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Force direction and arm position affect contribution of clavicular and sternal parts of pectoralis major muscle during muscle strength testing

Hsin-Min Lee PT, PhD *

Department of Physical Therapy, I-Shou University, Kaohsiung, Taiwan, ROC

A R T I C L E   I N F O

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Study Design: Cross-sectional study.
Purpose of the Study: The study aims to determine the effects of force direction and arm position in differentiating the clavicular (PMc) and sternal (PMs) parts of the pectoralis major (PM) muscle during maximal voluntary isometric contraction (MVIC) to provide basic evidence to support the clinical thinking behind muscle strength testing of PM.
Methods: Nine experimental conditions with 3 force directions of horizontal adduction (+30° oblique, horizontal, and −30° oblique to the transverse plane) and 3 arm rotation positions (0°, 45°, and 90° shoulder external rotation from the transverse plane) were randomly tested for 26 healthy male participants. The MVIC force level was monitored and measured with a fixed dynamometer, and the surface electromyographic (EMG) signals of the PMc, PMs, anterior deltoid, middle deltoid, and latissimus dorsi were collected during the test for each condition. The PMc/PMs EMG ratio and normalized EMG amplitude were used to quantify the contribution of the tested muscles.
Results: The MVIC force level significantly declined when the arm's external rotation increased ($P < .01$; the grand mean decreased from 106.7 N ± 27.8 N to 89.5 N ± 22.6 N). The PMc/PMs EMG ratio showed that the best test condition to differentiate the PMc and PMs was the force direction of +30° oblique to the transverse plane and the 45° arm rotation position. Other muscles contributed less than 40% of their MVIC activity levels, with a higher activation level found in the anterior deltoid muscle ($P < .01$).
Conclusions: Arm rotation position should be considered as a predominant factor when clinically examining the strength of horizontal adduction movement. All tested conditions failed to fully separate PMc and PMs activation during MVIC and suggested that functional differentiation of the PM might not be applicable to maximal exertion.
Level of Evidence: NA.

Introduction

Examining the muscle strength of the pectoralis major (PM) can be essential for patients who have suffered injuries during sports[1] or weight training.[2] With different muscle fiber orientations (due to different origins) and respective nerve innervations (ie, lateral and medial pectoral nerves), the PM could be anatomically and neurophysiologically divided into the clavicular part (PMc) and the sternal part (PMs).[3] For patients with brachial plexus injuries[4] or cervical spinal cord injuries,[3] examination of separate parts of the PM to test the involvement of certain nerve roots is also essential. In clinics, manual muscle testing (MMT) has been commonly used to selectively apply tension to the injured muscles to examine the muscle strength.[5] A couple of MMT textbooks suggested that horizontal adduction of the arm against the upper and lower oblique resistance directions could be used to differentiate the PMc and PMs.[3,6] Although the procedures[3,6] were rational as the force exertion direction and mechanical line of action were matched for the tested muscle part, the textbooks did not clearly describe the details of the patient's arm position that might affect the muscle functions. The validity of these procedures in functional differentiation of PMc and PMs was also not known, to the best of our knowledge. Furthermore, there has been little discussion about the contribution of function-related muscles (such as the deltoids and latissimus dorsi) during PM muscle

* Corresponding author. Department of Physical Therapy, I-Shou University, No.8, Yida Rd., Jiaosu Village, Yanchao District, Kaohsiung, Taiwan, ROC. Tel.: +886 7 6151100#7562; fax: +886 7 6155150.
E-mail address: hmlee@isu.edu.tw.

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strength testing, leaving uncertainty and possibilities to the clinical examiner.

The MMT approach is therapist-oriented and is valuable in a clinical setting to document the impairments in muscle strength.[7] However, scale-based MMT evaluation might lack sensitivity[8] to detect the force change of the target muscle among various test conditions. Also, examiner-centered grading largely depends on the evaluator's experience and providing object data for comparison might be difficult.[9] To assess muscle strength, quantitative measurement of the force level of the tested muscle during maximal voluntary isometric contraction (MVIC) is another choice. MVIC measurements are commonly used as the outcome measures in studies of neuromuscular conditions to monitor disease progression and to evaluate treatment interventions.[10] Compared to MMT, the MVIC approach using a dynamometer might provide more objective and reliable data[8,9,11,12] for determining the best tested force directions and arm positions. However, MVIC tests for shoulder muscles might maximally activate more than one muscle simultaneously.[13] To solve the problem, measurement of the electromyographic (EMG) signal to monitor and differentiate the activities of the synergic muscles is necessary.[14] By using EMG amplitude ratios of 2 muscles,[15] the contribution of separate muscle fibers (such as the PMc and PMs) might be estimated when applying tension to the tested muscles. By using the EMG measurement, many studies have focused on the differences in PMc and PMs activation during bench presses[16-18] or push-ups,[19] but the results have seldom provided useful information for clinical testing of the PMc and PMs. Only one previous EMG study tested the best arm position and force direction for recruiting maximal activities of the PMc, PMs, and deltoids.[20] The results showed that both the PMc and PMs activate most in the horizontal adduction force direction with a 90°-flexion arm position. However, the study tested only 2 force directions (flexion and horizontal adduction) but did not test other oblique force directions that align the directions of the PMc or PMs fibers.[3] Also, as muscle activities of the PMc and PMs were not compared among test conditions in their study, insufficient information was provided to understand the contribution of the PMc and PMs during test conditions. Therefore, no consistent suggestions for clinical testing were provided in either the studies or the textbooks, especially with respect to detailed information on arm positions such as rotation.

