CHANGE IN MUSCLE ACTIVITY PATTERNS OF THE BRACHIALIS AND BICEPS BRACHII DURING DYNAMIC ELBOW FLEXION

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In this study, we investigated the changes in the muscle activities of the brachialis (BR) and biceps brachii (BB) during dynamic elbow flexion under different movement velocity and load conditions. Twenty healthy adult males performed isotonic elbow flexions in the full range of motion (0–140°) under angular velocities of 30 and 60 °/s, and with (30% maximum torque) and without load conditions. Muscle activity was measured using surface electromyography. The muscle activity of the BR and BB was compared to their response to different angle-phase, angular velocity, and load conditions. Both muscle activities of the BR and BB significantly increased in the initial angle-phases of the elbow flexion. Muscle activity of the BR progressively increased with increasing elbow flexion, whereas that of the BB plateaued regardless of the velocity and load conditions. Specifically, BB muscle activity plateaued after an initial increase in the earliest phase at 60 °/s with load conditions. It was suggested that the BR

and BB contributed to the control of the movement in a different way during dynamic elbow flexion.

Keywords: Surface electromyography; Joint angle; Amount of load; Velocity; Rehabilitation

1. Introduction

The brachialis (BR) and biceps brachii (BB) muscles are primarily responsible for elbow flexion. [1-3] These muscles play an important role in improving elbow utility following elbow injury, such as brachial plexus palsy[4-6] and BR or BB rupture. [7-9]

The respective roles of the BR and BB in elbow flexion have been described in previous studies. [1-3, 10] The muscle activities of BR and BB have been investigated at various elbow joint angles using electromyography (EMG) and their muscle activity patterns have been discussed. Generally, these studies reported that EMG amplitude readings of the BR intensified with increasing elbow joint angles, that is, with increasing elbow flexion, [11] whereas that of the BB remained constant at all joint angles. [12] Moreover, because a moment arm of the BB is longer than that of the BR, [3, 13] BB muscle activity increases from the beginning of elbow flexion. In contrast, in a fully flexed elbow position, the force-generating potential of the BB is compromised, [3] and BR muscle activity increases in the terminal elbow angle-phase to compensate for the BB. However, these previous studies performed evaluations of the BR and BB muscle activities under static conditions (isometric contraction); thus, whether the BR and BB would have similar muscle activity patterns under dynamic conditions (isotonic contraction) remains unknown. A previous study reported that the neural drive to muscle and recruitment pattern of motor units do not change between static and dynamic conditions. [14] Generally, the moment arms of muscles also remain the same between static and dynamic conditions if the measured angle joints are the same. Therefore, we hypothesized that the muscle activation patterns of the BR and BB under dynamic conditions are similar to those observed under static conditions in previous studies.

However, muscle activation patterns depend on the movement velocity and load. As the BR and BB have different muscle lengths (the BB has a longer muscle length than the BR), [3, 10] the BR and BB muscle activities have increased at faster and slower movement velocities, respectively. A study using magnetic resonance imaging investigated BB and BR activities at 2 and 10 s durations during a full flexion contraction of the elbow joint. The results showed that the BR is recruited more during the slower (10 s) contraction, whereas the BB is recruited more during the faster (2 s) contraction. [15] Additionally, because the BR is a multipennate muscle with the largest physiological cross-sectional area of the elbow flexors, [16, 17] it is activated under high load conditions on the elbow joint. However, there are no studies clarifying how BR and BB muscle activities respond to different combinations of movement velocity and load conditions during dynamic elbow flexion.

If the BR and BB have different muscle activity patterns under different experimental conditions, such as angle-phase, movement velocity, and load, then electromyographic support for the significance of BR and BB reconstructions in patients with brachial plexus palsy, and for the development of specific rehabilitation programs for the BR and BB in postoperative therapy must be considered. In this study, we investigate the changes in BR and BB muscle activities during dynamic elbow flexion in healthy participants under different combinations of movement velocity and load.

2. Methods and Materials

2.1 Ethical approval

The studies involving human participants were reviewed and approved by the Research Ethics Committee of the Hiroshima University Hospital (Approval Number: C299) and all experiments were performed in accordance with the Declaration of Helsinki. All patients/participants provided their written informed consent to participate in this study.

