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Diaphragmatic mobility in children with spastic cerebral palsy and differing motor performance levels

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ABSTRACT

The aim of this study was to compare diaphragmatic mobility (DM) and respiratory function between children with cerebral palsy (CP) and healthy controls (HC). CP was divided into non-ambulatory CP (NACP) and ambulatory CP (ACP). Eighteen children with NACP, 18 with ACP and 18 HC age between 8 and 18 years were recruited. Ultrasound was used to measure DM on both sides. Respiratory muscle strength (RMS), pulmonary function (PF) and chest expansion (CE) were also measured. The results showed that there was significantly lower right DM in CP than HC group. The NACP group had significantly lower DM than the ACP group. There were also significantly lower values of RMS, PF and CE in CP, compared to the HC group. There are significant impairments of diaphragmatic and respiratory function in CP, relative to HC. Thus, appropriate interventions to improve diaphragmatic muscle strength are necessary for children with CP, especially in the NACP.

1. Introduction

Spastic cerebral palsy is the most common type of movement disorder, occurring in around 75% of all cases of CP (Beaman et al., 2015). It is defined as “hypertonia in which resistance to passive movement increases with increasing velocity of movement” (Rethlefsen et al., 2010), and is characterized by muscle stiffness and awkward movements. This affects balance and movement, and hence the activities of daily life (Saether et al., 2013).

Based on the Gross *Motor* Function Classification System (GMFCS), CP can be categorized into five levels (where Level I is the least severe and Level V is the most), according to the individual’s *Motor* performance limitations (Palisano et al., 1997; Palisano et al., 2007). However, some authors divide these into just two types, namely ambulatory CP (Level I to III) and non-ambulatory CP (Level IV and V). Children with ambulatory CP can walk with or without assistive devices, but may be limited in walking outdoors and in the community, while those with non-ambulatory CP need to be transported by powered mobility aids or manual wheelchairs, and spend most of their time in a sitting position (Palisano et al., 2007). The severity of abnormal muscle tone, postural control and muscle weakness are also greater in non-ambulatory CP (Palisano et al., 2007).

The main cause of muscle weakness in CP is damage to the primary *Motor* cortex and corticospinal tract (Beaman et al., 2015). There are also variations in muscle fibers with a decrease in sarcomeres resulting in decreased energy for muscle contractions (Givon, 2009; Saether et al., 2013). Most of the muscle weakness in CP is apparent in the postural control muscles such as the head, neck, trunk and abdominal muscles (Massery, 1991; Massery, 2006). These postural control muscles, especially in the trunk and abdomen, are the main muscles affecting the mechanism of respiration (Massery, 2006). Poor trunk control affects the alignment of the ribcage, which is attached to the thoracic vertebrae, leading to limited ribcage movements in both lateral and anterior–posterior expansions (Beaman et al., 2015). In the presence of poor trunk control, the diaphragm is also forced to work harder to regulate the pressure between the thoracic and abdominal cavities, leading to fatigue of the diaphragm (Hodges and Gandevia, 2000). Abdominal muscle weakness also results in an abnormally low

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diaphragmatic resting position, leading to ineffective diaphragmatic contraction and hence insufficient inspiration (Massery, 2012). However, the primary cause of limited diaphragm movement in CP is damage to the central nervous system, such as the phrenic motoneurones, *Motor* cortex, postural control center and respiratory center. Such damage results in a decrease in automatic stimulating impulses to diaphragmatic muscle fibers and hence paralyzed or weak diaphragm (Givon, 2009; Hodges and Gandevia, 2000; Aisen et al., 2011; Heyrman et al., 2013; Shin et al., 2015; Gandevia et al., 2002). It is hypothesized that this abnormal position and weakness of the diaphragm limits its movement in CP. A previous study has reported that there are decreases in chest wall mobility and pulmonary function in children with CP, when compared with healthy controls (Ersöz et al., 2006). Park and colleagues also reported that upper and lower chest ratio in children with CP is lower than in normal children, due to chest wall deformity (Park et al., 2006). Moreover, previous studies have indicated that respiratory function among children with CP was reduced because of insufficient respiratory muscle strength and limited chest wall expansion, when compared to children with normal development (Wang et al., 2012; Kwon and Lee, 2013; Kwon and Lee, 2015). Although the diaphragm is the main muscle of inspiration, there is only one recent publication reporting diaphragmatic function in CP with different degrees of *Motor* performance (Kwon and Kim, 2018). However, this study examined diaphragmatic movement only on the side of the dominant arm among ambulatory CP but not in non-ambulatory CP and healthy children.

The function of the diaphragm can be assessed by its mobility during inspiration and expiration (American Thoracic Society/European Respiratory Society., 2002). There are many methods to detect diaphragmatic mobility, such as fluoroscopy, lower chest expansion, respiratory muscle strength, spirometry and ultrasound (American Thoracic Society/European Respiratory Society., 2002; Boussuges et al., 2009). Traditionally, physicians detect diaphragmatic mobility by fluoroscopy. Although this is a standard imaging technique for evaluating the position and movement of the diaphragm, it has some limitations. The patients have to be exposed to ionizing radiation, which increases their risk of radiation-induced cancer. There are also some complications, ranging from erythema to more serious burns (Houston et al., 1995). Measurements of lower chest expansion, respiratory muscle strength and spirometry are indirect methods to indicate diaphragmatic function (Ersöz et al., 2006; Domènech-Clar et al.2003) and also reflect the function of other respiratory muscles such as abdominal, intercostal and accessory respiratory muscles (Wang et al., 2012)

Ultrasound (US) has been used to evaluate the function of many important internal organs such as the heart, kidneys and liver (Barnett et al., 2000). It is non-invasive, involves no exposure to ionizing radiation and can be used at the bedside (Matamis et al., 2013; Boussuges et al., 2009). Moreover, the data from US can be stored for later analysis. Thus, ultrasound is an appropriate tool to measure the movement of the diaphragm. There are some studies which have applied US to detect diaphragmatic mobility in healthy people (Kantarci et al., 2004; Boussuges et al., 2009; Testa et al., 2011), in various pulmonary diseases (Epelman et al., 2005) and in stroke patients (Jung et al., 2014). However, there is only one recent publication which reported diaphragmatic mobility among children with ambulatory CP using US, but with no comparison with healthy controls or non-ambulatory CP (Kwon and Kim, 2018). Ultrasound presents significant advantages when applied to patients with CP. The main advantage is the ease with which it can be applied, requiring little coordination from the patient. This is in contrast to other techniques that require much more involvement and coordination from the patient – even pulmonary function testing or spirometry, the gold standard of lung function measurement, requires coordinated breathing maneuvers that are difficult for patients with CP, especially children, to achieve.