As most available textbooks pertaining to MMT provide the procedure for differentiating the PMc and PMs by mainly anatomical properties and clinical experience,[3,6] it is important to provide quantitative evidence for the proper force direction and arm position to help the clinician in better differentiating the PMc and PMs during muscle strength testing. According to the original textbook suggestion,[3] horizontal adduction with 3 force directions (ie, +30°, 0°, and −30° oblique to the transverse plane of the body) was tested under 3 arm rotation positions (ie, 0°, 45°, and 90° of shoulder external rotations from the transverse plane) to understand the force exertion and the contribution of the PMc, PMs, and related muscles during the isometric strength testing. This study intended to quantify the contribution of the PMc and PMs during MVIC using surface EMG (sEMG) signals. It was hypothesized that the force output level and the activation of the tested muscles would be altered with the different force directions and arm positions chosen in the study.

Methods

Participants and experimental design

Twenty-six healthy male participants were enrolled from a college student population. All participants were right handed and had suffered no previous injuries in their right shoulder regions. Table 1 shows the summarized data of the participants' characteristics, including age, height, weight, and ergonomic data of the upper extremity. All participants signed informed consents to the protocol approved by the local ethical committee.

All recruited participants were instructed on the experiment protocol before testing. All participants were tested in supine position on a firm treatment bed with the right shoulder and elbow positioned at 90° flexion. As shown in Figure 1A, isometric horizontal adduction with 3 different force directions was chosen to differentiate the 2 parts of the PM.[3] For clarity, we used U30 (upper 30°), H0 (horizontal 0°), and L30 (lower 30°) to represent the force exertion directions aligned +30° oblique, horizontal, and −30° oblique to the transverse plane of the body, respectively. To study the arm position effects, the participant was asked to keep the shoulder joint in 3 different rotation positions by adjusting the forearm in positions of 0°, 45°, and 90° angling to the transverse plane (Arm0, Arm45 and Arm90 positions in Fig. 1A) for every contraction direction. Nine test conditions of horizontal adduction consisting of 3 tested force directions and 3 external rotation positions were randomly sorted for every participant. After several submaximal contractions to familiarize the participant with the test conditions, 3 voluntary isometric contraction trials were conducted with a 1-minute rest between them. During the contraction test, the force and EMG signal were recorded simultaneously and could be monitored via a custom-made LabVIEW program (National Instruments Inc) on the PC.

Force measurement and test procedure

A custom-made and validated dynamometer was used to measure the contraction force of the shoulder adduction. As shown in Figure 1B, an arm pad was mounted on the medial side of the upper arm to attach the limb to the force-sensing device (see Video). The orientation of the participant along with the treatment bed needed to be adjusted to align the dynamometer to the desired force direction. The force was delivered to a load cell (Model LCN-A-500N; KYOWA Inc, measured range: 0∼500 N with linearity error of 0.15%) via a steel cord connected to the pad, and the force signal was displayed simultaneously in the PC and on a projector screen on the ceiling above the participant. During force measurement, the participant was asked to perform a preset pattern of force generation (Fig. 2A). First, a 3-kg (29.4 N) force was generated for at least 2 seconds to ensure the proper contact of the upper arm and the force measurement device. When the stable 3-kg force level was achieved, the participant performed a slow, gradual isometric contraction toward the maximal contraction and maintained the MVIC force plateau for at least 3 seconds.[21] The participant was instructed to make his maximal effort to generate the maximal force without causing discomfort. The force-monitoring program on the projector screen (Figs. 2B and 2C) provided visual feedback of the contraction force level to help the participant follow the contraction pattern[22] shown in Figure 2A (see Video). Additionally, several strategies were used to

Table 1
Summary of the subjects' relevant data

$N = 26$	Age (y)	Height (cm)	Weight (kg)	SH width (cm)	UA length (cm)
Min−max	19−25	164−183	53−90	36−45	26−33
Mean ± SD	21.0 ± 1.7	172.7 ± 5.3	66.6 ± 9.2	40.7 ± 2.6	30.7 ± 1.6

Shoulder (SH) width measured the distance between acromions of bilateral shoulder joints. UA (upper arm) length measured the distance from the ulnar olecranon to the acromion of the tested (right) arm.

