Effects of proprioceptive neuromuscular facilitation combined with threshold inspiratory muscle training on respiratory function in neurocritical patients with weaning failure: a randomized controlled trial

Qian Zhou[a], Yuanyuan Zhang[a], Wei Yao[a], Sijie Liang[b], Hui Feng[a] and Huaping Pan[a]

Downloaded from http://journals.lww.com/intjrehabilres by BhDMf5ePHKav1zEoum1tQfN4a+kJLhEZgbsIHo4XMi0hCywCX1AWnYQp/IlQrHD3i3D0OdRyi7TvSFl4Cf3VC4/OAVpDDa8KKGKV0Ymy+78= on 05/14/2024

The purpose of this study was to determine the effects of combining proprioceptive neuromuscular facilitation (PNF) with threshold inspiratory muscle training (TIMT), compared with TIMT alone, on respiratory function in neurocritical patients who experienced a weaning failure. Forty-seven participants (mostly after a stroke), were randomly divided into the experimental group ($n = 24$) and the control group ($n = 23$). The control group received usual care and TIMT, whereas the experimental group, in addition, underwent four 90-s periods of manual PNF. Both groups performed training in the ICU twice a day for 5 consecutive days. The main outcome measures included maximum inspiratory pressure, diaphragmatic excursions, diaphragm thickening fraction, oxygenation index, and forced expiratory volume in 1 s/forced vital capacity. The results showed a significant group-by-time interaction effect for maximum inspiratory pressure [$F(1, 45) = 17.84$, $\eta^2 = 0.328$, $P < 0.001$] and oxygenation index [$F[1, 45) = 5.58$, $\eta^2 = 0.11$, $P = 0.023$]. When compared with the control group, the experimental group showed overall significantly higher maximum inspiratory pressure [mean difference = 4.37 cm H_2O, 95% confidence interval (CI) 0.25–8.50, $P = 0.038$]. No other significant group differences were found. Combining PNF with TIMT may improve respiratory function in neurocritical patients with weaning failure. This combination approach may increase the likelihood of survival of neurocritical patients in the ICU. *International Journal of Rehabilitation Research* XXX: XXXX–XXXX Copyright © 2024 The Author(s). Published by Wolters Kluwer Health, Inc.

International Journal of Rehabilitation Research XXX, **XXX**:XXXX–XXXX

Keywords: proprioceptive neuromuscular facilitation, respiratory function, stroke, threshold inspiratory muscle training, weaning failure

[a]Department of Rehabilitation Medicine, The Affiliated Jiangning Hospital of Nanjing Medical University, Nanjing and [b]Department of Rehabilitation Medicine, The Affiliated Hospital of Xuzhou Medical University, Xuzhou, China

Correspondence to Hui Feng, MD, Department of Rehabilitation Medicine, The Affiliated Jiangning Hospital of Nanjing Medical University, No. 168, Gushan Road, Jiangning District, Nanjing 211100, China
Tel: +86 138 5195 9264; e-mail: fenghuiwz@stu.njmu.edu.cn

Received 21 February 2024 **Accepted** 31 March 2024.

Introduction

Stroke affects not only the control of volitional movements but can also decrease respiratory muscle strength. The severity of these impairments may increase mortality and prolong the length of stay in the ICU [1]. Mechanical ventilation [2,3] is an essential life-saving intervention that can prevent respiratory infections and other complications. Current studies on mechanical ventilation, however, indicated that prolonged mechanical ventilation can lead to impaired inspiratory muscle strength and endurance, pneumonia, and other related complications [4]. In a study of 124 patients ventilated for more than 24 h, 54% had detectable inspiratory muscle weakness before ventilatory weaning and inspiratory muscle weakness was independently associated with 1 year mortality [5]. Therefore, numerous clinical studies have recommended respiratory capacity training for the prevention of weaning failure [4,6,7].

