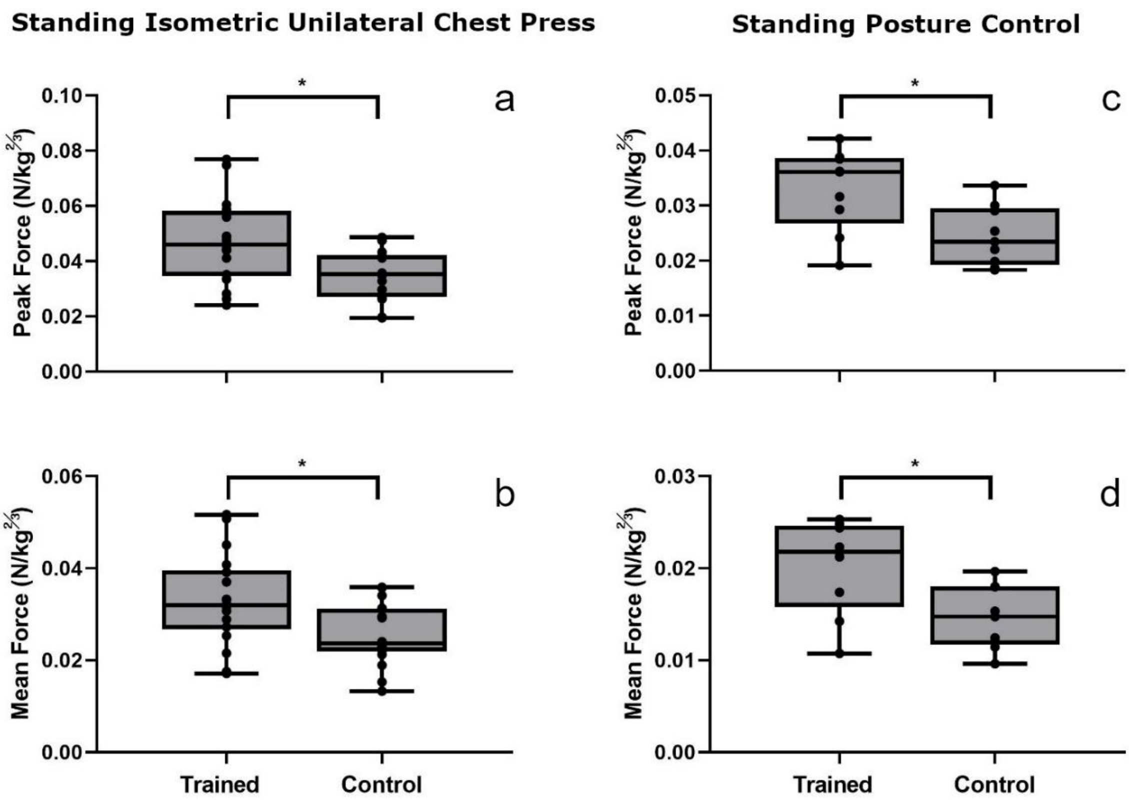

Fig. 3 Peak (A and C top panel) and mean force (B and D bottom panel) normalised for body mass$^{2/3}$ applied during the Standing Isometric Unilateral Chest Press and Standing Posture Control tasks. *Significantly different from control group, $P < 0.05$

Respiratory pressures

Respiratory pressures during the Standing Isometric Unilateral Chest Press and Standing Posture Control tasks for the trained and control groups are shown in Table 2 and Fig. 4. For the Standing Isometric Unilateral Chest Press task, all P_e measures were lower for the trained group ($P < 0.05$, $d > 0.93$) except for ΔP_e, which was not different between groups ($P = 0.08$, $d = 0.61$). All P_g and P_{di} measures were higher for the trained group ($P < 0.05$, $d > 0.74$). The relative contribution of P_g/P_e (reflecting the pattern of abdominal to chest wall muscle recruitment) and the relative contribution of P_{di}/P_e (reflecting the pattern of diaphragm to chest wall muscle recruitment) were higher for the trained group ($P < 0.05$, $d > 3.12$; Fig. 4). For the Standing Posture Control task, mean P_e and mean P_e (%max) were lower for the trained group ($P < 0.05$, $d > 0.92$). Except for P_{di} at peak force, all other P_{di} measures were higher for the trained group (*P* < 0.05). All P_{di} measures had a large effect size (*d* > 0.87). There were no differences in P_g between the groups for this task, but P_g/P_e and P_{di}/P_e were higher for the trained group (*P* < 0.05, *d* > 1.56; Fig. 4).