Thus, the aim of this study is to compare diaphragmatic function, measured by ultrasound, respiratory muscle strength, pulmonary function and chest expansion, between children with CP at different severities of *Motor* performance impairment and healthy controls. This will reveal whether there is a decrease in diaphragmatic movement in children with CP and different severities of *Motor* impairment. Quantitative assessment of diaphragmatic mobility using ultrasound would allow clinicians to measure the effectiveness of any treatment regime and to make changes if the results showed that there was insufficient improvement, thus ensuring that the most appropriate interventions are applied.

2. Materials and methods

2.1. Participants

A convenience sample of children with CP was recruited from Sri Sangvalya Khon Kaen School, which is a special school for CP. Healthy children were recruited from other schools in Khon Kaen province. Inclusion criteria for both CP and healthy controls were children aged between 8 and 18 years, who were willing to participate in the study. Inclusion criteria for the CP groups were a diagnosis of CP by their doctors from medical history, a GMFCS level I to V assessed by their physical therapists, no comorbidities such as blindness or deafness and the ability to follow the study instructions. Inclusion criteria for healthy controls were no diagnosis of abnormal diaphragmatic function such as phrenic nerve injury from their medical history, no chest wall deformity such as scoliosis, kyphosis from physical examination by the researcher and normal body mass index (18.5-22.99 $kg\,m^{-2}$). Exclusion criteria for CP and healthy controls were any acute or current respiratory infection, other respiratory conditions such as asthma, influenza or common cold and any clinically significant cardiovascular, neurological, renal, endocrine, gastrointestinal, hepatic or haematological abnormalities which were uncontrolled with standard treatments. The study was approved by the Ethical Committee of Khon Kaen University, Khon Kaen, Thailand. Written informed consent was obtained from each child's parents or caregivers.

2.2. Measurements

2.2.1. Inter- and intra-rater reliability tests

Inter- and intra-rater reliability tests were performed for all measurements. Inter-rater reliability tests were conducted in ten healthy participants (aged between 8 and 18 years), between the researcher who measured the variables and an expert in ultrasound measurement and a respiratory physiotherapist, both with 20 years of experience. Intra-rater reliability tests were also performed for all variables. The results showed a high intra-class correlation coefficient, between 0.94 and 0.95, for both inter and intra-rater reliability tests.

2.2.2. Ultrasound measurement of diaphragmatic mobility

All participants were investigated over two consecutive days, the first day for ultrasound measurement and respiratory muscle strength and the second day for pulmonary function and chest wall expansion. Ultrasound measurements were performed one to two hours after a light meal. M-Mode US (LOGIQ V2, GE Healthcare, Chicago, Illinois, USA) was applied to assess diaphragmatic mobility among the participants. Diaphragmatic mobility was measured with a 4 MHz convex transducer, programmed for a depth of 17 cm with a scan rate of 14 s per screen. The participants were asked to lie on their back with a pillow under their neck and knees for support, with their head up at an angle of 45 °. The US probe was placed below the right costal margin along the mid-clavicular line in the anterior subcostal area, and between the left anterior and mid-axillary lines in the subcostal area (Boussuges et al., 2009; Jung et al., 2014; Fig. 1). The diaphragmatic movements were measured and recorded during six deep breathing cycles per participant per attempt. An appropriate rest was given to each participant after taking the measurement on each side. The best

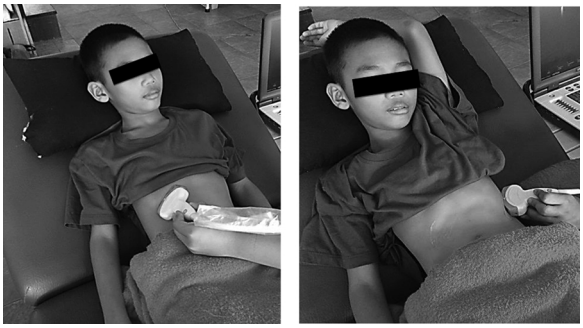

Fig. 1. Position of ultrasound probe.

results (the highest value recorded from three attempts) were used for data analysis (Testa et al., 2011).

2.2.3. Respiratory muscles strength

Participants were taught to perform inspiratory and expiratory muscle strength testing, following American Thoracic Society/ European Respiratory Society (ATS/ERS) guidelines (ATS/ERS, 2002). Briefly, they sat on a comfortable chair and wore a mouthpiece attached to a portable respiratory muscle testing machine (MicroRPM, CareFusion, San Diego, California, USA) and nasal clips. To measure the maximum inspiratory pressure (MIP), participants were asked to breathe out as much as they could and then breathe in as deeply and quickly as they could, followed by breath-hold for two seconds during which the pressure generated was recorded from the machine. To measure the maximum expiratory pressure (MEP), participants were asked to breathe in as much as they could and then breathe out as deeply and quickly as they could, followed by breath-hold for two seconds during which the pressure generated was recorded from the machine. This procedure was repeated three times for each of MIP and MEP, with five minutes to rest between each set, and the best results (highest value recorded from three attempts) were used for data analysis. This process took around 30 minutes per participant.