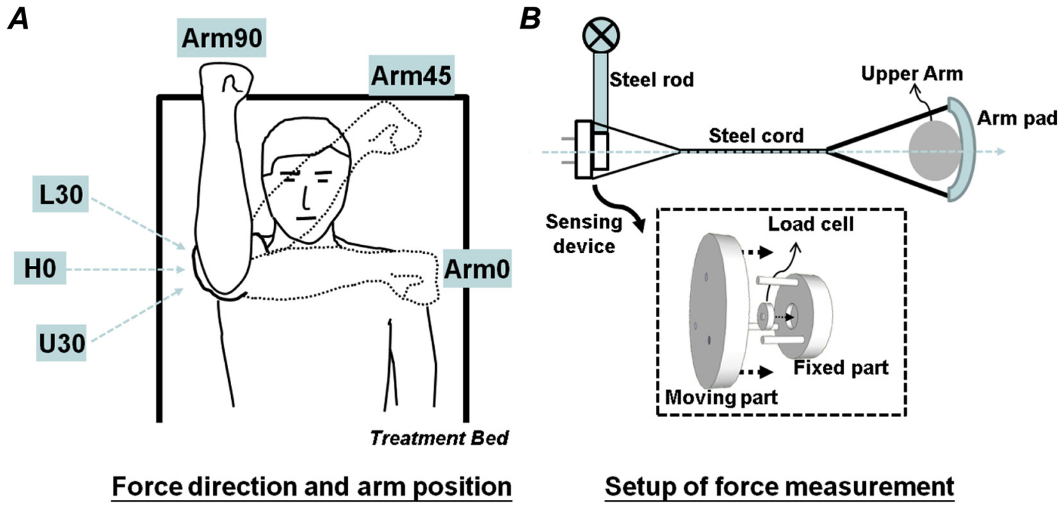

Fig. 1. Top view of the force measurement device and experimental setup. (**A**) The participant was supine on a treatment bed with 90° flexions of the shoulder and elbow joints. With the forearm in a neutral position, the shoulder was placed in 3 different rotation positions (0°, 45°, and 90°). Under each arm position, MVIC contraction was performed in 3 different force directions (U30: +30° oblique to the transverse plane; H0: horizontal to the transverse plane; L30: −30° oblique to the transverse plane).The arm pad along with the force measurement device was repositioned each time to align to these 3 force directions to measure the contraction force; (**B**) The arm pad was connected to the moving part of the sensing device via a steel cord. The fixed part of the device was fixed on an unmovable table via a steel rod. A load cell was implemented in the fixed part to measure the compression force from the moving part. The moving and fixed parts were connected via 3 sliding tracks to decrease the friction during compression. U30 = upper 30°; H0 = horizontal 0°; L30 = lower 30°.

ensure the best performance of the force generation pattern. Before the testing trials, the participant was trained to familiarize himself with the force generation pattern on the contralateral shoulder, especially for the gradual contraction. During the test procedure, the instructor guided the participant by verbal commands and encouraged the individual to achieve the best possible performance. Also, the instructor monitored the forearm position to keep it still to ensure the correct arm position while taking measurements. Furthermore, to minimize the involvement of the trunk and scapular muscles,[23] the trunk and scapula were not allowed to leave the bed during the trials.

Surface EMG measurement

Muscle contraction activities of 5 muscles were detected by disposable sEMG electrodes (Medi-Trace 100 Foam Electrode; Kendall Inc, 1-cm diameter disc and 4-cm interelectrode distance) during trials. Before electrode placement, necessary procedures, including shaving and cleaning with alcohol swabs, were carried out to reduce the interface impedance. Extra adhesive tape was used to affix the electrodes to prevent the disconnection of the electrodes or leads and reduce the electrode motion on the skin surface. After palpation of the PMc and PMs by an experienced PT, the margins of the 2 parts were marked with a colored pen (as shown in Fig. 3A). For the PMc, 2 electrodes were placed medially along the belly of the clavicular part to get the best signal.[24] For the PMs, the bisector of an imaginary angle formed by the margins of the PMs was marked first. Two electrodes were then placed medially along the bisector to measure the activity of the sternal part (Fig. 3A). In addition to the PM muscles, the EMG of 3 muscles—the anterior deltoid (AD) and middle deltoid (MD) as well as the latissimus dorsi (LD) muscles—were measured to analyze their contributions. Although primarily acting as a shoulder flexor, the AD muscle was found to be acting as a shoulder adductor when in shoulder flexion position.[25] Another measured muscle of the primary shoulder adductor is the LD,[25] although the tested posture in the study is not in its best acting posture. Finally, an antagonist muscle for horizontal adduction (ie, the MD muscle)[26] was measured as a reference. The electrode placements of these 3 muscles, detailed in Figure 3, followed the procedures suggested in the previous EMG books.[27,28] All EMG signals were amplified by the amplifier (Model QP511; Astro-Med Inc) with a gain of 5000 and bandpass filtering of 30∼1000 Hz. The EMG signal and the force signal were sent to the PC for further analysis via a 16-bit data acquisition device (PCI-6259; National Instruments Inc) with a sampling rate of 1000 Hz.

Data processing and statistical analysis

The force signal was processed with low-pass filtering of 15 Hz to ignore unwanted noise. All collected EMG signals were processed with 60-Hz band-reject filtering, 30-300 Hz bandpass filtering and rectification to retrieve the amplitude of the EMG signal. The moving average technique (window size: 0.1 seconds)[29] was then used to smooth the EMG amplitude curve. The maximal muscle activities during each MVIC trial were calculated with the averaged amplitude of the 3-second EMG data during the MVIC plateau period. Two types of EMG parameters were used to evaluate the muscle activities during MVIC. To quantify the contribution of the PMc and PMs during different MVIC trials, the PMc/PMs EMG ratio was used.[30] The EMG ratio is derived from the nonnormalized amplitudes of the PMc and PMs. A higher EMG ratio indicates the test condition relatively putting more tension on the PMc than on the PMs, that is, the contribution of the PMc is relatively larger. A decrease in the EMG ratio indicates the contribution of the PMs being relatively increased. To evaluate the contributions of the AD, MD, and LD muscles during the test conditions, a normalized EMG amplitude[31] was used. MVIC EMG amplitude of the AD, MD, and LD muscles was first collected under shoulder flexion (in 90° flexion position), shoulder abduction (in 45° abduction position), and shoulder extension (in a neutral position), respectively. Normalized EMG amplitude was then represented as a percentage (%) of the MVIC EMG amplitude.[31] The average of the force amplitude, EMG ratio, and normalized EMG amplitude over 3 trials was finally used to estimate the force level and muscle activities for each test condition.

