The Journal of Physical Therapy Science

S P T S

Original Article

Muscle activation patterns in acceleration-based phases during reach-to-grasp movement

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Abstract.   [Purpose] An earlier study divided reaching activity into characteristic phases based on hand velocity profiles. By synchronizing muscle activities and the acceleration profile, a phasing approach for reaching movement, based on hand acceleration profiles, was attempted in order to elucidate the roles of individual muscle activities in the different phases of the acceleration profile in reaching movements. [Subjects and Methods] Ten healthy volunteer subjects participated in this study. The aim was to electromyographically evaluate muscles around the shoulder, the upper trapezius, the anterior deltoid, the biceps brachii, and the triceps brachii, most of which have been used to evaluate arm motion, as well as the acceleration of the upper limb during simple reaching movement in the reach-to-grasp task. [Results] Analysis showed the kinematic trajectories of the acceleration during a simple biphasic profile of the reaching movement could be divided into four phases: increasing acceleration (IA), decreasing acceleration (DA), increasing deceleration (ID), and decreasing deceleration (DD). Muscles around the shoulder showed different activity patterns, which were closely associated with these acceleration phases. [Conclusion] These results suggest the important role of the four phases, derived from the acceleration trajectory, in the elucidation of the muscular mechanisms which regulate and coordinate the muscles around the shoulder in reaching movements.
Key words: Reach-to-grasp movement, Electromyography, Acceleration

INTRODUCTION

Grasping is a highly dexterous and sophisticated process. The ability to reach, grasp, transport, and release objects is essential for performing activities of daily living (ADL)[1]. The ADL that require large glenohumeral elevation angles like combing hair and reaching are comparable to abduction and forward flexion motions[2]. This implies that rotator cuff muscle weakness can also affect the degree of restriction of ADL. However, during rehabilitation immediately after surgery, patients may need to learn compensatory movements for ADL[2]. Therefore, reach-to-grasp movement plays an important role in the rehabilitation of patients with shoulder disorders, and interest in the quantitative analysis of upper arm movements is rapidly increasing in biomechanical research and clinical applications.

Owing to the complexity of the reach-to-grasp movement, grasping movement research still lags behind that of gait. The gait phases can be clearly distinguished: the stride phase, stance phase, and swing phase. In addition, these phases are further divided into sub-phases, which are well established in gait analysis[3]. In contrast, the grasping movement is highly complex and depends on many factors, including the position and shape of the target, orientation, perturbation, and presence of

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obstacles[4]). To evaluate the kinematics of the reaching activity, Morasso investigated arm trajectories based on hand velocity profiles in 1983[5]). Subsequently, it was proposed that there are two independent components of the grasping movement: the transport component, and the grip component[6]). On the basis of this approach, a variety of reports have suggested the presence of a channel controlling hand aperture, which has access to information about the progress of hand transport[7, 8]), indicating the importance of regulation of the transport component. Supuk et al. demonstrated that the reach-to-grasp movement can be divided into characteristic phases by simultaneously observing two aspects of the movement, hand transport and finger preshaping, on 3D video recordings. They also suggested the importance of evaluation of reaching movement, that is, hand transport, by quantitative methods from the viewpoint of rehabilitation[9]).

Sabatini[10]) showed that natural upper-arm movement is composed of sequential phases of reaching, grasping, and retrieval in the horizontal plane, using electromyography (EMG) and a 3D-motion analysis system. Reach-to-grasp movement and hand velocity are regulated rigorously by an integrated complex of multiple muscle activities. Since single muscle activity regulates angular velocity in both acceleration and braking, a phasing approach of the reaching movement on the basis of hand acceleration profiles may provide a method for elucidating the role of individual muscles in the reaching movement of the reach-to-grasp task.

Muscle activities of the upper extremity during reaching movements have been examined by several investigators. Sabatini demonstrated that: the upper trapezius activity is tonic when holding the limb up against the force of gravity; the anterior deltoid activity is spread over the whole duration of the movement; the biceps brachii activity has a phasic drive at both movement onset and object grasping; and the triceps brachii activity is essentially tonic[10]). Prange compared the surface EMGs of the muscle activities of healthy elderly people with and without gravity compensation, and demonstrated that gravity compensation only influences the level of muscle activity, not the muscle activation pattern in terms of timing[11]). On the basis of these findings, it has been suggested that: the upper trapezius elevates the arm at the start of reaching and retrieval and appropriately positions the scapula during the movements; the anterior deltoid maintains a certain degree of shoulder abduction, to anteflex the shoulder during reaching and to decelerate retroflexion during retrieval; the biceps brachii lifts and holds the lower arm above the table and aids in anteflexion of the shoulder; and the muscle activity of the triceps brachii contributes to extension of the elbow towards the target[10, 11]).