2.2.4. Pulmonary function test

A portable spirometer (Pony FX, Cosmed, Rome, Italy) was used for measuring pulmonary function, following ATS/ERS guidelines (ATS/ ERS, 2002). Participants sat on a chair with a backrest and wore a mouth piece and nasal clip. They were instructed to breathe out as much as possible through the mouthpiece and then breathe in deeply as much as possible and breathe out again as much and as quickly as possible, with maximum force, followed by a six-second breath-hold. After that, they relaxed with normal breathing. They repeated this three times, with one minute to rest between each set, and the assessment took around 30 minutes per person. The best value (highest value recorded from three attempts) was used for data analysis and the values of FVC, FEV_1 and FEV_1/ FVC, FVC percentage predicted (FVC%pp) and FEV_1 percentage predicted (FEV_1%pp) were calculated.

2.2.5. Chest expansion

Chest expansion was measured using a tape measure. Participants sat on a chair without armrests, with their arms resting on their hips. The researcher measured around their bodies at three positions: 1) upper chest, under the armpit mid-sternal line; 2) lower chest, the xiphoid process mid-sternal line; and 3) abdomen, at the umbilical area. They were asked to perform maximum exhalation and hold for three seconds, then perform maximum inhalation and hold for three seconds. They repeated this three times per position, with one minute to rest between each set. The best value (highest value recorded from three attempts) was used for data analysis. This process took around 30 minutes per participant. The researcher measured the circumference of the chest wall during maximum exhalation and maximum inhalation in centimeters. The difference between the inspiratory measurement and expiratory measurement was used to represent chest expansion at each level for data analysis.

2.3. Data analysis

Baseline characteristics such as age, height, weight, body mass index and waist circumference were summarized in terms of their means and standard deviations (SDs). Descriptive statistics were used to describe participant demographics and the findings of the study. The one-way ANOVA with Fisher's LSD post-hoc analysis was used to compare diaphragmatic mobility, respiratory pressure (MIP and MEP), pulmonary function (FEV_1, FVC, FEV_1/FVC, FVC, FVC%pp and FEV_1% pp), and chest expansion between the three groups. Pearson correlation was also used to examine the correlation between right diaphragmatic mobility, left diaphragmatic mobility and pulmonary function (FVC, FVC%pp, FEV_1, and FEV_1%pp) variables among CP. Correlation was interpreted as weak if $r < 0.50$, moderate if r was 0.50 - 0.70 and strong if $r > 0.70$ (Akoglu, 2018). All analyses were performed using SPSS version 20.0 (SPSS, Chicago, Illinois). Statistical significance level was set as $p < 0.05$.

3. Results

3.1. Demographic data

Demographic data for the participants are shown in Table 1. Most of the participants (72%) in the CP groups had spastic diplegia (determined by physical examination by the physiotherapist). The GMFCS was rated between level I and level IV, with no children at level V.

One way ANOVA revealed that there were no statistically significant differences in age, body mass index and waist circumference across the groups (F (2, 51) = 2.14, p = 0.128; (F (2, 51) = 1.47, p = 0.241 and (F (2, 51) = 2.21, p = 0.120, respectively). There were significant differences in height and weight among the three groups ((F (2, 51) = 7.37, p = 0.002 and (F (2, 51) = 4.62, p = 0.014, respectively). Post hoc comparison across the three groups incorporating a Fisher's LSD test showed that children in the healthy control group were taller than those in the non-ambulatory CP group (t (51) = 3.29, p = 0.002) and the ambulatory CP group (t (51) = -3.39, p = 0.001). Children in the healthy control group were also heavier than those in the ambulatory CP group (t (51) = -3.01, p = 0.004).

3.2. Diaphragmatic mobility and respiratory muscle strength

Table 2 shows right and left diaphragmatic mobility, MIP and MEP across the three groups. One-way ANOVA showed that all of these measures demonstrated statistically significant differences between the three groups (F (2, 51) = 31.03, p < 0.001; (F (2, 51) = 15.41, p < 0.001; F (2, 51) = 31.65, p < 0.001 and F (2, 51) = 27.57, p < 0.001). Post hoc comparison across the three groups incorporating a Fisher's LSD test indicated that the right diaphragmatic mobility was lower in the non-ambulatory CP group, when compared with both the ambulatory CP group (t (51) = 3.96, p < 0.001) and the healthy controls (t (51) = 7.88, p < 0.001). There was also a significantly lower right diaphragmatic mobility in the ambulatory CP group, when compared with the healthy control group (t (51) = -3.95, p < 0.001). There was a significantly lower left-side diaphragmatic mobility among children with non-ambulatory CP, compared with healthy controls (t (51) = 4.97, p < 0.001). The left-side diaphragmatic mobility was also significantly lower in the non-ambulatory CP group, when compared with ambulatory CP (t (51) = 4.40, p < 0.001).

Post-hoc analysis with Fisher's LSD test indicated that there was a significantly higher MIP and MEP in healthy controls than non-ambulatory CP (t (51) = 7.14, p < 0.001; t (51) = 6.94, p < 0.001). MIP and MEP were also lower in ambulatory CP (t (51) = -6.61, p <

Table 1
Demographic data for the participants.

Variable	Non-ambulatory CP (n = 18)	Ambulatory CP (n = 18)	Healthy controls (n = 18)
Age (years)	14.83 ± 2.60	13.06 ± 2.46	13.56 ± 2.90
Gender (M/F) (n; %)	11/7; 39/61%	10/8; 56/44%	10/8; 56/44%
Height (cm)	143.39 ± 9.85*	142.89 ± 11.11*	155.83 ± 13.17
Weight (kg)	40.53 ± 12.12	36.58 ± 7.60*	46.86 ± 10.46
Body mass index ($kg\,m^{-2}$)	19.39 ± 4.34	17.72 ± 1.99	19.05 ± 2.37
Waist circumference (cm)	70.47 ± 10.05	64.25 ± 8.50	67.35 ± 7.96
GMFCS [n (%)]			
I	-	7 (38.89)	-
II	-	4 (22.22)	-
III	-	7 (38.89)	
IV	18 (100)	-	-
Classification [n (%)]			
Diplegia	16 (89)	12 (66.67)	-
Hemiplegia (Right/Left)	-	5 (27.78) (3/2)	-
Quadriplegia	2 (11)	1 (5.55)	-
Chest deformity [n (%)]			
Normal	14 (78)	15 (83)	18 (100)
Funnel chest	4 (22)	3 (17)	-

Abbreviations: CP = Cerebral palsy, M = Male, F = Female, GMFCS = Gross *Motor* Function Classification System, n = number of participants.
* Significantly different from healthy controls (Fisher's LSD test, $p < 0.05$).