The onset of P_g with respect to the onset of force application was earlier for the trained group than for the control group in the Standing Isometric Unilateral Chest Press (*P* = 0.0008, *d* = -1.5) and the Standing Posture Control tasks (*P* = 0.048, *d* = -1.09) (Fig. 4).

Table 2. Respiratory pressures. Values are mean ± standard deviation.

	Standing Isometric Unilateral Chest Press		Standing Posture Control	
	Trained	Control	Trained	Control
Mean P_e, cmH_2O	8 ± 7*	25 ± 12	0.6 ± 6*	11 ± 12
Mean P_e, %max	10 ± 9	27 ± 13	0.5 ± 7*	7 ± 5
Peak P_e, cmH_2O	31 ± 14*	45 ± 16	11 ± 8	19 ± 6
Peak P_e, %max	39 ± 20*	55 ± 20	23 ± 22	32 ± 26
P_e at Peak Force, cmH_2O	13 ± 12*	27 ± 16	4 ± 10	15 ± 11
P_e at Peak Force, %max	16 ± 15*	29 ± 12	5 ± 13	16 ± 8
ΔP_e, cmH_2O	39 ± 15	48 ± 16	16 ± 8	17 ± 5
Mean P_g, cmH_2O	73 ± 42*	49 ± 19	49 ± 24	34 ± 21
Mean P_g, %max	40 ± 12*	31 ± 5	28 ± 6	22 ± 9
Peak P_g, cmH_2O	112 ± 58*	72 ± 34	105 ± 65	69 ± 43
Peak P_g, %max	66 ± 14*	48 ± 11	59 ± 20	44 ± 19
P_g at Peak Force, cmH_2O	85 ± 45*	50 ± 19	79 ± 50	58 ± 39
P_g Peak Force, %max	48 ± 15*	33 ± 7	44 ± 14	36 ± 16
ΔP_g, cmH_2O	92 ± 50*	59 ± 33	56 ± 34	43 ± 33
Mean P_{di}, cmH_2O	63 ± 43*	23 ± 11	48 ± 23*	26 ± 14
Mean P_{di}, %max	41 ± 19*	21 ± 10	33 ± 7*	20 ± 7
Peak P_{di}, cmH_2O	100 ± 50*	48 ± 18	87 ± 41*	39 ± 21
Peak P_{di}, %max	72 ± 18*	48 ± 20	68 ± 19*	37 ± 16
P_{di} at Peak Force, cmH_2O	72 ± 49*	22 ± 12	72 ± 45	37 ± 27
P_{di} at Peak Force, % max	48 ± 24*	20 ± 14	48 ± 18*	31 ± 13
ΔP_{di}, cmH_2O	94 ± 41*	47 ± 23	46 ± 21*	21 ± 11

P_e, oesophageal pressure; P_g, gastric pressure; P_{di}, transdiaphragmatic pressure. *Significantly different from the control group, *P* < 0.05.

Neuromuscular activation

Neuromuscular activation during the Standing Isometric Unilateral Chest Press and Standing Posture Control tasks for the trained and control groups are shown in Table 3. In the Standing

Isometric Unilateral Chest Press task, the trained group utilised a higher percentage of EMG$_{tra/io}$ at peak force than the control group (P = 0.01, d = 1.09), but not throughout the task (P = 0.17, d = 0.89). The effect sizes for both of these measures were large. There were no differences between the groups for EMG$_{di}$ (P = 0.12, d = 0.56; P = 0.14, d = 0.56), EMG$_{ra}$ (P = 0.46, d = 0.25; P = 0.14, d = 0.5), and EMG$_{scm}$ (P = 0.38, d = 0.3; P = 0.76, d = 0.1) in the Standing Isometric Unilateral Chest Press task both throughout the task and at peak force, respectively. There were medium effect sizes for EMG$_{di}$ both throughout the task and at peak force. In the Standing Posture Control task, the trained group utilised a higher percentage of EMG$_{di}$ than the control group, both throughout the movement (P = 0.048, d = 1.08) and at peak force (P = 0.02, d = 1.29). There were no differences between the groups for EMG$_{tra/io}$ (P = 0.22, d = 0.65; P = 0.37, d = 0.46), EMG$_{ra}$ (P = 0.95, d = 0.03; P = 0.81, d = 0.12), and EMG$_{scm}$ (P = 0.70, d = 0.2; P = 0.85, d = 0.1) in the Standing Posture Control task for both throughout the task and at peak force, respectively. There was a medium effect size for EMG$_{tra/io}$ throughout the task.