Threshold inspiratory muscle training (TIMT) is a promising treatment and has been used in neurocritical patients with weaning failure [6]. TIMT exerts a load on the diaphragm and accessory inspiratory muscles and requires patients to initiate inspiratory flow by generating negative intrathoracic pressure. Thus, TIMT can help to increase inspiratory muscle strength and respiratory function [8]. The most common complication in patients is diaphragmatic weakness, which may be accompanied by increased airway resistance, decreased respiratory compliance, and increased respiratory load. Nevertheless, TIMT is a widely used training method for improving respiratory dysfunction. Bissett *et al.* [9] showed that mechanical threshold loading inspiratory muscle training improves the quality of life and dyspnoea in patients who are ventilator-dependent even in the absence of strength improvements or acceleration of ventilator liberation.

Proprioceptive neuromuscular facilitation (PNF) has gained considerable interest in the field of neurophysiological facilitation of respiration. The presumed physiological mechanisms of PNF include autogenic inhibition,

This is an open-access article distributed under the terms of the Creative Commons Attribution-Non Commercial-No Derivatives License 4.0 (CCBY-NC-ND), where it is permissible to download and share the work provided it is properly cited. The work cannot be changed in any way or used commercially without permission from the journal.

Downloaded from http://journals.lww.com/intjrehabilres by BhDMf5ePHKav1zEoum1tQfN4a+kJLhEZgbsIHo4XMi0hCywCX1AWnYQp/IlQrHD3i3D0OdRyi7TvSFl4Cf3VC4/OAVpDDa8KKGKV0Ymy+78= on 05/14/2024

reciprocal inhibition, stress relaxation, and the gate control theory [10,11]. PNF is believed to stimulate proprioceptive receptors in perioral, thoracic, and abdominal muscles as well as sensory inputs from peripheral organs by influencing motor outputs of the central nervous system and stimulating the corresponding nerve reflex, which may help patients develop correct movement patterns [12,13] and induce physiological reactions, such as cough and expectoration.

PNF has been an effective strategy for stimulating active breathing, rhythmic initiation, and stabilization [10,11]. Seo and Cho [14] showed that PNF respiration exercise is effective in increasing expiratory reserve volume and vital capacity and suggested that PNF can improve pulmonary function. A recent study in patients demonstrated that bioelectrical activity in accessory respiratory muscles was considerably decreased, suggesting that PNF exercise leads to respiratory muscle relaxation and reduced spasticity, thus improving respiratory function [15].

Numerous studies have explored respiratory function in neurocritical patients with weaning failure with a focus on inspiratory muscles and early activity and training of expiratory muscles, including intercostal and abdominal wall muscles [6,16]. Previous studies mainly used PNF for proprioceptive stimulation. Information about the combined effects of PNF and TIMT, however, is lacking. Therefore, the purpose of this randomized control study was to determine the effects of PNF and TIMT on respiratory function in neurocritical patients with weaning failure. We hypothesized that a combination of PNF and TIMT will be superior to TIMT alone when it comes to the maximum inspiratory pressure, diaphragmatic excursions, and diaphragm thickening fraction (DTF).

Materials and methods

Study design

This was a parallel two-arm non-blinded randomized controlled trial where the participants were randomized to the control and experimental groups by utilizing a computer-generated random number sequence (Q.Z.). The study was approved by the human ethics committee of the affiliated Jiangning Hospital of Nanjing Medical University in May 2023 (2023-03-032-K01), and the experiment was performed between May and October 2023. All patients provided written informed consent before the participation. This study has been registered on Chinese Clinical Trial Registry (ChiCTR2200055267).

Participants

Based on the previous results [10], the required sample size was 50 assuming 80% power and an α level of 0.05. The eligible patients were those who were 16–75 years old, had undergone mechanical ventilation for at least 48 h in a controlled mode [16,17] and were able to participate in training actively. Exclusion criteria were a condition that can compromise weaning, such as heart failure, or that can prevent adequate performance of inspiratory muscle training, such as neuropathy or myopathy. Patients were excluded when they had been tracheostomised before the commencement of weaning or had a major neurological comorbidity [2,18]. The majority of recruited participants suffered a stroke.