2.2. Participants

A priori power analysis was performed using G*Power statistical packages (version 3.1.9.2; G*Power, Universität Düsseldorf, Düsseldorf, Germany) [18] to determine the sample size required for this study. ANOVA (repeated measures; within factors) was used to analyze required samples with 95% power, an α error probability of 0.05, medium effect size of 0.25, [19] correlation (r) among repeated measures of 0.4, and a minimum of 16 different combinations of measurement values (four angle-phase conditions, two movement velocity conditions, and two load conditions per individual). The required sample size was calculated to be 18 participants. Therefore, a total of 20 healthy adult males were recruited for this study. The demographic data of enrolled participants are shown in Table 1. The weight and center of mass of the forearm, as presented in Table 1, were estimated using formulas from a previous study. [20] The moment of inertia of the forearm was subsequently calculated from these estimated values. [20] All participants were recruited from a local university, and they regularly performed sports at an amateur level. The participants had no musculoskeletal or neurological dysfunction and had no limitation in the range of motion of the elbow joint. Handedness was assessed using the Edinburgh inventory, [21] and all participants were classified as consistent right-handers (scoring above 80% on this scale).

Table 1. Participants' demographic data.

n	20
Age (years)	24.4 ± 3.9
Height (m)	1.73 ± 0.05
Weight of the total body (kg)	66.9 ± 9.2
Weight of the forearm (kg) [20]	1.25 ± 0.17
Length of the forearm (m)	0.25 ± 0.01
Center of mass of the forearm (m) [20]	0.14 ± 0.01
Moment of inertia of the forearm (kg.m^2)	0.02 ± 0.01

Data are presented as mean ± standard deviation.
Definition of the length of the forearm (m): distance from the head of the radius to the styloid process of the radius.

2.3. Experimental setup

The participants were asked to perform an isotonic elbow flexion task using their right upper limb. Before task execution, each participant was seated in a chair approximately 1 m away from an 18-inch computer screen. The right shoulder joint was flexed 0°, abducted 0°, and slightly externally rotated with the forearm maintained in supination. The left upper limb was placed against the side of the body with the forearm in a neutral position. The participants held cylindrical handles connected to a digital dynamometer (HUMAC NORM Model 770; CSMi, Stoughton, MA, USA) (one in each hand with a closed grip). For each participant, the digital dynamometer was externally tilted between 5 and 10° from the vertical line, and the rotation axis was aligned with the line connecting the lateral and medial epicondyles. The length of the lever arm was adjusted to match the forearm length of each participant. Extraneous movements of each participant trunk and right upper arm were limited by an elastic belt (Fig. 1A). During task execution, the participants were instructed to gaze at the computer screen displaying the movement velocities of the elbow flexion (solid lines in Fig. 1B) and a targeted velocity level (a band between two parallel outlines in Fig. 1B). Each participant had to maintain their movement velocity approximate to the targeted velocity level. These two parallel outlines were set to ±10 °/s of the targeted velocity. All the visual feedback systems were customized by the control software of the digital dynamometer.

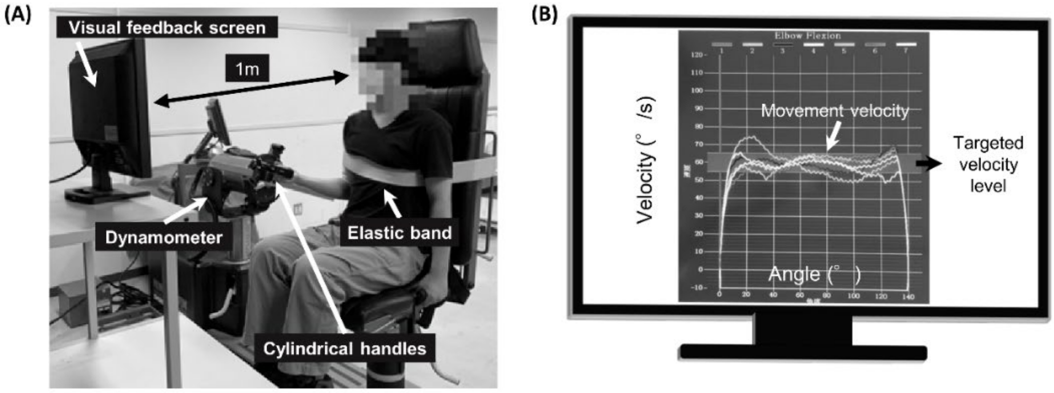

Fig. 1. (A) Experimental setup of a participant. (B) Visual feedback screen displaying movement velocities; vertical and horizontal axes represent the angular velocity and angle of elbow flexion, respectively. Screenshot shows a participant performing the task at 60 °/s without load.