Table 3. Neuromuscular activation during the Standing Isometric Unilateral Chest Press and Standing Posture Control tasks for the trained and control groups. Values are mean ± standard deviation.

	Standing Isometric Unilateral Chest Press		Standing Posture Control	
	Trained	Control	Trained	Control
Mean EMG$_{di}$ RMS, %max	121 ± 43	98 ± 38	103 ± 43*	66 ± 22
EMG$_{di}$ RMS at peak force, %max	113 ± 47	92 ± 28	129 ± 67*	65 ± 20
Mean EMG$_{tra/io}$, %max	89 ± 49	70 ± 29	63 ± 34	45 ± 19
EMG$_{tra/io}$ RMS at peak force, %max	94 ± 34*	65 ± 21	79 ± 38	62 ± 34
Mean EMG$_{ra}$ RMS, %max	87 ± 2	81 ± 14	76 ± 22	76 ± 13
EMG$_{ra}$ RMS at peak force, %max	114 ± 84	84 ± 16	94 ± 31	91 ± 23
Mean EMG$_{scm}$ RMS, %max	40 ± 30	51 ± 44	30 ± 24	35 ± 26
EMG$_{scm}$ RMS at peak force, %max	47 ± 38	51 ± 42	33 ± 26	35 ± 27

EMG$_{di}$, crural diaphragm EMG; EMG$_{tra/io}$ transverse abdominis/internal oblique EMG; EMG$_{ra}$, rectus abdominis EMG; EMG$_{scm}$, sternocleidomastoid EMG; RMS, root mean square. *Significantly different from the control group, $P < 0.05$.