Intervention

After the initial assessment, the control group received TIMT in addition to common usual care (Q.Z.), such as secretion clearance, massage, and passive activities [19]. The TIMT device has a spring-loaded one-way valve that provides titratable inspiratory resistance in a range of 9–41 cm H_2O [9] (Threshold IMT device HS730; Respironics, Parsippany, New Jersey, USA). It was connected to an endotracheal tube and was verified to be reliable for inspiratory muscle training [4,20]. Firstly, with patients in 45° supine position, they were instructed to exhale slowly, empty the air in the lungs and then inhale deeply and vigorously as fast as possible. The maximal inspiratory pressure (MIP) was recorded. The inspiratory resistance was set at 50% of MIP [16,21]. When the heart rate, pulse oxygen, and respiratory rate were relatively stable during inspiratory training, the inspiratory resistance was increased by 1–2 cm H_2O per day. Each patient performed 10 breaths × five sets × twice daily × 5 days/week [22]. The intervention was stopped if any adverse sign was observed.

The experimental group received PNF training in addition to TIMT. Firstly, the patients performed passive and active movements to learn the correct breathing pattern in the presence of directional resistance [23]. After it was confirmed that the patients understood the PNF technique, four 90-s manual respiratory patterns of PNF were performed in the supine position by a cardiopulmonary physiotherapist [18] (Q.Z.). During PNF, the therapists placed hands bilaterally on the first four ribs in the hemiclavicular line, on the sternum, on the four last ribs, and on the lower edges of the 8th/9th ribs, respectively, to help resist and assist the ribs' movements during the inspiration and expiration. The patients received verbal commands during PNF and rested for 1 min after each set.

Outcomes

Maximum inspiratory pressure (MIP) was measured using an electronic inspiratory training device (Powerbreath K5, Murrysville, Pennsylvania, USA) (Q.Z.), which has been used widely as a test of inspiratory muscle strength [16] and has shown excellent reliability in quantifying the degree to which the breathing pattern is fast and shallow [24]. The ultrasound images of diaphragmatic excursions and DTF were obtained using a portable GE LOGIQ E machine with an L8-18I-D probe (5–18 MHz; GE Healthcare) [25,26]. Oxygenation index was defined

Downloaded from http://journals.lww.com/intjrehabilres by BhDMf5ePHKav1zEoum1tQfN4a+kJLhEZgbsIHo4XMi0hCywCX1AWnYQp/IlQrHD3i3D0OdRyi7TvSFl4Cf3VC4/OAVpDDa8KKGKV0Ymy+78= on 05/14/2024

by a ratio between the arterial partial pressure of oxygen and fraction of inspired oxygen (PaO_2/FiO_2), which was evaluated using a gold standard method based on the laboratory benchtop blood gas analyzer GEM premier 3500 (Werfen Group IVD, Barcelona, Spain) [27]. The forced vital capacity (FVC) and forced expiratory volume in 1 s (FEV1) were also measured as common indicators of lung function.

Statistical analysis

All data were presented as mean and SD. The normality of the parameters was tested using the Shapiro–Wilks test. Two-way repeated measurement analysis of variance was used to compare MIP, diaphragmatic excursions, DTF, oxygenation index, and FEV1/FVC between two groups over time. Bonferroni post-hoc tests were conducted to compare specific differences. All statistical analyses were performed by the SPSS 22.0 software. The significance level was set at $P < 0.05$.

Results

A total of 50 patients on intubation and mechanical ventilation were included in the study: 25 allocated to the experimental group and 25 allocated to the control group. One of the patients died, and two were transferred to another center during the study period because of personal reasons. Groups were generally comparable at baseline. Participant characteristics on enrolment are presented in Table 1.