2.4. Experimental protocol

The experimental protocol is shown in Fig. 2. Initially, the participants performed three isometric trials of maximum flexion torque exertion at 90° elbow flexion, with a trial interval of 3 s and a rest period of at least 60 s between each trial. We identified the maximum flexion torque for each trial and obtained the average of the three peak torque values. Based on these averaged values, the load condition was determined as 30% of the maximum flexion torque, as per the protocol outlined below. Subsequently, the participants performed the elbow flexion task, which involved a range of motion from 0° (full-extension) to 140° (full-flexion) (Fig. 3). The study was comprised of four conditions, combining two angular velocities (30 and 60 °/s), and two loads (with and without load set at 30% of the maximum flexion torque). These conditions were randomized and repeated seven times. To prevent fatigue, rest intervals of at least 30 s were set between trials and 5 min between conditions. Following the task, the participants performed isometric maximum voluntary contractions (MVCs) of the elbow flexion and extension at 90° elbow flexion, with a trial interval of 3 s and a rest period of at least 60 s between each trial. Flexion and extension of the elbow at MVC were performed three times each.

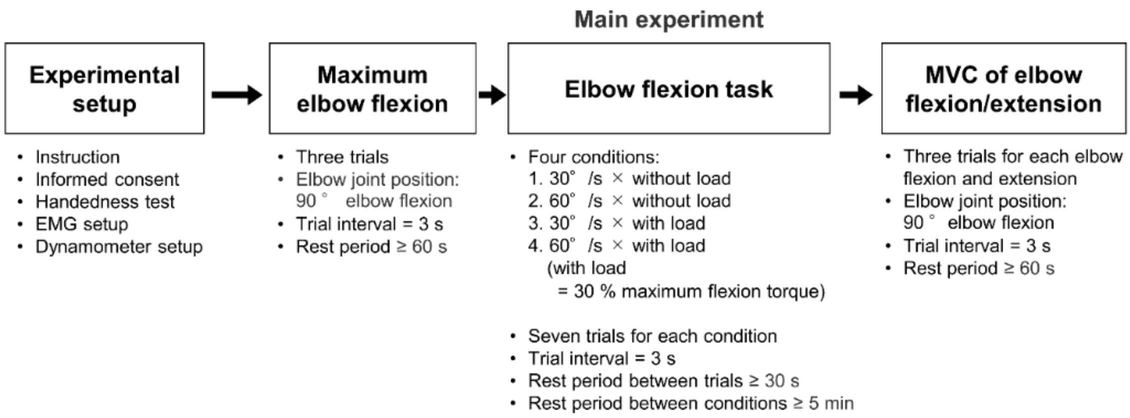

Fig. 2. Experimental protocol.

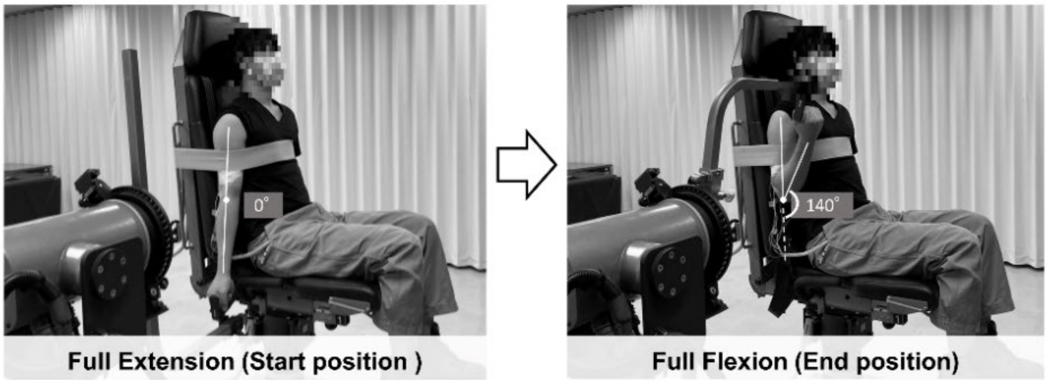

Fig. 3. A demonstration of the elbow flexion task.

2.5. Muscle activity

Muscle activity was assessed using EMG signals from the BR, long heads of the BB, as well as from antagonist muscles, long and lateral heads of the triceps brachii (TB_{long} and TB_{lat}, respectively). EMG was measured using Ag-AgCl disposable surface electrodes (Ambu® Blue Sensor N-00-Sm, Ambu A/S, Ballerup, Denmark) in a bipolar configuration with a 20 mm inter-electrode distance. The electrode locations in each muscle were confirmed using ultrasonographic guidance (SONIMAGE MX1, Konica Minolta Inc., Tokyo, Japan). The ultrasonography probe was placed transversely on the elbow muscles to visually confirm the location of each muscle. Electrode locations were validated during dynamic elbow flexion using ultrasonography.[22] Reference electrodes were attached to the skin over the lateral epicondyle of the right elbow. EMG signals were recorded using a wireless EMG system (Intercross-413, Intercross Inc., Tokyo, Japan). The signals were amplified with a gain of 1,000, band-pass filtered (20–499 Hz), and recorded on a personal computer. The sampling frequency was set to 1,000 Hz.