0.001; t (34) = -5.75, $p <$ 0.001) when compared with healthy controls. However, there were no significant differences in MIP and MEP between non-ambulatory and ambulatory CP (t (51) = 0.53, $p =$ 0.60; t (34) = 1.19, $p =$ 0.24).

3.3. Pulmonary function and chest expansion

Pulmonary function test and chest expansion data are presented in Table 3. One-way ANOVA showed that there were statistically significant differences in FVC, FVC%pp, FEV_1, FEV_1%pp, FEV_1/FVC and chest expansion at upper chest, lower chest and abdominal level between the three groups (F (2, 51) = 31.89, $p <$ 0.001; F (2, 51) = 27.27, $p <$ 0.001; F (2, 51) = 29.23, $p <$ 0.001; F (2, 51) = 32.23, $p <$ 0.001; F (2, 51) = 3.45, $p =$ 0.039; F (2, 51) = 19.68, $p <$ 0.001; F (2, 51) = 32.35, $p <$ 0.001 and F (2, 51) = 106.74, $p <$ 0.001). Post hoc comparison across the three groups incorporating a Fisher's LSD test showed that the FVC, FVC%pp, FEV_1 and FEV_1%pp were significantly lower in non-ambulatory CP than healthy controls (t (51) = 7.61, $p <$ 0.001; t (34) = 7.38, $p <$ 0.001; t (51) = 7.24, $p <$ 0.001; t (51) = 8.03, $p <$ 0.001;). FVC, FVC%pp, FEV_1, and FEV_1%pp were significantly lower in ambulatory CP than healthy controls (t (51) = -5.90, $p <$ 0.001; t (51) = -3.92, $p <$ 0.001; t (51) = -5.75, $p <$ 0.001 and t (51) = -4.05, $p <$ 0.001). FVC%pp and FEV_1%pp were significantly lower in non-ambulatory CP than ambulatory CP (t (51) = 3.47, $p =$ 0.001 and t (51) = 3.98, $p <$ 0.001). However, there were no significant differences in FVC and FEV_1 between the non-ambulatory and ambulatory CP groups (t (51) = 1.71, $p =$ 0.093 and t (51) = 1.49, $p =$ 0.143 respectively). FEV_1/FVC was significantly lower in non-ambulatory CP than healthy controls (t (51) = 2.47, $p =$ 0.017).

Post-hoc analysis with Fisher's LSD test also revealed that there was a significantly lower chest expansion at upper, lower and abdominal levels among the non-ambulatory CP group than in healthy controls (t (51) = 5.97, $p <$ 0.001; t (51) = 7.57, $p <$ 0.001 and t (51) = 13.81, $p <$ 0.001). The chest expansion at upper, lower, and abdominal levels was also significantly lower in the ambulatory CP group than in healthy controls (t (51) = -4.70, $p <$ 0.001; t (51) = -6.14, $p <$ 0.001 and t (34) = -11.03, $p <$ 0.001). Post-hoc analysis using the Fisher's LSD test also demonstrated that abdominal chest expansion was significantly lower in non-ambulatory CP than ambulatory CP (t (51) = 2.78, $p =$ 0.008). However, there were no significant differences in chest expansion at upper and lower levels between ambulatory and non-ambulatory CP (t (51) = 1.32, $p =$ 0.194 and t (51) = 1.43, $p =$ 0.157).

Table 3
Comparison of pulmonary function and chest expansion data in children with non-ambulatory and ambulatory CP, and healthy controls.

Parameters	Non-ambulatory CP (n = 18)	Ambulatory CP (n = 18)	Healthy controls (n = 18)
FVC (l)	1.44 ± 0.46*	1.70 ± 0.33*	2.59 ± 0.54
FVC (% predicted)	60.28 ± 13.97†,*	68.56 ± 11.48*	86.56 ± 9.04
FEV_1 (l)	1.35 ± 0.43*	1.56 ± 0.28*	2.38 ± 0.53
FEV_1 (% predicted)	60.22 ± 14.57†,*	74.67 ± 9.62*	89.39 ± 7.17
FEV_1/FVC ratio	92.44 ± 4.53	93.22 ± 4.35	96.67 ± 6.30
Chest expansion (cm)			
Upper chest	3.51 ± 0.61*	3.77 ± 0.46*	4.69 ± 0.70
Lower chest	2.92 ± 0.68*	3.24 ± 0.56*	4.64 ± 0.80
Abdominal	2.39 ± 0.74†,*	2.97 ± 0.54*	5.26 ± 0.57

* Significantly different from healthy controls (Fisher's LSD test, $p < 0.05$).
† Significantly different from ambulatory CP (Fisher's LSD test, $p < 0.05$).

Table 2
Comparison of diaphragmatic mobility and respiratory muscle strength in children with non-ambulatory and ambulatory CP, and healthy controls.

Parameters	Non-ambulatory CP (n = 18)	Ambulatory CP (n = 18)	Healthy controls (n = 18)
Right diaphragmatic mobility (mm)	35.14 ± 10.64†,*	46.31 ± 8.06*	57.75 ± 6.37
Left diaphragmatic mobility (mm)	26.57 ± 10.17†,*	37.07 ± 4.25	38.42 ± 5.62
MIP (cmH2O)	37.67 ± 13.03*	40.22 ± 11.99*	71.89 ± 17.50
MEP (cmH2O)	38.89 ± 14.31*	44.83 ± 13.05*	73.50 ± 17.20

* Significantly different from healthy controls (Fisher's LSD test, $p < 0.05$).
† Significantly different from ambulatory CP (Fisher's LSD test, $p < 0.05$).