We found a significant group-by-time interaction effect for MIP [$F\ (1, 45) = 17.84$, $\eta^2 = 0.328$, $P < 0.001$] and oxygenation index [$F\ (1, 45) = 5.58$, $\eta^2 = 0.11$, $P = 0.023$]. No significant interaction effects were found for diaphragmatic excursions, DTF, and FEV1/FVC ($P > 0.05$).

For the group factor, significant main effects were only found for MIP [$F\ (1, 45) = 4.55$, $\eta^2 = 0.09$, $P = 0.038$], the combined difference for pre- and post-intervention revealed that the experimental group had a significantly higher MIP (mean difference [MD] = 4.37 cm H_2O, 95%CI 0.25–8.50 cm H_2O, $P = 0.038$) than the control group. No significant main differences were found in other parameters.

For the time factor, a significant difference in MIP [F (1, 45) = 40.06, $\eta^2 = 0.471$, $P < 0.001$], oxygenation index [$F\ (1, 45) = 98.88$, $\eta^2 = 0.687$, $P < 0.001$], and diaphragmatic excursions [$F\ (1, 45) = 37, 28$, $\eta^2 = 0.453$, $P < 0.001$] was found. The combined difference for pre- and post-intervention found that the MIP (MD = 8.84 cm H_2O, 95%CI 6.20–11.48 cm H_2O, $P < 0.001$), oxygenation index (MD = 32.50 mm Hg, 95%CI 22.13–42.87 mm Hg, $P < 0.001$), and diaphragmatic excursions (MD = 0.25 cm, 95%CI 0.11–0.39 cm, $P = 0.002$) in the experimental group were significantly greater than in the control group. No significant difference was found in other parameters (Table 2).

Table 1 **Baseline characteristics of participants**

Characteristic	Control group ($N = 24$)	Experimental group ($N = 23$)
Age (years), mean (SD)	59.7 ± 13.5	63.9 ± 8.3
Sex, *n* (males (%))	16 (67)	13 (57)
Height (cm)	168.4 ± 7.9	167.0 ± 7.1
Weight (kg)	61.5 ± 5.5	61.1 ± 8.9
BMI (kg/m^2)	21.7 ± 1.5	21.8 ± 2.2
Diagnosis, *n* (%)		
Cerebral infarction	8 (33)	9 (39)
Cerebral hemorrhage	7 (29)	7 (30)
Posttraumatic brain injury	5 (21)	2 (9)
Hypoxic-ischemic encephalopathy	2 (8)	1 (4)
Glioma	1 (4)	0 (0)
Spinal cord injury	1 (4)	0 (0)
Pulmonary encephalopathy	0 (0)	2 (9)
Nervous system infection	0 (0)	1 (4)
Guillain-barre syndrome	0 (0)	1 (4)

Discussion

The main finding of the study in neurocritical patients, mainly after a stroke, is that combining PNF and TIMT training resulted in significantly higher MIP when compared with TIMT alone.

MIP is one of the most commonly used indicators of inspiratory muscle strength. Although no significant difference was found in the control group, our experimental group improved significantly after the training. Our results are similar to the recent report indicating that PNF combined with elastic resistance bands showed a significant 72% increase in MIP compared to the control group [28]. Although Areas *et al.* [28] combined the upper extremity PNF with elastic resistance bands, the results suggest that PNF may stimulate the main respiratory muscles (diaphragm and intercostals) and other accessory muscles [16,28]. Notably, our findings are also supported by the results previously reported by Song and Park [29] who demonstrated that chest resistance and chest expansion exercises are effective in improving respiratory function. PNF techniques may increase air entry and facilitate secretion in tracheotomy patients. Thus, PNF could act as lung expansion therapy for neurological ICU patients with reduced respiratory muscle strength [30,31].

Oxygenation index can serve as an indicator of lung ventilation in neurocritical patients with weaning failure. The results demonstrated that the oxygenation function considerably improved in both groups after combined PNF and TIMT training. Further, the results show that the control group started with lower oxygenation index and improved more than the experimental group, which may indicate that patients with poorer respiratory function could benefit more after training.