2.6. Torque, movement velocity, angle, and angular acceleration

In this study, toque (Nm), angular velocity (°/s), and angle of the elbow flexion (°) were measured using the digital dynamometer at a sampling frequency of 100 Hz. The data obtained from the digital dynamometer were synchronized with the EMG data and recorded on a personal computer for further analysis. Angular acceleration ($°/s^2$) was calculated through differentiation of the angular velocity to assess the changes in the elbow movement, particularly at the initiation and termination of the movement.

2.7. Data processing

The torque, angular velocity, angular acceleration, and EMG data were analyzed using an original MATLAB-based program (R2020b, The MathWorks Inc., Natick, MA). The analyzed interval for each data value was from 0 to 140° elbow flexion (Fig. 4A). The torque, angular velocity, and angular acceleration data from this range were then normalized to 140 points.

EMG signals were zero-lag band-pass filtered between 20 and 450 Hz (4th order, Butterworth) and smoothed using a moving root-mean-square filter (time window: 100 ms) (Fig. 4B). EMG signals during the task was normalized to 140 points based on the angle data ranging from 0 to 140°. EMG amplitude was normalized as a percentage of the MVC (%MVC).

For each participant and muscle, the average values of the torque, angular velocity, angular acceleration, and EMG data were calculated from five out of seven trials, and then divided into five phases: P1 (0–28°), P2

(28–56°), P3 (56–84°), P4 (84–112°), and P5 (112–140°) for further statistical analysis of changes in the data values per angle-phase during dynamic elbow flexion.

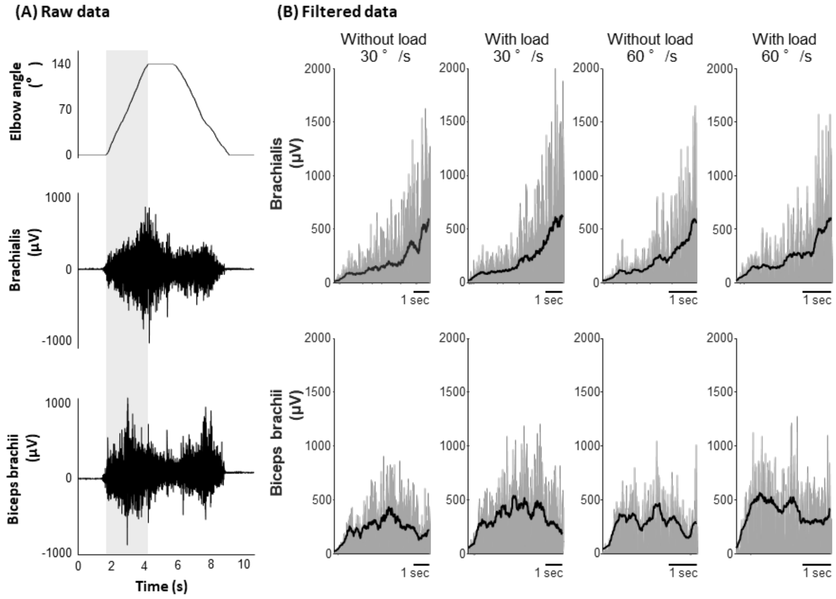

Fig. 4. Representative data during elbow flexion at 60 °/s without load. (A) Top trace indicates the angle data from full elbow extension (0°) to flexion (140°), to full extension again. Bottom two traces indicate raw EMG signals of the brachialis (BR) and biceps brachii (BB) muscles. Shaded areas indicate the analyzed interval of the torque, angular velocity, angular acceleration, and EMG data. (B) Each trace shows the full-waved rectified EMG signals (in grey) and the smoothed waveforms (in black) of the BR and BB.

2.8. Statistical analysis

All data are presented as the mean ± standard deviation (SD) for each condition. SPSS statistical software (version 23; IBM Inc., Chicago, IL, United States) was used for statistical analysis. Statistical significance was set at $p < 0.05$.

The torque, angular velocity, angular acceleration, and activity of each muscle were compared using a three-way ANOVA for angle-phase (P1, P2, P3, P4, and P5), angular velocity (30 and 60 °/s), and load (with and without load). If the results had a significant effect or interaction, the Bonferroni correction method was used as a post-hoc test.