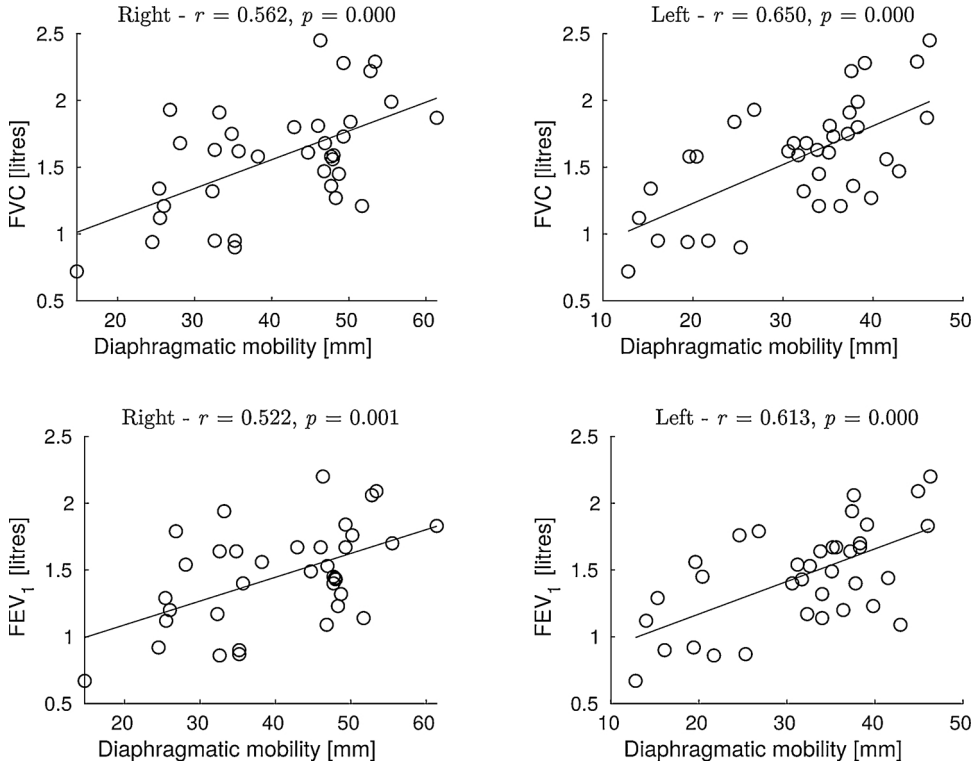

Fig. 2. Correlations between right and left diaphragmatic mobility and FVC and FEV_1.

3.4. Relationships between diaphragmatic mobility and pulmonary function among CP

The results of correlation testing between the diaphragm mobility measurements and pulmonary function testing were shown in Figs. 2 and 3. There were statistically significant, moderate correlations between both right and left diaphragmatic mobility and FVC, FEV_1, FVC% pp and FEV_1%pp.

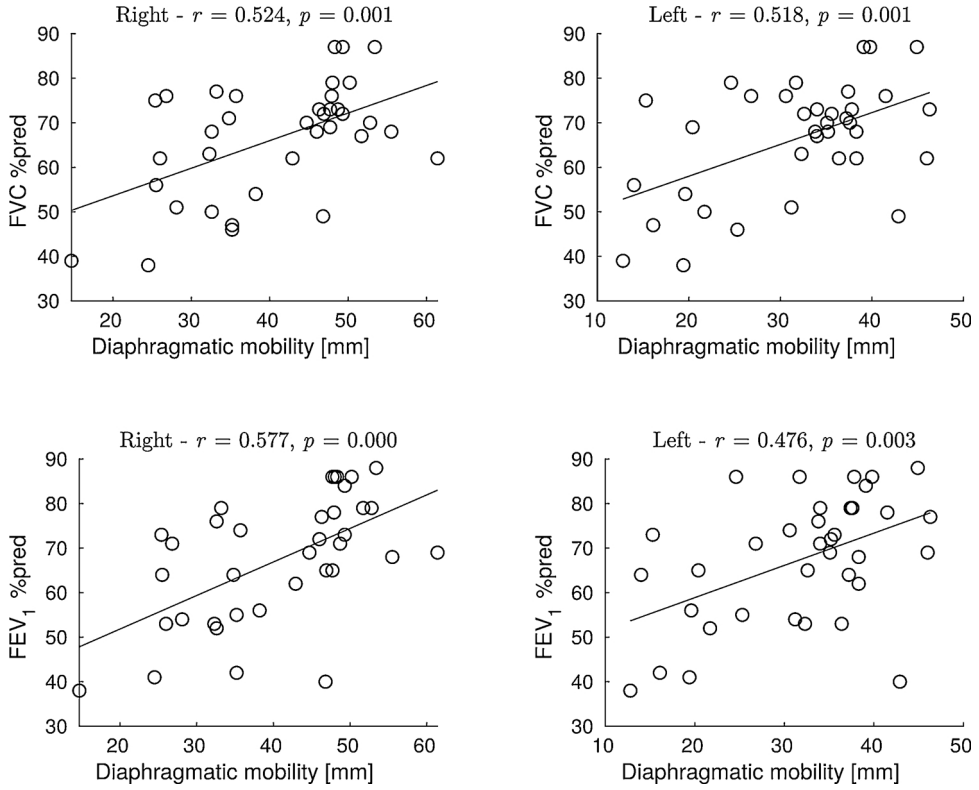

Fig. 3. Correlations between right and left diaphragmatic mobility and FVC% predicted and FEV_1% predicted.

4. Discussion

This study is the first to apply US, which is a reliable technique for detecting DM, among children with CP and to compare children with different levels of *Motor* performance to healthy children. The results showed a significant difference in right-side DM between children with CP and healthy controls. There was also significantly lower DM on both sides among children with non-ambulatory CP, compared with the ambulatory CP group. These results suggested lower diaphragmatic function among CP children, especially in the non-ambulatory group.