As suggested by previous study, Morales *et al.* [32] applied PNF to the hemiplegic arm and reported an increase in contralateral irradiation of muscle activity. PNF training

Downloaded from http://journals.lww.com/intjrehabilres by BhDMf5ePHKav1zEoum1tQfN4a+kJLhEZgbsIHo4XMi0hCywCX1AWnYQp/IlQrHD3i3D0OdRyi7TvSFl4Cf3VC4/OAVpDDa8KKGKV0Ymy+78= on 05/14/2024

Table 2 **Effects of proprioceptive neuromuscular facilitation on respiratory function in neurocritical patients with weaning failure**

				P-value		
		Experimental groups	Control group	Interaction	Group	Time
MIP	Pre	19.39 (7.73)	18.55 (6.52)	**<0.001**	**0.038**	**<0.001**
	Post	28.23 (8.9)	20.32 (7.04)			
	Post-Pre	8.83 (6.1)	1.76 (5.36)			
	$95\%_{Post-Pre}$	(6.19–11.48)	(-0.50–4.02)			
Oxygenation index	Pre	174.95 (34.82)	147.58 (29.26)	**0.023**	0.057	**<0.001**
	Post	207.45 (34.68)	200.33 (35.51)			
	Post-Pre	32.49 (23.98)	52.75 (33.74)			
	$95\%_{Post-Pre}$	(22.12–42.87)	(38.50–67.00)			
Diaphragmatic excursions	Pre	1.22 (0.43)	1.10 (0.31)	0.476	0.380	**<0.001**
	Post	1.47 (0.37)	1.42 (0.31)			
	Post-Pre	0.24 (0.33)	0.31 (0.30)			
	$95\%_{Post-Pre}$	(0.1–0.39)	(0.18–0.44)			
DTF	Pre	21.10 (4.16)	20.72 (4.35)	0.528	0.992	0.054
	Post	21.87 (4.35)	22.22 (4.20)			
	Post-Pre	0.76 (3.3)	1.49 (4.45)			
	$95\%_{Post-Pre}$	(−0.65–2.19)	(−0.38–3.38)			
FEV1/FVC	Pre	52.59 (5.58)	53.18 (6.89)	0.974	0.742	0.070
	Post	54.01 (6.04)	54.54 (6.69)			
	Post-Pre	1.41 (3.82)	1.36 (6.13)			
	$95\%_{Post-Pre}$	(−0.23–3.06)	(−1.22–3.95)			

Values are expressed as a mean (SD); significant differences ($P < 0.05$) are highlighted in bold for interaction effect, group effect, and time effect.
DTF, diaphragm thickening fraction; FEV1/FVC, forced expiratory volume in 1 s/forced vital capacity; MIP, maximum inspiratory pressure.

in the experiment group could have helped the patients increase activity in the respiratory muscles, bilaterally. Therefore, we believe PNF training is a viable alternative directed at accessory respiratory muscles, which can improve lung ventilation and tissue oxygenation, especially in stroke survivors.

The diaphragm is the primary muscle involved in respiration, and its dysfunction is an important risk factor for respiratory difficulties [33,34]. Although DTF has been found a predictor of the weaning outcome [35], our results suggest no effect of PNF training on diaphragmatic excursions. The reason may be that PNF mainly stimulates proprioceptive receptors in the thoracic and abdominal muscles and less so in the diaphragm. Considering that the effects of PNF on respiratory function are underexplored, more studies are needed [36].

A marked decrease in lung capacity and a considerable increase in lung residual capacity are often observed in neurocritical patients with weaning failure. However, we did not find a significant difference in FEV1 or FVC between the two groups. Kim and Lee [37] demonstrated that FEV1 improved more considerably after 6 weeks of PNF training in chronic low back pain patients. These discrepancies may be explained by our recruitment of neurocritical patients mainly after stroke who were in poor physical condition and more prone to fatigue. Also, the patients were only given the training for 5 days. We suspect that 5 days were too short to increase expiratory volume in mechanically ventilated patients.