3. Results

3.1 Muscle activity

The results of the BR and BB muscle activities in relation to the angle-phase are shown in Fig. 5, while their values in relation to different angular velocity and load conditions are described in Table 2. BR and BB muscle activities significantly differed among angle-phases (BR, $F = 45.4$, $p < 0.05$; BB, $F = 5.4$, $p < 0.05$), angular velocities (BR, $F = 12.5$, $p < 0.05$; BB, $F = 45.4$, $p < 0.05$), and load conditions (BR, $F = 62.3$, $p < 0.05$; BB, $F = 67.1$, $p < 0.05$). There was also a significant three-way interaction effect between the angle-phase, angular velocity, and load for BB values ($F = 4.3$, $p < 0.05$).

First, by focusing on the angle-phase (Fig. 5), BR muscle activity significantly increased between P1 and P2, P3 and P4, or P4 and P5, while BB muscle activity did not exhibit any significant changes between P3 and P4, or P4 and P5 for all combinations of angular velocity and load conditions. Specifically, BB muscle activity was not different between P1 and P2 or P2 and P3 at 60 °/s with load condition.

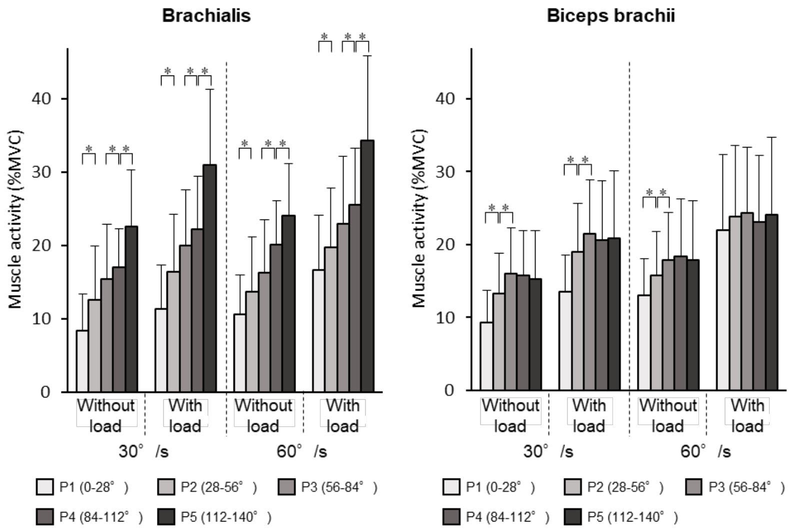

Fig. 5. Muscle activities of the brachialis (left) and biceps brachii (right) muscles under different combinations of velocity and load conditions. Each asterisk (*) indicates significant differences between the adjacent angle-phases ($p < 0.05$).
Abbreviations: %MVC = ratio of the maximum voluntary contraction

Subsequently, by focusing on the angular velocity and load conditions (Table 2), the values at 60 °/s were significantly higher than those at 30 °/s for both BB and BR muscle activities. Moreover, BR and BB muscle activities with load were significantly higher than those without load in all angle-phases.

Table 2. Muscle activities of the brachialis (BR) and biceps brachii (BB) muscles (%MVC).

		Angular velocity			
		30 °/s		60 °/s	
		Load			
		Without load	With load	Without load	With load
	Angle-phase				
BR	P1 (0-28°)	8.35 ± 5.05	11.29 ± 6.06 [c]	10.58 ± 5.35 [††]	16.72 ± 7.44 [†††, c]
	P2 (28-56°)	12.57 ± 7.38	16.46 ± 7.77 [c]	13.76 ± 7.41	19.75 ± 8.14 [††, c]
	P3 (56-84°)	15.47 ± 7.44	20.05 ± 7.55 [c]	16.33 ± 7.14	22.99 ± 9.19 [†, c]
	P4 (84-112°)	17.07 ± 5.26	22.26 ± 7.21 [c]	20.11 ± 6.03 [††]	25.60 ± 7.64 [††, c]
	P5 (112-140°)	22.65 ± 7.67	30.96 ± 10.32 [c]	24.06 ± 7.13	34.4 ± 11.49 [c]
BB	P1 (0-28°)	9.33 ± 4.39	13.57 ± 5.03 [c]	13.08 ± 5.04 [†††]	21.99 ± 10.32 [†††, c]
	P2 (28-56°)	13.28 ± 5.59	19.00 ± 6.62 [c]	15.79 ± 5.97 [†††]	23.79 ± 9.86 [†††, c]
	P3 (56-84°)	16.05 ± 6.27	21.48 ± 7.42 [c]	17.89 ± 6.47 [†]	24.37 ± 8.99 [†, c]
	P4 (84-112°)	15.80 ± 6.14	20.66 ± 8.08 [b]	18.44 ± 7.88 [†]	23.05 ± 9.21 [†, c]
	P5 (112-140°)	15.23 ± 6.74	20.89 ± 9.20 [b]	17.89 ± 8.19	24.10 ± 10.57 [†, c]

Data are presented as mean ± standard deviation.
Abbreviations: BB = biceps brachii muscle; BR = brachialis muscle; MVC = maximum voluntary contraction.
[†]: $p < 0.05$, [††]: $p < 0.01$, [†††]: $p < 0.001$: Significant difference from the 30°/s angular velocity.
a: $p < 0.05$, [b]: $p < 0.01$, [c]: $p < 0.001$: Significant differences (without load).