A significant difference in diaphragmatic mobility, on both sides, between non-ambulatory CP and ambulatory CP groups can be explained by better postural and trunk control among children with ambulatory CP, leading to better alignment of the diaphragm and hence better mobility. The children in the non-ambulatory group may also have greater impairment of pulmonary function and abdominal muscles than the ambulatory group, due to most of the participants in this group (89%) having spastic diplegia. Previous studies have reported that respiratory muscle strength and pulmonary function in spastic diplegia were lower than in spastic hemiplegia (Know and Lee, 2013; Kwon and Lee, 2015; Shin et al., 2015). This is because of the distribution of abnormalities found in spastic diplegia, which involves both upper and lower extremities, while spastic hemiplegia affects only one half of the body (Damiano et al., 2006; Kwon and Lee, 2013). Another factor is that there is more opportunity to move in the case of ambulatory CP, which may lead to better training of the diaphragmatic muscles to provide sufficient oxygen for muscle contractions. As a result, diaphragmatic muscles may work better than in non-ambulatory CP, where they are more likely to stay in one position. Previous studies have reported a positive relationship between respiratory muscle strength and activity in daily living among children with CP (Wang et al., 2012). Due to the activity of daily living being decreased where the severity of CP is greater (i.e., in non-ambulatory CP), it seems that the diaphragmatic muscle tends to be weaker in this group (Smits et al., 2010).

The difference in DM between the healthy and CP groups can be explained by the following possible factors. First, an abnormal *Motor* cortex and respiratory center, which regulate involuntary respiration or autonomic breathing in CP, results in less input to stimulate diaphragmatic mobility and hence less diaphragmatic movement (Aisen et al., 2011; Heyrman et al., 2013; Shin et al., 2015). Second, diaphragmatic dysfunction also causes reduced feedback to phrenic motoneurons, resulting in a decrease in automatic stimulating impulses to diaphragmatic muscle fibers and hence a paralyzed or weak diaphragm. Consequently, these cause a decrease in the number of sarcomeres in diaphragmatic muscle fibers, leading to insufficient ability to generate force during contraction (Givon, 2009). Third, an impairment of the postural control center causes abnormal postural control, which affects voluntary breathing, making the diaphragm work harder to compensate for the loss of respiratory function, which eventually leads to an overloaded and exhausted diaphragm (Hodges et al., 2001). Fourth, poor trunk control leads to abnormal alignment of the ribcage and diaphragmatic attachment to the ribcage, resulting in an abnormal resting position of the diaphragm and hence less effective contraction and mobility from abnormal mechanics of the ribcage structure (Beaman et al., 2015; Massery, 2012). Moreover, the impairment of peripheral receptor inputs from respiratory muscles, such as the abdominal and intercostal muscles, may also limit the feedback signal to the respiratory centers to control the movement of diaphragm (Hodges and Gandevia, 2000; Gandevia et al., 2002).

The descending corticospinal tract plays an important role in voluntary breathing by the activation of the *Motor* neurons innervating the diaphragm and intercostal muscles during hypoxia, hypercapnia, speaking, singing, movement and response to stressors including defense and emotional reactions (Nogués et al., 2002; Horn and Waldrop, 1998). In CP, there may therefore be impairment of voluntary breathing which is regulated from the higher brain centers such as the cerebral cortex, hypothalamus, amygdala and periaqueductal gray matter of the midbrain, leading to abnormal voluntary breathing control (Nogués et al., 2002; Horn and Waldrop, 1998) and consequently reduced diaphragmatic movement. Stressors such as defense and emotional reactions, including anxiety may therefore also impact on breathing (Nogués et al., 2002; Horn and Waldrop, 1998) and diaphragmatic movement, which could potentially impact the results of this study. These were not specifically controlled for during data collection; however the measurements were made in the physical therapy room of the school. This was an environment that the students were already familiar with, thus minimizing their anxiety.

Our results also showed a decrease in MIP, MEP, FVC, FVC%pp, FEV_1 and FEV_1%pp in the CP children, compared to healthy controls. This can be explained by restrictive lung dysfunction caused by limited movement, and not due to the parenchymal lung dysfunction found in CP (Park et al., 2006; Ersöz et al., 2006; Seddon and Khan, 2003). Trunk and abdominal muscle weakness found in CP also causes abnormal alignment of the ribcage, spine and diaphragm during respiration (Massery, 1991; Massery, 2012), and consequently low lung volume. These results are consistent with those of previous studies in CP (Kwon and Lee 2013; Kwon and Lee, 2014; Kwon and Lee, 2015). In the presence of poor trunk control, the diaphragm is forced to work harder to regulate the pressure between the thoracic and abdominal cavities, leading to fatigue of the diaphragm (Hodges and Gandevia, 2000). Abdominal muscle weakness also causes an abnormally low diaphragmatic resting position, which results in ineffective diaphragmatic contraction and hence low inspiratory volume (Massery, 2012). This result is also consistent with some previous studies in CP (Moerchen, 1994; Massery, 2012; Kwon, 2016). However, there were no significant differences in MIP and MEP between the ambulatory and non-ambulatory CP groups. This may indicate a compensation of intercostal and respiratory accessory muscles in the non-ambulatory group, to generate the change of pressure during a short period of forced inspiration and expiration when they perform the respiratory muscle strength testing (Kwon, 2016).

The moderate correlation between right and left diaphragmatic mobility and FVC, FVC%pp, FEV1 and FEV1%pp in CP can be explained by the fact that the diaphragm is still the main muscle of inspiration and may contribute most of the vital capacity. Therefore during forced inspiration and expiration, the diaphragm would move downward and upward to contribute this volume and this can be measured by its mobility during deep breathing. This result is consistent with previous studies in healthy participants (Houston et al., 1995), stoke patients (Jung et al., 2014) COPD and asthma (Zanforlin et al., 2014). The non-ambulatory CP group also had significantly lower FVC%pp and FEV1%pp when compared with ambulatory CP, which is confirmed by the lower diaphragmatic movement observed in the non-ambulatory CP group compared to the ambulatory CP (Table 2).