The present study has several limitations. First, the same nonblinded investigator performed all treatments and assessments, which may have introduced bias. The TIMT was given according to the standardized protocol; however, the assessment of MIP is not as prone to the assessor bias. Second, because the time patients spend in the ICU is usually short, we limited PNF to only 5 days. Third, no follow-up was performed, and thus the long-term effects are unknown. Thus, future studies should incorporate other ventilatory parameters and examine the long-term effects of PNF on ventilatory responses in patients with weaning failure.

Conclusion

The present study demonstrated the value of combining PNF with TIMT for improving respiratory function in neurocritical patients with weaning failure. PNF training can improve MIP and oxygenation index, which may be an effective strategy to reverse residual inspiratory muscle weakness by stimulating active breathing. Therefore, this combination approach may increase the likelihood of survival of neurocritical patients in the ICU.

Acknowledgements

We thank the affiliated Jiangning Hospital of Nanjing Medical University, and particularly the patients and families who participated in this study.

This study was supported by the Project of science and technology benefits the people program of Jiangning (2023087S).

Q.Z. contributed to the methodology, validation, formal analysis, investigation, resources, data curation, writing – original draft, writing – review and editing, and project administration. Y.Z. contributed to the methodology, validation, investigation, resources, data curation, writing – original draft, writing – review and editing, and project administration. W.Y. contributed to the methodology, validation, resources, data curation, investigation, and writing – review and editing. S.L. contributed to the

Downloaded from http://journals.lww.com/intjrehabilres by BhDMf5ePHKav1zEoum1tQfN4a+kJLhEZgbsIHo4XMi0hCywCX1AWnYQp/IlQrHD3i3D0OdRyi7TvSFl4Cf3VC4/OAVpDDa8KKGKV0Ymy+78= on 05/14/2024

validation, resources, and writing – review and editing. H.F. contributed to the validation, resources, and writing – review and editing. H.P. contributed to the conceptualization, methodology, validation, formal analysis, investigation, resources, writing – review and editing, and project administration.

The original contributions presented in the study are included in the article, and further inquiries can be directed to the corresponding author.

Conflicts of interest

There are no conflicts of interest.

References

1 Coplin WM, Pierson DJ, Cooley KD, Newell DW, Rubenfeld GD. Implications of extubation delay in brain-injured patients meeting standard weaning criteria. *Am J Respir Crit Care Med* 2000; **161**:1530–1536.

2 da Silva AR, Novais MCM, Neto MG, Correia HF. Predictors of extubation failure in neurocritical patients: a systematic review. *Aust Crit Care* 2023; **36**:285–291.

3 Barbas CS, Ísola, AM, Farias, AM, Cavalcanti, AB, Gama, AM, Duarte, AC, *et al*. Brazilian recommendations of mechanical ventilation 2013. Part 2. *J Bras Pneumol* 2014; **40**:458–486.

4 Bissett B, Leditschke IA, Green M, Marzano V, Collins S, Van Haren F. Inspiratory muscle training for intensive care patients: a multidisciplinary practical guide for clinicians. *Aust Crit Care* 2019; **32**:249–255.

5 Medrinal C, Prieur G, Frenoy E, Robledo Quesada A, Poncet A, Bonnevie T, *et al*. Respiratory weakness after mechanical ventilation is associated with one-year mortality – a prospective study. *Crit Care* 2016; **20**:231.

6 Elkins M, Dentice R. Inspiratory muscle training facilitates weaning from mechanical ventilation among patients in the intensive care unit: a systematic review. *J Physiother* 2015; **61**:125–134.

7 Khodabandeloo F, Froutan R, Yazdi AP, Shakeri MT, Mazlom SR, Moghaddam AB. The effect of threshold inspiratory muscle training on the duration of weaning in intensive care unit-admitted patients: a randomized clinical trial. *J Res Med Sci* 2023; **28**:44.