The muscle activity results for the TB_{long} and TB_{lat} are presented in Table 3. There were significant differences in several angle-phase, angular velocity, and load conditions; however, their activity was relatively low (< 10 %MVC) under all conditions (TB_{lat}: 3.21 ± 2.41 ~ 9.67 ± 4.42 %MVC; TB_{long}: 1.64 ± 0.68 ~ 3.89 ± 1.41 %MVC).

Table 3. Muscle activities of the triceps brachii muscles [%MVC].

		Angular velocity			
		30 °/s		60 °/s	
		Load			
		Without load	With load	Without load	With load
	Angle-phase				
TB_{lat}	P1 (0-28°)	3.21 ± 2.41	4.23 ± 2.69^{c}	4.16 ± 2.72†††	5.73 ± 3.22$^{\dagger\dagger\dagger, c}$
	P2 (28-56°)	4.15 ± 2.55**	5.29 ± 2.94$^{***, c}$	4.74 ± 2.74††	6.29 ± 3.25$^{\dagger\dagger, c}$
	P3 (56-84°)	4.71 ± 2.73***	5.91 ± 3.09$^{**, c}$	5.06 ± 2.62†	6.34 ± 2.86^{c}
	P4 (84-112°)	5.17 ± 2.90*	6.39 ± 3.37^{c}	5.70 ± 2.52$^{**, \dagger}$	7.02 ± 3.19$^{**, \dagger\dagger, c}$
TB_{long}	P5 (112-140°)	7.58 ± 4.02**	9.15 ± 5.16$^{**, c}$	7.58 ± 4.02**	9.67 ± 4.42$^{***, c}$
	P1 (0-28°)	1.64 ± 0.68	2.23 ± 0.99^{c}	2.12 ± 0.75†††	3.15 ± 1.55$^{\dagger\dagger\dagger, c}$
	P2 (28-56°)	2.33 ± 0.87***	3.09 ± 1.30$^{***, c}$	2.64 ± 1.00$^{**, \dagger\dagger}$	3.63 ± 1.61$^{**, \dagger, c}$
	P3 (56-84°)	2.77 ± 1.01***	3.50 ± 1.33$^{***, c}$	2.96 ± 1.06$^{**, \dagger}$	3.78 ± 1.74^{c}

Data are presented as mean ± standard deviation.
Abbreviations: MVC = maximum voluntary contraction; TB_{lat} = lateral head of the triceps brachii muscle; TB_{long} = long head of the triceps brachii muscle.
*: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$: significant differences between adjacent angles. Letters are added to the subsequent angle when there are significant differences.
†: $p < 0.05$, ††: $p < 0.01$, †††: $p < 0.001$: Significant differences (30°/s angular velocity).
a: $p < 0.05$, ^{b}: $p < 0.01$, ^{c}: $p < 0.001$: Significant differences (without load).

3.2. Torque, angular velocity, and angular acceleration

Torque was significantly different among angle-phases (F = 188.7, $p < 0.05$), angular velocities (F = 81.4, $p < 0.05$), load conditions (F = 100.4, $p < 0.05$), and angle-phase × angular velocity × load (F = 21.1, $p < 0.05$) interactions (Table 3). Specifically, the torques of P1 were significantly higher than those at any other angle-phase, regardless of the angular velocity and load conditions. Moreover, the torques at P1 for the 60 °/s velocity condition were significantly higher than those for the 30 °/s. Angular velocity values were significantly different among angular velocity conditions (F = 2458.3, $p < 0.05$). Significant differences were observed among several angle-phases, except for P1 and P5, which represented the acceleration and deceleration angle-phases; however, the values were relatively consistent at the targeted angular velocities (30 and 60 °/s), indicating that the reliability and validity of the methodology used in this study regarding all angular velocity and load conditions. Furthermore, the angular velocities at 60 °/s were significantly faster than those at 30 °/s under all angle-phase and load conditions. Angular acceleration was significantly different among angle-phases (F = 1491.8, p < 0.05), and angle-phase × angular velocity × load (F = 7.8, p < 0.05) interactions. Angular accelerations at P1 and P5 significantly differed from those at all other angle-phases, irrespective of angular velocity and load conditions. P1 exhibited the highest angular acceleration, while P5 showed the lowest angular acceleration. Moreover, the angular accelerations for the 60°/s velocity condition were significantly higher at P1 and significantly lower at P5 than those for the 30°/s in both load conditions.