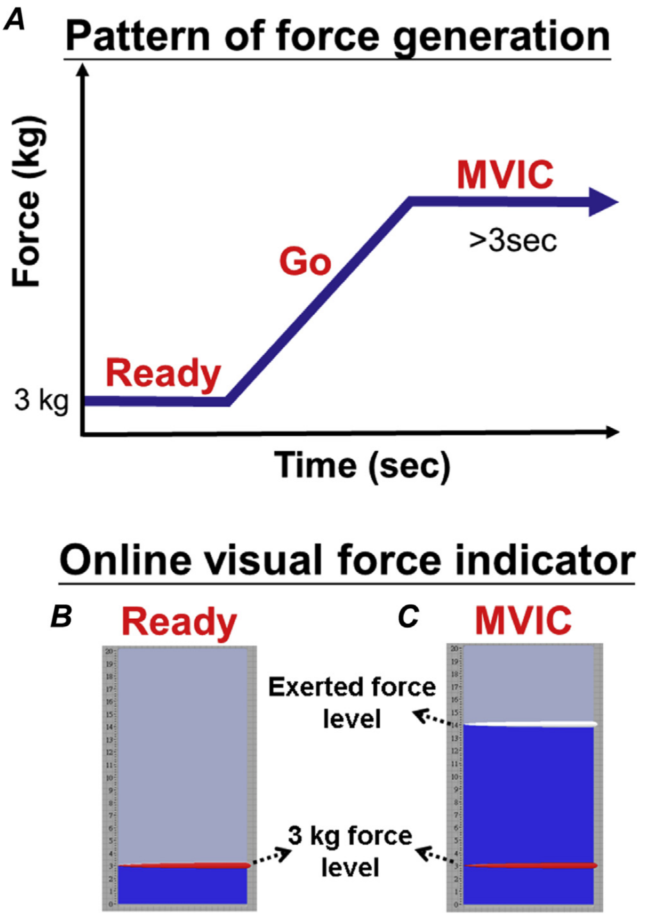

Fig. 2. Preset pattern for force generation and online force indicator during MVIC trials. (**A**) Three target phases including "ready," "go," and "MVIC" phases to follow. The force level in the ready phase was 3 kg (29.4 N). A visual force indicator in the LabVIEW program on the projector screen was used to guide the participant to follow the pattern in the ready phase (**B**) and in the MVIC phase (**C**). The participant was asked to keep the force indicator still to maintain the MVIC plateau for at least 3 seconds. MVIC = maximal voluntary isometric contraction.

Data analysis, including force, EMG signal, and their parameters, was all done using the customized programs written with MATLAB software (version 7.0, the MathWorks Inc).

Two-way repeated-measures analysis of variance (ANOVA) was used to check whether the force direction and arm position could affect the force output and EMG ratios of the PM. To analyze the contribution from the other muscles (AD, MD, and LD), 2-way repeated-measures ANOVA was also employed. Geisser-greenhouse correction was used if the sphericity assumption was not passed by the Mauchly's test in ANOVA analysis. Multiple comparisons with *t* test were further performed to examine the differences between pairs within levels of the main factors. *P* values below .01 and .01/3 (adjusted for pairwise comparison by Bonferroni correction) were considered statistically significant in the results of ANOVA and multiple comparisons, respectively.

Results

MVIC force level

None of the 26 healthy young participants reported fatigue or soreness after a total of 27 contraction trials (9 test conditions × 3 trials). As shown in Figures 4A and 4B, the averaged force level for all test conditions ranged from 89.2 N ± 25.1 N (U30 + Arm90) to 110.2 N ±29.0 N (L30 + Arm0). Two-way repeated-measures ANOVA for force showed that only arm position significantly affected the force output level ($P < .01$ in Table 2), and there were no significant differences in force level among the 3 force directions. They demonstrated a decreased trend from Arm0 position to Arm90 rotation position (Fig. 4B and all $P < .01$ in Table 2) with the grand mean declining from 106.7 N ± 27.8 N to 89.5 N ±22.6 N. Arm0 position showed a significantly larger force output than the other 2 arm positions in almost all force directions, except Arm45 position, which had a force output level similar to Arm0 in U30 direction (Fig. 4A).