8 Moodie LH, Reeve JC, Vermeulen N, Elkins MR. Inspiratory muscle training to facilitate weaning from mechanical ventilation: protocol for a systematic review. *Bmc Res Notes* 2011; **4**:283.

9 Bissett BM, Leditschke IA, Neeman T, Green M, Marzano V, Erwin K, *et al*. Does mechanical threshold inspiratory muscle training promote recovery and improve outcomes in patients who are ventilator-dependent in the intensive care unit? The IMPROVE randomised trial. *Aust Crit Care* 2023; **36**:613–621.

10 Liu K, Yu X, Cui X, Su Y, Sun L, Yang J, *et al*. Effects of proprioceptive neuromuscular facilitation stretching combined with aerobic training on pulmonary function in COPD patients: a randomized controlled trial. *Int J Chron Obstruct Pulmon Dis* 2021; **16**:969–977.

11 Zwoliński T, Wujtewicz M, Szamotulska J, Sinoracki T, Wąż P, Hansdorfer-Korzon R, *et al*. Feasibility of chest wall and diaphragm proprioceptive neuromuscular facilitation (PNF) techniques in mechanically ventilated patients. *Int J Environ Res Public Health* 2022; **19**:960.

12 Beckers DB. *PNF in practice: an illustrated guide*. 5th ed. Springer; 2021. pp. 37–57.

13 Hindle KB, Whitcomb TJ, Briggs WO, Hong J. Proprioceptive neuromuscular facilitation (PNF): its mechanisms and effects on range of motion and muscular function. *J Hum Kinet* 2012; **31**:105–113.

14 Seo K, Cho M. The effects on the pulmonary function of normal adults proprioceptive neuromuscular facilitation respiration pattern exercise. *J Phys Ther Sci* 2014; **26**:1579–1582.

15 Slupska L, Halski T, Żytkiewicz M, Ptaszkowski K, Dymarek R, Taradaj J, *et al*. Proprioceptive neuromuscular facilitation for accessory respiratory muscles training in patients after ischemic stroke. *Adv Exp Med Biol* 2019; **1160**:81–91.

16 Cader SA, Vale RG, Castro JC, Bacelar SC, Biehl C, Gomes MC, *et al*. Inspiratory muscle training improves maximal inspiratory pressure and may assist weaning in older intubated patients: a randomised trial. *J Physiother* 2010; **56**:171–177.

17 Chang AT, Boots RJ, Brown MG, Paratz J, Hodges PW. Reduced inspiratory muscle endurance following successful weaning from prolonged mechanical ventilation. *Chest* 2005; **128**:553–559.

18 de Souza RJP, Brandão DC, Martins JV, Fernandes J, Dornelas de Andrade A. Addition of proprioceptive neuromuscular facilitation to cardiorespiratory training in patients poststroke: study protocol for a randomized controlled trial. *Trials* 2020; **21**:184.

19 Liu JF, Kuo NY, Fang TP, Chen JO, Lu HI, Lin HL. A six-week inspiratory muscle training and aerobic exercise improves respiratory muscle strength and exercise capacity in lung cancer patients after video-assisted thoracoscopic surgery: a randomized controlled trial. *Clin Rehabil* 2021; **35**:840–850.

20 Bissett B, Gosselink R, van Haren FMP. Respiratory muscle rehabilitation in patients with prolonged mechanical ventilation: a targeted approach. *Crit Care* 2020; **24**:103.

21 Shimizu JM, Manzano RM, Quite´ rio RJ, Alegria VTC, Junqueira TT, El-Fakhouri S. Determinant factors for mortality of patients receiving mechanical ventilation and effects of a protocol muscle training in weaning. *Man Ther Posturology Rehabil J* 2014; **12**:136–142.

22 Caruso P, Denari SD, Ruiz SA, Bernal KG, Manfrin GM, Friedrich C, *et al*. Inspiratory muscle training is ineffective in mechanically ventilated critically ill patients. *Clinics (Sao Paulo, Brazil)* 2005; **60**:479–484.