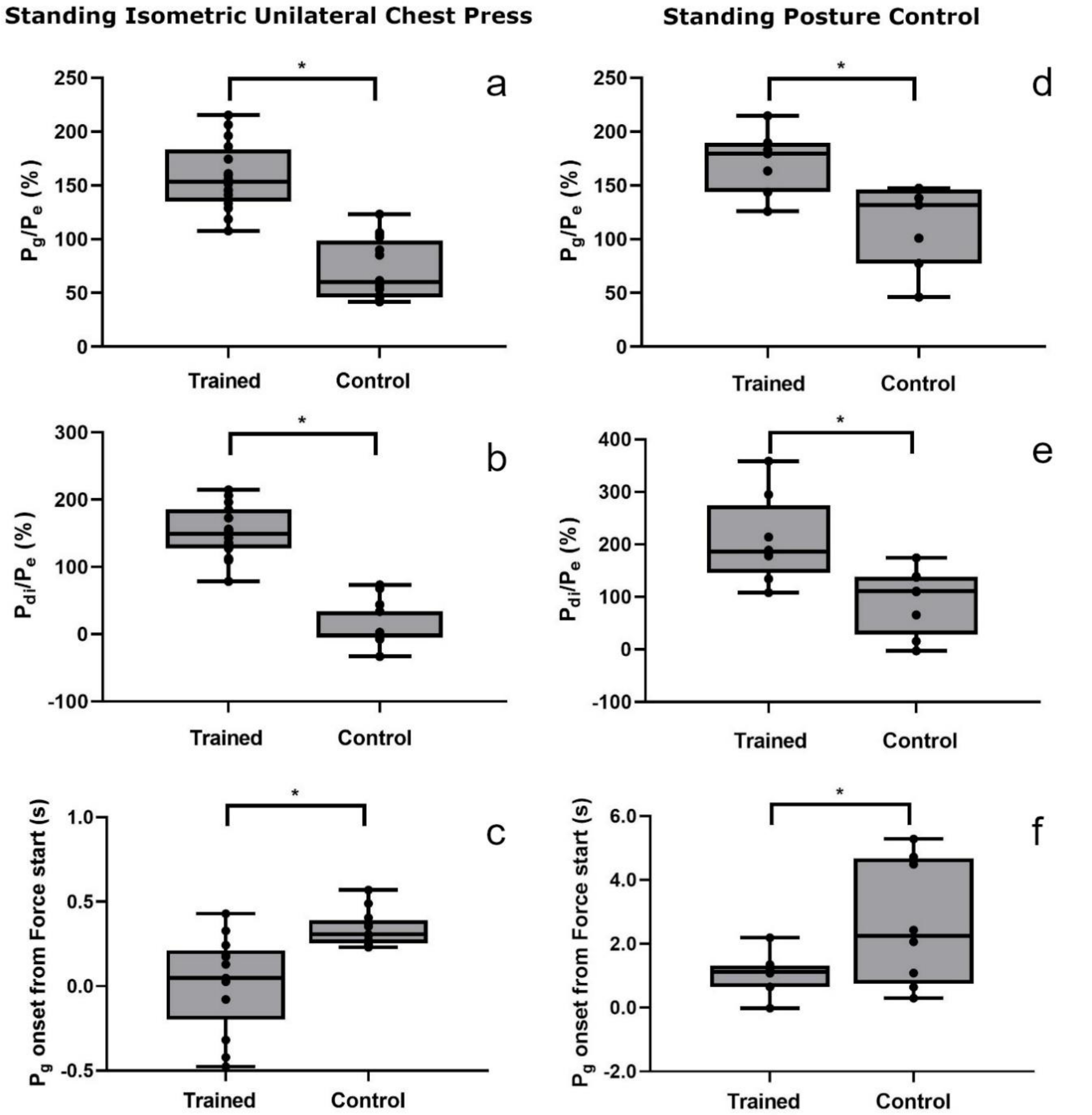

Fig. 4 Relative contribution of gastric/oesophageal pressure (P_g/P_e; A and D), relative contribution of transdiaphragmatic/oesophageal pressure (P_{di}/P_e; B and E) and time of gastric pressure (P_g) onset from onset of force production (C and F) during the Standing Isometric Unilateral Chest Press (left hand panel) and Standing Posture Control (right hand panel) tasks. *Significantly different from the control group, $P < 0.05$

DISCUSSION

Main findings

This is the first study to investigate whether the greater ability of trained martial arts practitioners to produce and resist forces is associated with an enhanced neuromuscular activation and control of the respiratory, abdominal, and pelvic floor musculature leading to higher intra-abdominal pressures. The main findings were that trained martial arts practitioners had higher forces normalised to body mass$^{2/3}$ than controls during tasks that required participants to produce (Standing Isometric Unilateral Chest Press) and resist (Standing Posture Control) maximal forces. This occurred with greater abdominal and diaphragm muscle recruitment relative to chest wall muscle recruitment, and higher P_g relative to P_e, for the trained group than for the control group. Compared to the control group, the trained group also demonstrated greater activation of the transverse abdominis/internal oblique musculature in the Standing Isometric Unilateral Chest Press task, and the diaphragm in the Standing Posture Control task.

Forces

We observed that trained martial arts practitioners produced (Standing Isometric Unilateral Chest Press) and resisted (Standing Posture Control) higher maximal isometric forces normalised to body mass$^{2/3}$ than untrained controls. Higher levels of force production are used by martial arts practitioners to aid combat performance. These results are in agreement with previous studies that have also demonstrated that trained martial arts practitioners can produce greater forces than untrained individuals (Galpin et al. 2015; Neto et al. 2008; Smith et al. 2000). The forces produced in the present study are lower than others reported for trained martial arts practitioners. This may be explained by the type of task undertaken as previous studies utilised striking tasks (Galpin et al. 2015; Neto et al. 2008; Smith et al. 2000) rather than the isometric force application used in the present study. Our findings indicate that the observed differences in respiratory pressures and neuromuscular activation between the trained martial arts practitioners and untrained controls may be a contributing factor towards the differences in force production. As both groups were matched across a number of key demographics, and the untrained group were physically active at a level similar to the trained group, the differences between the two groups are likely to be attributed to either, or a combination of, martial arts training and breath control training. Further studies are therefore needed to separate the role of breath control training and martial arts training in force production, levels of P_g and P_e and neuromuscular activation of the diaphragm and transverse abdominis/internal oblique musculature.