There was also a decrease in chest expansion, at all three levels, between children with CP and healthy controls. This can be explained by abnormal chest wall structure, respiratory muscle fatigue and abnormal lung compliance, which are commonly apparent in CP (Park et al., 2006; Massy, 2012). Deformity of the spine and chest wall limits thoracic and ribcage expansion, which is a cause of respiratory muscle weakness in children with CP (Moerchen, 1994). The children with CP also present abdominal and trunk muscle weakness, leading to limited chest expansion in both the lateral and anterior–posterior axes (Ersöz et al., 2006; Beaman et al., 2015; Kwon, 2016). The abnormal lung compliance also induces rapid shallow breathing patterns, due to increased elastic recoil of respiratory muscles, which consequently leads to a decrease in chest wall expansion (Park et al., 2006). The results from this study also demonstrated a significantly lower abdominal expansion in non-ambulatory CP when compared with ambulatory CP. Since abdominal expansion is the primary function of the diaphragm, this finding means that diaphragm muscles in non-ambulatory CP were

weaker than in ambulatory CP. This was also supported by a lower diaphragmatic mobility measured using US among non-ambulatory CP children, when compared with the ambulatory CP group. The values of chest expansion in this study were also consistent with previously reported data from children with CP at a similar age (Ersöz et al., 2006; Kwon and Lee, 2013).

5. Conclusion

This study was the first to look at diaphragmatic mobility in children with CP across different levels of *Motor* performance impairment and to compare with healthy controls. Children with ambulatory CP had greater diaphragmatic mobility than non-ambulatory CP. Both ambulatory and non-ambulatory CP had lower diaphragmatic mobility compared to healthy controls. Abdominal expansion was lower in non-ambulatory CP compared with ambulatory CP and healthy controls.Children with ambulatory CP seem to have better respiratory function than those with non-ambulatory CP due to having better diaphragmatic function, which was confirmed using ultrasound measurements. Therefore, diaphragmatic muscle rehabilitation should be considered for children with cerebral palsy, especially those in the non-ambulatory group.

6. Study limitations

This study has a few limitations that need to be acknowledged. Firstly, most of the participants with CP had spastic diplegia, making it difficult to generalize to the other types of CP. However, as spastic diplegia is the most common type of CP, our results could represent respiratory impairment among CP. Secondly, this study did not examine abdominal and trunk muscle strength, which affects the function of the diaphragm, and future studies, should consider measuring these variables. Thirdly, a different definition of ambulatory CP is used in this study, compared to some previous studies, which may affect the results. Kwon and colleague (Kwon et al., 2013) defined GMFCS level III as non-ambulatory CP, while this study defined this as ambulatory CP. However, the current study followed the definition of GMFCS by Palisano and colleagues in 2007 (Palisano et al., 2007), which was a better evaluation of disability level in children and adolescents with CP, who were the participants in this study.

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Conflict of interest

The Authors declared that there is no conflict of interest.

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References

Akoglu, H., 2018. User's guide to correlation coefficients. Turkish Journal of Emergency Medicine. 18, 91–93.
Aisen, M.L., Kerkovich, D., Mast, J., Mulroy, S., Wren, T.A., Kay, R.M., Rethlefsen, S.A., 2011. Cerebral palsy: clinical care and neurological rehabilitation. Lancet Neurol. 10, 844–852.
American Thoracic Society/European Respiratory Society, 2002. ATS/ERS statement on respiratory muscle testing. Am J Respir Crit Care Med. 166, 518–624.
Barnett, S.B., Ter Haar, G.R., Ziskin, M.C., Rott, H.D., Duck, F.A., Maeda, K., 2000. International recommendations and guidelines for the safe use of diagnostic ultrasound in medicine. Ultrasound Med Biol. 26, 355–366.
Beaman, J., Kalisperis, F.R., Miller-Skomorucha, K., 2015. The infant and child with cerebral palsy. In: Tecklin, J.S. (Ed.), Pediatric Physical Therapy. Lippincott Williams & Wilkins., Philadelphia, pp. 187–246.
Boussuges, A., Gole, Y., Blanc, P., 2009. Diaphragmatic motion studied by m-mode ultrasonography: methods, reproducibility, and normal values. Chest. 135, 391–400.
Damiano, D., Abel, M., Romness, M., Oeffinger, D., Tylkowski, C., Gorton, G., Bagley, A., Nicholas, D., Bornes, D., Calmes, J., Kryscio, R., Roger, S., 2006. Comparing functional profiles of children with hemiplegic and diplegic cerebral palsy in GMFCS Levels I and II: are separate classifications needed? Dev Med Child Neurol. 48, 797–803.
Domènech-Clar, R., López-Andreu, J.A., Compte-Torrero, L., De Diego-Damiá, D., Macián-Gisbert, V., Perpiñá-Tordera, M., RoquésSerradilla, J.M., 2003. Maximal static respiratory pressures in children and adolescents. Pediatr Pulmonol. 35, 126–132.
Epelman, M., Navarro, O.M., Daneman, A., Miller, S.F., 2005. M-mode sonography of diaphragmatic motion: description of technique and experience in 278 pediatric patients. Pediatr Radiol. 35, 661–667.
Ersöz, M., Selcuk, B., Gündüz, R., Kurtaran, A., Akyüz, M., 2006. Decreased chest mobility in children with spastic cerebral palsy. Turk J Pediatr. 48, 344–350.
Gandevia, S.C., Butler, J.E., Hodges, P.W., Taylor, J.L., 2002. Balancing acts: respiratory sensations, motor control and human posture. Clin Exp Pharmacol Physiol. 29, 118–121.
Givon, U., 2009. Muscle weakness in cerebral palsy. Acta orthopaedica et traumatologica turcica 43, 87–93.
Heyrman, L., Desloovere, K., Molenaers, G., Verheyden, G., Klingels, K., Monbaliu, E., Fey, H., 2013. Clinical characteristics of impaired trunk control in children with spastic cerebral palsy. Res Dev Disabil. 34, 327–334.
Hodges, P.W., Gandevia, S.C., 2000. Changes in intra-abdominal pressure during postural and respiratory activation of the human diaphragm. J Appl Physiol. 89, 967–976.
Hodges, P.W., Heijnen, I., Gandevia, S.C., 2001. Postural activity of the diaphragm is reduced in humans when respiratory demand increases. J Physiol. 537, 999–1008.
Horn, E.M., Waldrop, T.G., 1998. Suprapontine control of respiration. Respiration Physiology. 114, 201–211.
Houston, J.G., Fleet, M., Cowan, M.D., McMillan, N.C., 1995. Comparison of ultrasound with fluoroscopy in the assessment of suspected hemidiaphragmatic movement abnormality. Clin Radiol. 50, 95–98.
Jung, K.J., Park, J.Y., Hwang, D.W., Kim, J.H., Kim, J.H., 2014. Ultrasonographic diaphragmatic motion analysis and its correlation with pulmonary function in hemiplegic stroke patients. Ann Rehabil Med. 38, 29–37.
Kantarci, F., Mihmanli, I., Demirel, M.K., Harmanci, K., Akman, C., Aydogan, F., Mihmanli, A., Uysal, O., 2004. Normal diaphragmatic motion and the effects of body composition determination with M-mode sonography. J Ultrasound Med. 23, 255–260.
Kwon, Y.H., Kim, B.J., 2018. Correlation between the dimensions of diaphragm movement, respiratory functions and pressures in accordance with the gross motor classification system levels in children with cerebral palsy. Journal of Exercise Rehabilitation. 4, 998–1004.
Kwon, Y.H., Lee, H.Y., 2013. Differences of the truncal expansion and respiratory function between children with spastic diplegic and hemiplegic cerebral palsy. J Phys Ther Sci. 25, 1633–1635.
Kwon, Y.H., Lee, H.Y., 2015. Differences in respiratory pressure and pulmonary function among children with spastic diplegic and hemiplegic cerebral palsy in comparison with normal controls. J Phys Ther Sci. 27, 401–403.
Kwon, Y.H., Lee, H.Y., 2014. Differences of respiratory function according to level of the gross motor function classification system in children with cerebral palsy. J Phys Ther Sci. 26, 389–391.