Table 4. Torque (Nm), angular velocity (°/s), and angular acceleration (° /s²).

		Angular velocity			
		30°/s		60°/s	
		Load			
	Angle-phase	Without load	With load	Without load	With load
Torque (Nm)	P1 (0-28°)	1.97 ± 0.62	3.82 ± 0.87 [c]	3.78 ± 0.70 [†††]	6.31 ± 1.56 [†††, c]
	P2 (28-56°)	0.82 ± 0.21 [***]	2.72 ± 0.58 [***, c]	1.22 ± 0.29 [***, †††]	3.54 ± 1.13 [***, †††, c]
	P3 (56-84°)	0.74 ± 0.21	2.41 ± 0.52 [**, c]	0.88 ± 0.19 [***, †]	2.84 ± 0.95 [***, †, c]
	P4 (84-112°)	0.52 ± 0.17 [***]	1.90 ± 0.62 [***, c]	0.85 ± 0.19 [†††]	2.04 ± 0.81 [***, c]
	P5 (112-140°)	0.77 ± 0.20 [***]	1.68 ± 0.78 [*, c]	1.29 ± 0.22 [***, †††]	2.05 ± 1.07 [†, b]
Angular velocity (°/s)	P1 (0-28°)	30.41 ± 2.42	27.85 ± 2.66 [c]	45.06 ± 2.45 [†††]	41.18 ± 3.86 [†††, c]
	P2 (28-56°)	32.25 ± 3.70 [*]	31.30 ± 2.80 [***]	61.22 ± 4.24 [***, †††]	59.97 ± 4.04 [***, †††]
	P3 (56-84°)	30.28 ± 2.54	31.98 ± 2.62 [a]	58.03 ± 3.93 [*, †††]	60.88 ± 3.87 [†††, a]
	P4 (84-112°)	30.80 ± 2.68	30.46 ± 2.00	55.95 ± 3.86 [†††]	58.33 ± 4.66 [†††, a]
	P5 (112-140°)	27.23 ± 3.34 [***]	27.49 ± 2.90 [***]	49.07 ± 5.27 [***, †††]	50.03 ± 4.99 [***, †††]
Angular acceleration (° /s)	P1 (0-28°)	117.19 ± 16.12	109.60 ± 16.89 [a]	203.27 ± 15.87 [†††]	196.00 ± 16.03 [†††]
	P2 (28-56°)	-20.56 ± 14.15 [***]	-1.98 ± 15.03 [***, c]	2.21 ± 11.09 [***, †††]	13.93 ± 14.76 [***, ††, b]
	P3 (56-84°)	9.84 ± 10.78 [***]	0.81 ± 9.04 [a]	-13.91 ± 17.86 [*, †††]	2.90 ± 20.41 [c]
	P4 (84-112°)	-5.63 ± 11.28 [*]	-9.00 ± 11.70	-5.80 ± 20.05	-18.26 ± 18.56 [†, b]
	P5 (112-140°)	-76.10 ± 13.28 [***]	-83.83 ± 15.72 [***, a]	-169.37 ± 21.35 [***, †††]	-167.21 ± 20.81 [***, †††]

Data are presented as mean ± standard deviation.
[*]: $p < 0.05$, [**]: $p < 0.01$, [***]: $p < 0.001$: significant differences between adjacent angles. The letters are added to the subsequent angle when there are significant differences.
[†]: $p < 0.05$, [††]: $p < 0.01$, [†††]: $p < 0.001$: Significant differences (30°/s angular velocity).
A: $p < 0.05$, [b]: $p < 0.01$, [c]: $p < 0.001$: Significant differences (without load).

4. Discussion

The main EMG results of this study showed that both BR and BB muscle activities increased during the initial angle phase of the elbow flexion from P1 (0–28°) to P2 (28–56°). Subsequently, characteristic activity patterns were observed for each muscle: BR muscle activity increased progressively with increasing elbow flexion, whereas BB muscle activity remained constant from P3 (56–82°) to P5 (112–140°). Additionally, the characteristics of the BB muscle activity pattern was more pronounced for the 60 °/s and with load condition: BB muscle activity plateaued from P1, the earliest elbow angle-phase of the elbow flexion.