Respiratory pressures

In support of our hypothesis, we observed that the trained individuals had higher P_g (a surrogate measure of intra-abdominal pressure) compared to the control group during the Standing Isometric Unilateral Chest Press task and they also had lower P_e, resulting in a higher P_{di}. These differences resulted in a higher P_g/P_e and P_{di}/P_e for the trained group. For the Standing Posture Control task, there were no differences in P_g between the groups, but mean P_e were lower for the trained group and most P_{di} measures were higher for the trained group. This resulted in P_g/P_e and P_{di}/P_e being higher for the trained group.

Cholewicki et al. (2002) found that it was generally not possible to generate intra-abdominal pressure without increasing P_e, but they did theorise that with training, individuals may be able to generate intra-abdominal pressure independently of P_e during physical activities. Our study indicates that through some forms of training, including qigong, martial arts practitioners may gain increased control over internal pressures, allowing them to pressurise the abdominal cavity independently of the thoracic cavity.

The differences in the control of respiratory pressures between the groups may be partly explained by the qigong training experience of the trained martial arts practitioners. Qigong is an integral part of traditional martial arts training that is traditionally thought to increase force production and core stability (Chen 2014). Practitioners undertake slow, deep and controlled breathing exercises, whilst controlling the pelvic floor musculature, increasing the sensation of pressure in the abdominal and pelvic cavities whilst allowing the upper torso to remain relaxed (Chen 2014). This is supported by the findings of Zhang et al. (1992) who utilised an alternative manoeuvre based on qigong exercises to address some of the drawbacks of the Anti-G straining manoeuvre. They observed that, in contrast to the conventional Anti-G Straining manoeuvre, when pilots utilised the qigong manoeuvre, their P_e remained negative or at low pressures while P_g were remarkably raised. Our study indicates that this recruitment strategy may also be advantageous to force production and stability.

A primary function of intra-abdominal pressure is to support and stabilise the trunk (Cholewicki et al. 1999; Stokes et al. 2010). Our results would support the notion that individuals experienced with breath control training such as Qigong have a greater ability to raise and control intra-abdominal pressure, which thereby facilitates increases in force production and core stability. These forms of training may thus have considerable application in other physical activities that may benefit from increased force production and core stability.

Coordination and association of gastric pressure and force

We observed that the onset of P_g with respect to the onset of force production occurred earlier in the trained group than the control group. This supports the findings of Essendrop et al. (2004) who reported that trained martial arts practitioners were able to rapidly generate intra-abdominal pressure (inferred from P_g) to support the lower back during sudden trunk loading. The earlier increase in P_g with respect to the onset of force production in the trained group may aid in providing a more rapid increase in force.

The mechanisms by which increased intra-abdominal pressure may lead to increased force production are not well understood. In addition to contributing to core stability, there is evidence to suggest that increases in intra-abdominal pressure may also contribute directly to muscle force production. Sleboda and Roberts (2019) tested a model of muscle structure which was pressurised during the middle of an isometric contraction using a pneumatic cuff and found that pressurisation increased isometric forces at long muscle lengths. Pressure levels in the abdominal cavity have been shown to affect pressure in surrounding structures (Emerson 1911; Narloch and Brandstater 1995; Porth et al. 1984; Sale et al. 1993). It is hypothesised that individuals who have enhanced control of the musculature affecting internal pressure levels resulting from martial arts training may utilise a sequence of muscle activations causing increased pressure levels in a form of pressure-based kinetic chain from the abdomen to the structures surrounding peripheral musculature during striking or grappling movements, thus contributing to force production.

Neuromuscular activation

We observed that EMG_{di} (in the Standing Posture Control task) and $EMG_{tra/io}$ (in the Standing Isometric Unilateral Chest Press task) were higher in the trained group than in the control group. These results show that the trained group was capable of a higher recruitment of the diaphragm, transverse abdominis, and internal oblique musculature. Greater recruitment of the transverse abdominis and internal oblique musculature is also indicative of greater pelvic floor activation. These findings concur with the observation that intra-abdominal pressure is strongly associated with the transversus abdominis, internal oblique, and pelvic floor muscles, and that the diaphragm has a causal effect on intra-abdominal pressure (Cresswell et al. 1994; Hemborg et al. 1985; Hodges 1999; Neumann and Gill 2002). The qigong training which these martial arts practitioners undertook may have therefore improved their ability to control and contract the diaphragmatic and pelvic floor musculature (Chen 2014).