Kwon, T.G., Yi, S.H., Kim, T.W., Chang, H.J., Kwon, J.Y., 2013. Relationship between gross motor function and daily functional skill in children with cerebral palsy. Ann Rehabil Med. 37, 41–49.
Kwon, H.Y., 2016. Comparison of differences in respiratory function and pressure as a predominant abnormal movement of children with cerebral palsy. J. Phys Ther Sci. 29, 261–265.
Massery, M., 1991. Chest development as a component of normal motor development: implications for pediatric physical therapists. Ped Phys Ther. 3, 3–8.
Massery, M., 2012. Multisystem consequences of impaired breathing mechanics and/or postural control. In: Frownfalter, D., Dean, E. (Eds.), Cardiovascular and Pulmonary Physical Therapy: Evidence to Practice. Mosby Inc., St. Louis, pp. 633–653.
Massery, M., 2006. Multisystem consequences of impaired breathing mechanics and/or postural control. In: Frownfalter, D., Dean, E. (Eds.), Cardiovascular and Pulmonary Physical Therapy: Evidence to Practice. Elsevier Health Sciences., St. Louis, pp. 695–717.
Matamis, D., Soilemezi, E., Tsagourias, M., Akoumianaki, E., Dimassi, S., Boroli, F., Richard, J.C.M., Brochard, L., 2013. Sonographic evaluation of the diaphragm in critically ill patients. Intensive Care Med. 39, 801–810.
Moerchen, V.A., 1994. Respiration and motor development: a systems perspective. J Neurol Phys Ther. 18, 8–10.
Nogués, M.A., Roncoroni, A.J., Brnarroch, E., 2002. Breathing control in neurological diseases. Clin Auton Res. 12, 440–449.
Palisano, R., Rosenbaum, P., Bartlett, D., Livingston, M.H., 2007. GMFCS - E & R Gross Motor Function Classification System Expanded and Revised. CanChild Centre for Childhood Disability. McMasters University, Hamilton.
Palisano, R., Rosenbaum, P., Walter, S., Russell, D., Wood, E., Galuppi, B., 1997. Development and reliability of a system to classify gross motor function in children with cerebral palsy. Dev Med Child Neurol. 39, 214–223.
Park, E.S., Park, J.H., Rha, D.W., Park, C.I., Park, C.W., 2006. Comparison of the ratio of upper to lower chest wall in children with spastic quadriplegic cerebral palsy and normally developed children. Yonsei Med J. 47, 237–242.
Rethlefsen, S.A., Ryan, D.D., Kay, R.M., 2010. Classification systems in cerebral palsy. Orthop Clin North Am. 41, 457–467.
Saether, R., Helbostad, J.L., Riphagen, I.I., Vik, T., 2013. Clinical tools to assess balance in children and adults with cerebral palsy: a systematic review. Dev Med Child Neurol. 55, 988–999.
Seddon, P.C., Khan, Y., 2003. Respiratory problems in children with neurological impairment. Arch Dis Child. 88, 75–78.
Shin, H.K., Byeon, E.J., Kim, S.H., 2015. Effects of seat surface inclination on respiration and speech production in children with spastic cerebral palsy. J Physiol Anthropol. 34, 17.
Smits, D.W., Gorter, J.W., Ketelaar, M., Van Schie, P.E., Dallmeijer, A.J., Lindeman, E., Jjongman, M., 2010. Relationship between gross motor capacity and daily-life mobility in children with cerebral palsy. Dev Med Child Neurol. 52, e60–66.
Testa, A., Soldati, G., Giannuzzi, R., Berardi, S., Portale, G., Silveri, N.G., 2011. Ultrasound M-mode assessment of diaphragmatic kinetics by anterior transverse scanning in healthy participants. Ultrasound Med Biol. 37, 44–52.
Wang, H.Y., Chen, C.C., Hsiao, S.F., 2012. Relationships between respiratory muscle strength and daily living function in children with cerebral palsy. Res Dev Disabil. 33, 1176–1182.
Zanforlin, A., Smargiassi, A., Inchingolo, R., Berardino, A.M., Valente, S., Ramazzina, E., 2014. Ultrasound analysis of diaphragmatic kinetics and the diagnosis of airway obstruction: the role of the M-mode index of obstruction. Ultrasound Med Biol 40, 1065–1071.