4.1. Muscle activity

In the initial angle-phases from P1 to P2, both BR and BB muscle activity significantly increased. This synergistic activation patterns could be attributed to the need for greater torque generation and angular acceleration, as shown in Table 4. In the angle-phase posterior to P3, the muscle activity patterns in relation to the angle-phase under dynamic conditions were similar to those observed under static conditions in previous studies. [10-12, 23, 24] BR muscle activity increased as elbow flexion increased, which could be due to the BR increasing the recruitment of motor units as elbow flexion progressed. [10, 23, 24] Additionally, because the BR is located close to the elbow joint and has a shorter moment arm than the BB, it could be assumed that the contribution of the BR increased at the terminal angle-phase where power was required for full elbow flexion. The BB showed plateaued muscle activity patterns, which occurred because neural drive to the muscle is constant at any joint angle. [12] Moreover, because the BB has a longer moment arm than the BR, these data suggest that the BB supplied the required power by contributing to the extensive angular range of elbow flexion. These results suggest that the two muscles work synergistically to generate elbow flexion torque during dynamic movements.

This study demonstrated that the BB respond differently according to the combinations of angular velocity and load conditions. At 60 °/s with load conditions, BB muscle activity was relatively high at 0–28° (P1) and showed no significant differences among the angle-phases. This result may be attributed to the anatomical characteristics of the BB. The BB is a biarticular muscle[15, 25] with a longer muscle length than the BR, [3] and therefore, it is more suited to high-velocity movement and more heavily loaded condition.

Muscle activities of the TB_{lat} and TB_{long}, which constitute one of the antagonist muscles of elbow flexion, were relatively low (< 10 %MVC) during dynamic elbow flexion. Therefore, the activities of these antagonist muscles are likely not required in elbow flexion under the angular velocity and load conditions used in the present study.

4.2. Torque, angular velocity, and angular acceleration

Torques and angular accelerations at P1 were significantly higher, whereas angular accelerations at P5 were significantly lower than those at any other angle-phase because the beginning and ending of the motion requires more power; therefore, the increased or decreased torque and acceleration could be attributed to both BR and BB. Each angular velocity value was relatively stable under both the 30 and 60 °/s velocity conditions, indicating that angular velocity modulation does not affect the muscle activity patterns of the BR and BB during dynamic elbow flexion.

Our findings provide electromyographic support for the significance of BR and BB reconstructions in patients with brachial plexus palsy. Based on the EMG results, we concluded that impaired elbow flexion could be restored solely by BB reconstruction; however, reconstruction of both the BR and BB would be reasonable to achieve the dynamic elbow flexion as their muscle activity patterns differed depending on the elbow flexion angles. Furthermore, our findings have implications for physiotherapeutic rehabilitation; for example, if a therapist focuses on the BR, elbow flexion exercises in the terminal range of motion are more effective. In contrast, for the BB, continuous elbow flexion exercises utilizing the full range of motion are more effective.

This study has some limitations. First, we only measured muscle activity in young healthy adult males, and it remains to be shown that the muscle activity patterns of the BR and BB are different in females, elderly people, and patients with musculoskeletal or neurological dysfunction. Second, elbow movements in this study were controlled by a digital dynamometer; therefore, the experimental movements differed from natural movements. [26, 27] Third, the forearm position was maintained in supination; therefore, the difference in muscle activity patterns of the elbow flexors in the pronated or neutral forearm positions remains unknown, and further study is required. In particular, since BB muscle activity is influenced by forearm position, [28] the muscle activity pattern of the BB and its associated other elbow flexors would likely be different to that observed in the current study. Finally, the brachioradialis and pronator teres muscles, which constitute elbow flexors, were not evaluated in this study. In future studies, it is necessary to investigate how muscle activity patterns of these muscles differ from those of the BB and BR.

In conclusion, in healthy adult males, both elbow flexors synergistically activated and contributed to torque during the early phase of the movement. Subsequently, the muscle activity of the BR increased with increasing elbow flexion, while that of the BB plateaued. These results suggested that the BR and BB contributed to the control of the movement in a different way during dynamic elbow flexion.

Running head

Muscle activity patterns of the brachialis and biceps brachii

Author contributions

SD, HK, and TS conducted the literature review, conceived the study, and structured the study design. SD, KK were involved in the data acquisition. SD, HK, YI, and TS were involved in obtaining the ethical approval. SD performed the data analysis. SD, HK, KK, and TS contributed to the interpretation of the results and writing of the article. All authors read and approved the final manuscript.

Ethical compliance

Research experiments conducted in this article with animals or humans were approved by the Ethical Committee and responsible authorities of our research organization(s) following all guidelines, regulations, legal, and ethical standards as required for humans or animals.

Yes

Conflicts of interest

There are no conflicts of interest to declare.

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