EMG ratio of PMc and PMs

As shown in Figures 4C and 4D, the averaged PMc/PMs EMG ratios for all test conditions ranged from 2.6 ± 0.9 (L30 + Arm90) to 4.1 ± 1.6 (U30 + Arm0). They demonstrated a decreased trend from force direction U30 to L30 (Fig. 4C and all $P < .01$ in Table 2). Two-way repeated-measures ANOVA for the EMG ratio revealed that both force direction and arm position were significant factors in altering the contribution of the PMc and PMs (both $P < .01$ in

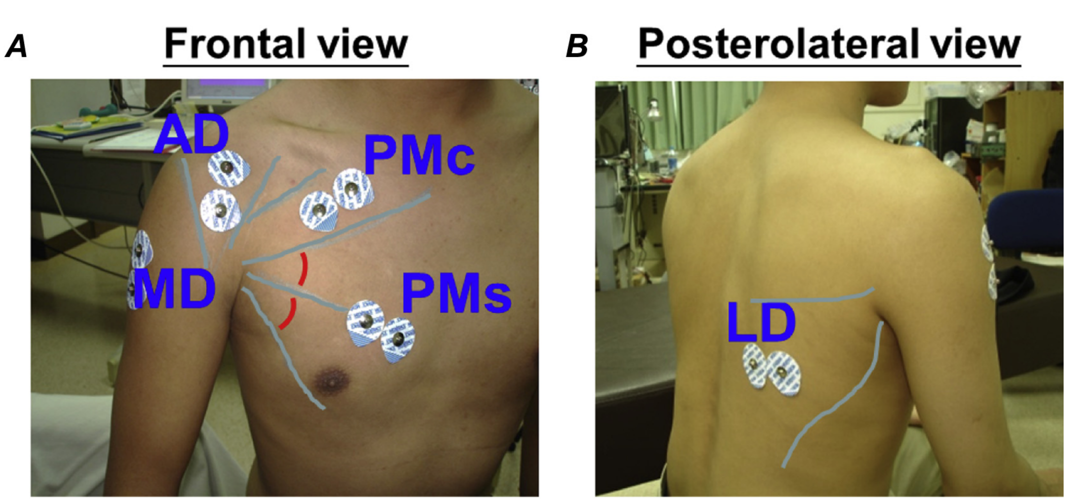

Fig. 3. Placement of surface electrodes follows the procedure of palpation, mark, and paste. (**A**) Anterior deltoid (AD): midway on the palpated muscle belly; middle deltoid (MD): approximately 3 cm below the acromion; clavicular part of pectoralis major (PMc): medially along the palpated muscle belly; sternal part of pectoralis major (PMs): medially along the imaginary angle bisector of PMs. (**B**) Latissimus dorsi (LD): midway on the palpated muscle belly.