23 Marek SM, Cramer JT, Fincher AL, Massey LL, Dangelmaier SM, Purkayastha S, *et al*. Acute effects of static and proprioceptive neuromuscular facilitation stretching on muscle strength and power output. *J Athl Train* 2005; **40**:94–103.

24 Lee KB, Kim MK, Jeong JR, Lee WH. Reliability of an electronic inspiratory loading device for assessing pulmonary function in post-stroke patients. *Med Sci Monit* 2016; **22**:191–196.

25 Le Neindre A, Philippart F, Luperto M, Wormser J, Morel-Sapene J, Aho SL, *et al*. Diagnostic accuracy of diaphragm ultrasound to predict weaning outcome: a systematic review and meta-analysis. *Int J Nurs Stud* 2021; **117**:103890.

26 Bandari E, Beuzen T, Habashy L, Raza J, Yang X, Kapeluto J, *et al*. Machine learning decision support for detecting lipohypertrophy with bedside ultrasound: proof-of-concept study. *JMIR formative research* 2022; **6**:e34830.

27 Suzuki K, Kondo N, Takagi K, Nishikawa A, Murakami Y, Otsuka M, *et al*. Validation of the bovine blood calcium checker as a rapid and simple measuring tool for the ionized calcium concentration in cattle. *J Vet Med Sci* 2021; **83**:767–774.

28 Areas GP, Borghi-Silva A, Lobato AN, Silva AA, Freire RC, Areas FZ. Effect of upper extremity proprioceptive neuromuscular facilitation combined with elastic resistance bands on respiratory muscle strength: a randomized controlled trial. *Braz J Phys Ther* 2013; **17**:541–546.

29 Song GB, Park EC. Effects of chest resistance exercise and chest expansion exercise on stroke patients' respiratory function and trunk control ability. *J Phys Ther Sci* 2015; **27**:1655–1658.

30 Ersson U, Carlson H, Mellström A, Pontén U, Hedstrand U, Jakobsson S. Observations on intracranial dynamics during respiratory physiotherapy in unconscious neurosurgical patients. *Acta Anaesthesiol Scand* 1990; **34**:99–103.

31 Bhat A, Chakravarthy K, Rao BK. Chest physiotherapy techniques in neurological intensive care units of India: a survey. *Indian J Crit Care Med* 2014; **18**:363–368.

32 Morales MB, Carvalho GA, Gomes EB. Análise eletromiográfica dos efeitos contralaterais da facilitação neuromuscular proprioceptiva. *Fisioter Bras* 2003; **4**:417–421.

33 Nason LK, Walker CM, McNeeley MF, Burivong W, Fligner CL, Godwin JD. Imaging of the diaphragm: anatomy and function. *Radiographics* 2012; **32**:E51–E70.

34 Goligher EC, Dres M, Fan E, Rubenfeld GD, Scales DC, Herridge MS, *et al*. Mechanical ventilation-induced diaphragm atrophy strongly impacts clinical outcomes. *Am J Respir Crit Care Med* 2018; **197**:204–213.

35 Mahmoodpoor A, Fouladi S, Ramouz A, Shadvar K, Ostadi Z, Soleimanpour H. Diaphragm ultrasound to predict weaning outcome: systematic review and meta-analysis. *Anaesthesiol Intensive Ther* 2022; **54**:164–174.

36 Cheng YY, Lin SY, Hsu CY, Fu PK. Respiratory muscle training can improve cognition, lung function, and diaphragmatic thickness fraction in male and non-obese patients with chronic obstructive pulmonary disease: a prospective study. *J Pers Med* 2022; **12**:475.

37 Kim BR, Lee HJ. Effects of proprioceptive neuromuscular facilitation-based abdominal muscle strengthening training on pulmonary function, pain, and functional disability index in chronic low back pain patients. *J Exerc Rehabil* 2017; **13**:486–490.