While we were not interested in examining differences between the two tasks, our results indicated that significant changes in some pressure and EMG responses between groups were dependent on the task performed (Table 2 and 3). It is likely that these task-dependent differences can be explained by the different characteristics of each task. The tasks used in this study were selected specifically to determine whether respiratory pressures were involved in both force production (Standing Isometric Unilateral Chest Press) and stabilisation of the body (Standing Posture Control). During the Standing Isometric Unilateral Chest Press task, the participant applied force with their hand against a load cell rigidly mounted to the wall. Due to the inherent stability of the wall, the participant was able to generate force perpendicularly to the force plate with minimal movement in other directions thus allowing higher forces to be produced in this task. During the Standing Posture Control task, force was applied directly against the participant's sternum, rather than to their hand.

This was done in order to reduce variations in the direction of the incoming force vector that would result from subtle changes in joint position at the wrist, elbow and shoulder. However, even with this approach, the forces resisted in this task were smaller than those generated in the Standing Isometric Unilateral Chest Press task. As such, differences in the magnitude of forces between tasks as well as the location at which force was applied/resisted may have contributed to the differences in pressure responses and neuromuscular activation that were observed between the two tasks.

While EMG_{di} was similar in both tasks for trained participants, the control group had lower EMG_{di} during the Standing Posture Control task than during the Standing Isometric Unilateral Chest Press task, resulting in a significant difference between the EMG_{di} in the two groups during the Standing Posture Control task. This may indicate that trained martial arts practitioners achieve greater diaphragm recruitment / activation that facilitates stabilisation of the body and greater resistance to forces. This may also indicate that it may be more difficult to recruit the diaphragm musculature when force is being resisted at the sternum as opposed to being produced with the arm.

In addition, while $EMG_{tra/io}$ was similar in both tasks for control participants, the trained group had higher $EMG_{tra/io}$ in the Standing Isometric Unilateral Chest Press task at peak force. This may indicate that trained martial arts practitioners are more able to recruit lower abdominal and pelvic floor musculature to increase force production than control participants. This may also indicate that it was easier to recruit lower abdominal and pelvic floor musculature while pushing with the arm than when force was applied directly to the sternum.

Methodological limitations

Due to the limited number of trained martial arts practitioners that we were able to recruit for this study, the sample size was limited to a convenience sample, and there were within-group variations in age, height, body mass and sex. These limitations were addressed by selecting controls who were matched to the trained group and as such there were no between-group differences in these variables. There was also a considerable variation in length of training in the trained group, ranging from 1 year to 22 years. Nevertheless, all trained individuals had completed an intensive twelve-month training program consisting of kung fu training, daily qigong, and basic potency exercises from the traditional Chang Hong kung fu system.

We chose to utilise maximal inspiratory and expiratory manoeuvres to obtain maximum EMG values because these manoeuvres were more repeatable with less variability in terms of respiration and muscle recruitment between individuals and between the two groups than the Standing Posture Control or Standing Isometric Unilateral Chest Press tasks. For some participants, we found that maximum measured EMG values occurred during the Standing Posture Control or Standing Isometric Unilateral Chest Press tasks rather than during the maximal respiratory manoeuvres. This resulted in some %max EMG values being reported as greater than 100%.

It was observed that most participants achieved higher P_g in subsequent attempts of each task. It is believed that this may be evidence of participants rapidly learning improved control of respiratory pressures through the use of biofeedback as participants were able to view a computer monitor showing pressure and EMG. We repeated trials until these measurements plateaued and participants were fully familiarised with the tasks.

Conclusion

The aim of this study was to investigate whether the greater ability of trained martial arts practitioners to produce and resist forces was associated with an enhanced control of respiratory pressures and neuromuscular activation of the respiratory, abdominal, and pelvic floor musculature. Our novel findings demonstrate that trained martial arts practitioners produced and resisted higher levels of force normalised to their body mass$^{2/3}$ and achieved this by utilising a greater contribution of abdominal and diaphragm musculature to chest wall recruitment. The trained group activated the transverse abdominis/internal oblique musculature more than controls in the Standing Isometric Unilateral Chest Press task and the diaphragm in the Standing Posture Control task. The results of this study indicate that trained martial arts practitioners may have a greater ability to control respiratory pressures and utilise these to produce and resist forces which would aid in combat performance. Future studies should be undertaken into the practicality and effectiveness of breath control training to improve force production in other sports and physical activities and in patients with reduced muscular strength.

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