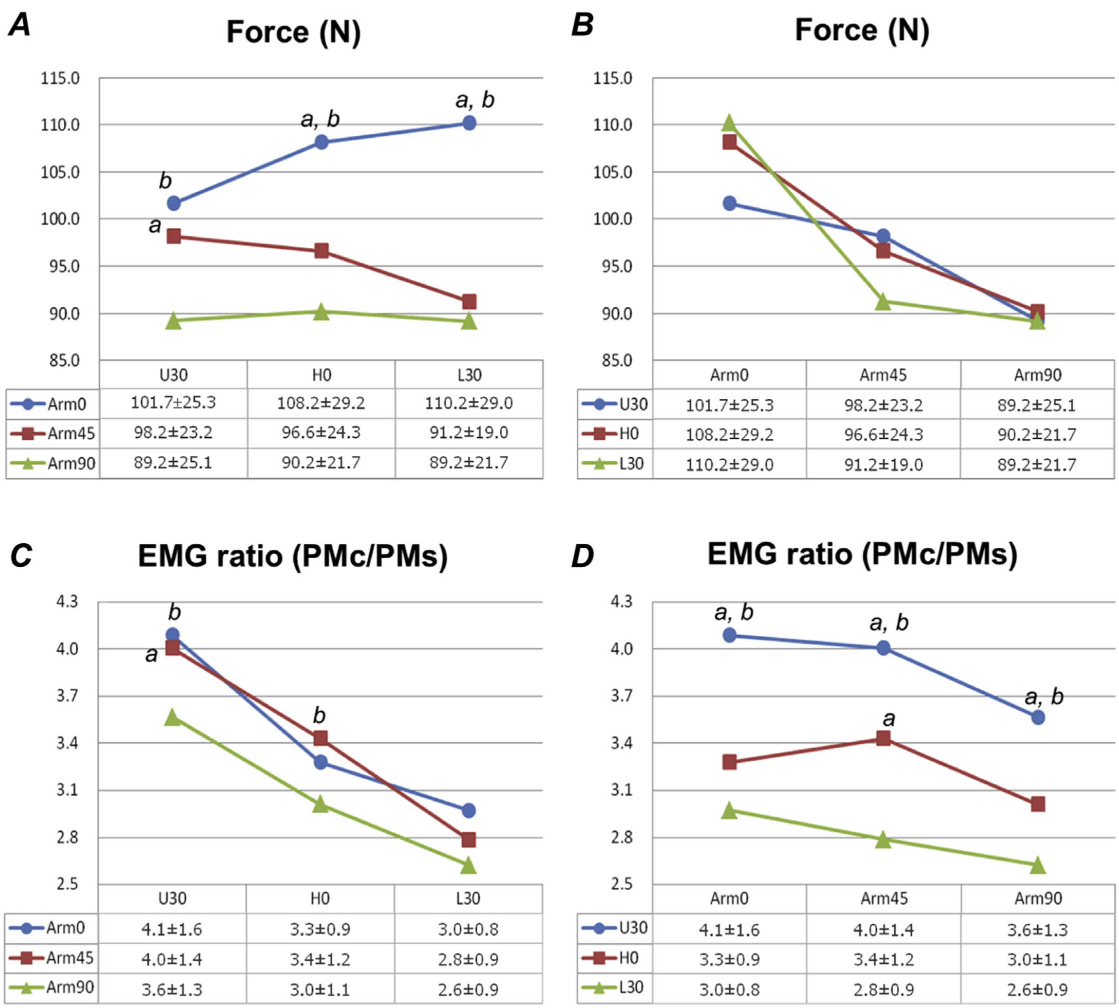

Fig. 4. Means and pairwise comparisons of exerted force level and PMc/PMs EMG ratio for all test conditions. For (**A**) and (**B**): each data point represents the averaged force of the participants ($N = 26$) for this test condition. For (**C**) and (**D**): Each data point represents the averaged PMc/PMs EMG ratio of the 26 participants. The data point marked with "a" means the distribution in this condition is significantly higher than the closest condition; "b" means the distribution in this condition is significantly higher than the second closest condition. All pairwise comparisons are considered statistically significant if $P < .01/3$ (adjusted). The tables below detail the mean ± SD of the respective data points. EMG = electromyographic; U30 = upper 30°; H0 = horizontal 0°; L30 = lower 30°; PMc = clavicular part of pectoralis major; PMs = sternal part of pectoralis major; SD = standard deviation.

Table 2). U30 force direction showed a significantly higher ability in differentiating the PMc and PMs than the other 2 force directions in all arm positions (Fig. 4D). Significant differences in the EMG ratios between adjacent force directions (ie, U30-H0 and H0-L30 pairs) were found only in Arm45 position (Fig. 4D).

Table 2
F values, degree of freedom (df), and *P* values of 2-way repeated-measures ANOVA for force level and PMc/PMs EMG ratios

$N = 26$	Force level			EMG ratio		
	F value	df	*P* value	F value	df	*P* value
Force direction (FD)	0.23	2	.79	36.08	1.66	<.001*
U30 vs H0	0.81	1	.38	23.13	1	<.001*
H0 vs L30	0.22	1	.64	19.69	1	<.001*
U30 vs L30	0.02	1	.89	54.23	1	<.001*
Arm position (AP)	41.65	2	<.001*	8.25	2	.001*
Arm0 vs Arm45	31.39	1	<.001*	0.79	1	.38
Arm45 vs Arm90	22.74	1	<.001*	14.60	1	.001*
Arm0 vs Arm90	54.65	1	<.001*	9.37	1	.005*
FD × AP	6.41	3.56	<.001*	1.09	4	.37

ANOVA = analysis of variance; EMG = electromyographic; PMc = clavicular part of pectoralis major; PMs = sternal part of pectoralis major.
FD and AP are main factors (both with 3 levels). For each main factor, within-subjects contrasts of any 2 levels are also examined. *P* values less than .01 are considered as statistically significant and are marked with asterisks.

To further reveal the change of the PMc and PMs activities in different force directions for Arm45 position, the nonnormalized EMG amplitudes of the PM muscles were presented in Figure 5. PMc activities of U30, H0, and L30 in Arm45 position are 0.36 ± 0.16, 0.37 ± 0.17, and 0.28 ± 0.15 mV, respectively. A significant decrease in PMc activities was found with a change of H0 force direction to L30 ($P < .01/3$ in Fig. 5A). PMs activities in U30, H0, and L30 directions were 0.09 ± 0.04, 0.11 ± 0.04, and 0.10 ± 0.05 mV, respectively. A significant increase in PMs activities was found only with a change of U30 direction to H0 direction ($P < .01/3$ in Fig. 5B).

Contribution of other muscles

As shown in Table 3, the averaged contribution of the AD muscle (normalized EMG amplitude ranged from 18.5% ± 9.1% to 37.2% ± 19.0%) during MVIC trials was significantly higher than that of the MD (which ranged from 4.5% ± 2.6% to 11.9% ± 6.5%) and the LD (which ranged from 4.7% ± 2.7% to 9.6% ± 4.9%) with both *P* values < .001. Similar to the EMG ratios of the PMc and PMs, 2-way repeated-measures ANOVA also revealed that both force direction

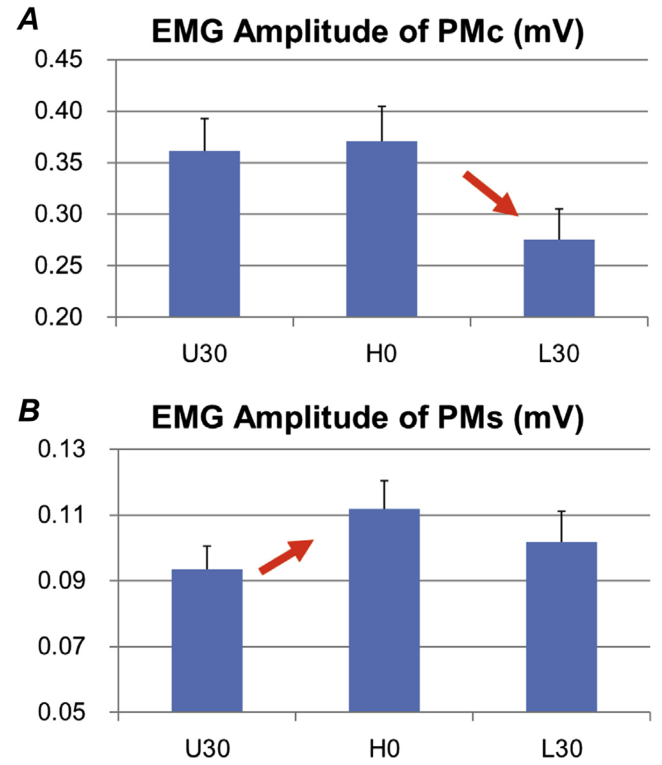

Fig. 5. Averaged nonnormalized amplitudes of PM EMG signals in Arm45 position for U30, H0, and L30 force directions. (**A**) PMc and (**B**) PMs. The *red arrows* indicate the change between 2 force directions is significant with $P < .01/3$ (adjusted). EMG = electromyographic; PMc = clavicular part of pectoralis major; PMs = sternal part of pectoralis major. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

and arm position significantly affected the contribution of the AD, MD, and LD muscles (both $P < .001$ in Table 3). As the contributions of the MD and LD were relatively small, only data of the AD were further analyzed. As shown in Table 3, a higher contribution from the AD muscle was found in U30 and H0 force directions (marked as "a" and "b"). With respect to the factor of arm position, the AD muscles significantly contributed more in Arm0 position to the H0 and L30 force directions (marked as "*" and "#").

Discussion

In this study, MVIC and sEMG techniques were used to realize the exerted force and contribution of the tested muscles (mainly the PMc and PMs) during muscle strength testing. With the help of online force feedback (Fig. 2) and the accessor's monitoring, the participants successfully performed the MVIC testing under all 9 conditions. As shown in Table 2, arm position was found to be more important than the force direction in the exerted force level. A descending trend of force level was found as the external rotation of the arm increased for all force directions (Fig. 4B). Therefore, to test the best force output in various horizontal adductions, the results suggest that Arm0 (forearm align with frontal axis) might be the best test position. The main reason might be that the humeral insertions of the horizontal adductors (including the PM and AD in the study) face farther away from the force directions when the arm external rotation increases and make the delivery of the contraction force more inefficient. The off-axis contraction also increases the rotatory moment of the humerus along the long axis and might cause the other stabilizing muscles to become involved during static MVIC testing. Another interesting finding was that although the textbook suggested that the H0 direction could test both the PMc and PMs,[3] the force levels of H0 in the participants seemed not significantly different from U30 or L30 for all arm positions (Fig. 4B). As force measurement could not estimate the contribution of the PMc and PMs or other related muscles during the MVIC trials, discussion on this issue might need further analysis with the EMG measurement for these muscles.

PMc and PMs muscles

As expected, force direction significantly affects the contribution of the PMc and PMs during MVIC strength testing (Table 2). Activation of PMc relatively decreased when the exerted force of horizontal adduction changed from the upper oblique direction to the lower oblique direction, as shown in the descending PMc/PMs EMG ratios from the U30 to L30 directions for all arm positions (Fig. 4C). During a muscle testing scenario, matching between the target muscle's mechanical line of action and the intended force direction was crucial when the target muscle was placed in the position of proper moment arm. In the present study, the test position of 90° shoulder flexion was better than the anatomical position as the humeral insertions moved to the transverse plane from the frontal plane and possessed larger moment arms for the oblique and horizontal directions of shoulder adduction. Obviously, the results of EMG ratios coincide with the textbook suggestion of using oblique resistance for the PMc and PMs,[3] but both the U30 and L30 directions fail to fully differentiate between the PMc and the PMs in the present study of healthy young participants. As fanlike PM was found to be functionally controlled as at least 6 segments,[2,32] MVIC testing with maximal exertion in either the U30 or L30 force

Table 3
Two-way repeated-measures ANOVA for normalized EMG amplitudes of anterior deltoid (AD), middle deltoid (MD), and latissimus dorsi (LD) muscles

Muscles	N = 26	Normalized muscle activities (mean ± SD, %)			*P* values		
		U30	H0	L30	FD	AP	FD × AP
AD	Arm0	37.2 ± 19.0[b]	36.7 ± 21.0[a,*]	28.6 ± 18.2[#]	<.001	<.001	<.001
	Arm45	35.8 ± 18.2[a,b]	29.6 ± 18.2[a]	18.5 ± 9.1			
	Arm90	34.8 ± 14.7[a,b]	28.7 ± 16.0[a]	21.2 ± 13.8			
MD	Arm0	11.9 ± 6.5	8.9 ± 6.0	5.8 ± 4.1	<.001	<.001	<.001
	Arm45	10.6 ± 6.5	6.6 ± 3.7	4.5 ± 2.6			
	Arm90	8.3 ± 4.6	6.3 ± 3.4	4.9 ± 3.0			
LD	Arm0	6.6 ± 3.2	6.0 ± 2.9	4.7 ± 2.7	<.001	<.001	.49
	Arm45	7.3 ± 4.8	5.9 ± 3.6	5.1 ± 3.6			
	Arm90	9.6 ± 4.9	9.0 ± 5.5	7.6 ± 4.9			

ANOVA = analysis of variance; EMG = electromyographic; U30 = upper 30°; H0 = horizontal 0°; L30 = lower 30°.
With respect to FD (force direction) comparisons, data marked with "a" indicate that the data distribution of this condition is significantly higher than that of its right condition. Data marked with "b" in U30 row indicate that the distribution is significantly higher than the L30 condition. In AP (arm position) comparisons, the symbol "*" marks that the distribution of the condition is significantly higher than both Arm45 and Arm90 conditions. The symbol "#" marks that the distribution of the condition is significantly higher only than Arm45 but not Arm90 condition. All pairwise comparisons are done only for AD muscles and are considered statistically significant if $P < .01/3$ (adjusted).

direction might maximally activate the segment with a matched action line but might also activate nearby segments in different weightings. Even though the muscle irradiation of the PM segments might confound the full differentiation of the PMc and PMs during strength testing, any decrease of contraction force in the U30 or L30 force direction would still help to clinically detect the weakness of the PMc or the PMs.

Compared to the positions of less external rotation (Arm0 and Arm45), significantly lower EMG ratios in the Arm90 position for U30 direction were noted (Fig. 4C). Although U30 direction is the best direction to differentiate between the PMc and PMs, Arm90 position will cause the PM insertions to face outward, and this lengthening of the PM muscle fibers seems to have different influences on PMc and PMs activities. Previous computer simulation study has shown that there are different patterns of muscle length change for the PMc and PMs during arm elevation and arm external rotation.[33] The speculations are supported by the previous study of bench presses that showed muscle activation was significantly greater in the PMs and lower in the PMc at a lower arm incline angle when both PM muscle fibers were lengthening.[16] Further study of the different behavior of the length-tension relationship between the PMc and PMs might help to find the better tested position to differentiate them.

From the viewpoint of arm position, the results suggest Arm45 positions have the best ability in differentiating PMc and PMs as only EMG ratios of Arm45 are significantly different among the 3 force directions (Fig. 4D). In this arm position, the nonnormalized EMG amplitude of the PMc and PMs confirms that the PMc contributes less in L30 direction (Fig. 5A) and the PMs contributes less in U30 direction (Fig. 5B). Although H0 force direction can maximally activate most parts of the PMc and PMs (Fig. 5), the nonprominent force level in H0 direction (Fig. 4B) mentioned previously indicates that the contribution from other muscles should be considered.

Contribution from other muscles

As shown in Table 3, the averaged activation levels of the other measured muscles (AD, MD, and LD) are lower than 40% of their MVIC EMG amplitudes. Although these muscles are not main acting muscles during horizontal adduction, their activated pattern of contribution is still affected by force direction and arm position (all $P < .001$ in Table 3). Among them, the AD significantly contributed more than the MD and LD muscles during the testing trials ($P < .001$). Moreover, the AD was similar to the PMc that activated significantly more at the U30 and H0 force directions (Fig. 5 and Table 3). Considering that the AD's line of action fit the force direction and the AD possessed the maximal moment arm in this position,[34] the EMG results suggested that the AD can be considered as a synergist of shoulder horizontal adduction in the currently tested position. The findings were supported by a previous study that found the AD acted as the adductor and increased the activation level with increased shoulder flexion.[25] The similarity between the PMc and the AD in the activation pattern was also supported by another study that found both the PMc and the AD synchronously activated more as the angle of the bench incline increased.[16] For patients with a weak PMc, the AD might need to be monitored to not compensate for the movement during strength testing. In contrast, current results suggest that the LD participates much less (averaged amplitude is lower than 10%) in the tested position of 90° shoulder flexion although the LD is found to be a primary adductor when the arm is in anatomic position.[35] In a previous study, the LD was also considered to play a trivial role in the horizontal shoulder adduction task.[25] Accordingly, to test the PM and reduce the participation of the LD in shoulder adduction, keeping the arm in the flexion position is suggested.

Study limitations

The major limitation of the study is that the MVIC of shoulder rotation was not tested in the current setup; therefore, it could not be determined whether internal rotation was more suited to elicit and differentiate between PMc and PMs activities.[36] Furthermore, the force direction was only tested in 90° shoulder flexion but not in other positions that were considered valid in separating the PMc and PMs (such as 60° flexion suggested in 1 textbook[6]). Further study with extended test positions and rotational movement patterns is therefore suggested.

Conclusions

This study has shown that a 0° arm rotation position was the best test position for maximal force output of shoulder horizontal adduction. The contribution of the PMc and PMs during MVIC coincides with the muscle fiber directions, as suggested by previous textbooks.[3,6] A 45° external rotation was suggested as the arm position to best differentiate the PMc and PMs during 3 force directions of muscle strength testing. The AD muscle behaves like the PMc and should be considered as a synergist of shoulder horizontal adduction when testing the PM's strength in the shoulder-flexion position. Although fully functional differentiation of the PM might not be applicable to maximal exertion, proper selection of force direction and arm position will help in the clinical detection of muscle strength decline of the PMc or PMs.

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Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jht.2017.08.007

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1. The contributions of the two portions of the PM were estimated by
  a. dynamic ratio analysis
  b. MMT
  c. surface EMG amplitudes
  d. sub-surface EMG amplitudes

2. Subjects participating in the study were
  a. 26 healthy male volunteers
  b. 50 healthy adult (male and female) volunteers
  c. 25 patients (male and female) with signs of mild rotator cuff impingement
  d. 25 patients and 25 healthy adults

3. The MVIC force level
  a. could not be assessed with the arm externally rotated
  b. remained constant regardless of arm position
  c. significantly increased with the arm externally rotated
  d. significantly declined with the arm externally rotated

4. Data were collected when the subjects performed
  a. eccentric contractions
  b. sub maximal contractions
  c. isometric contractions
  d. concentric contractions

5. No tested conditions succeeded in differentiating the two portions of the PM during activation
  a. false
  b. true

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