It is very important to evaluate reaching with quantitative methods for rehabilitation, in order to objectively assess and describe the coordination and functional status of the impaired upper limb. The analysis of reach-to-grasp phases could potentially help determine how the impairment affects the upper limb movements and to plan the rehabilitation process more effectively. Annett et al. examined the control of movement in the dominant and non-dominant hands, and reported that non-dominant arm motor output was subject to increased variability, which necessitated a greater number of corrective movements[12]). The present study focused on the reaching movement, namely, hand transport in the reach-to-grasp task. By synchronizing muscle activities and the acceleration profile, phasing of the reaching movement of the hand based on acceleration profiles, was attempted in order to elucidate the direct role of the individual muscle activities in the different acceleration profiles, differences between the dominant arm and the non-dominant arm muscle activation patterns in the reaching movement. The ultimate goal of the present research is to establish a method of evaluation of hand movements for rehabilitation.

SUBJECTS AND METHODS

Ten healthy volunteer subjects (four males, six females; age, 21.5 ± 1.0 years; height, 162.1 ± 8.4 cm; weight, 55.8 ± 8.6 kg; mean ± SD) with no neurological or muscular disorders, participated in this study. They were all right-hand dominant, and subjects were excluded if they had received surgery related to upper limb structures.

The subjects were fully informed about the protocol and gave their informed consent to the experimental procedure, which was approved by the Epidemiological Research Ethics Committee of Gunma University Faculty of Medicine (No. 25–29).

The aim of this study was to evaluate EMG and acceleration of the upper limb during a simple reaching movement in a reach-to-grasp task. The task was to move the arm from the initial position in order to grasp a target in front of it. The target-reaching movements were performed in the sagittal plane and corresponded to a cylindrical palmar prehension motion.

The test procedure was performed according to Louis et al[13]). Briefly, the subjects were seated in front of a table. The measurements were carried out in the order of the dominant and then the non-dominant upper extremity. In the initial position, the measured forearm rested on the table and the shoulder was stabilized in the anatomical reference position with the elbow at 90° flexion. Before beginning the movement, the arm was relaxed. The target was placed at a distance of 30 cm in front of the hand on the table. The subjects were informed that no trunk movement was allowed, so they could only move the arm in order to grasp the target. To simulate reaching in normal life, the target was a 0.5 kg cylindrical bottle (6.5 cm in diameter). At the end of the movement, the measured forearm rested on the table in the initial position. The movements were repeated 10 times. The average values of the 10 trials were used as representative of each subject, after confirmation of the normal distribution of data using the Shapiro-Wilk's test.

The EMG signals of four muscles were recorded, the upper trapezius, the anterior deltoid, the biceps brachii, and the triceps brachii, most of which have been used to evaluate arm motion[14]). The subjects were prepared for the placement of EMG electrodes by shaving the skin of each electrode site and cleaning it carefully with an alcohol wipe. Pairs of Ag-AgCl

pregelled surface electrodes (DL-141, S & ME Co., Japan) were applied along the muscle fibers over the bellies of the four muscles for EMG data acquisition, as described by Zipp[15]. Electrode placement was confirmed by voluntary muscle contraction. The electrodes were secured with surgical tape and a cloth wrap to minimize disruption during the movement. A ground electrode was placed on the wrist on the side opposite to the measured upper extremity.

Acceleration was recorded with an accelerometer attached to the measured wrist (the dorsal midpoint between ulnar and radial styloid processes). The accelerometer was secured with surgical tape and a cloth wrap to minimize disruption during the movement. The x-axis was the orientation of the long axis of the forearm. Acceleration of the forward movement was recorded along the x-axis.

Verification of signal quality was completed for each muscle by having the subject perform a resisted contraction in muscle test positions specific to each muscle of interest[16]. For a normalization reference, EMG data were collected during maximal voluntary contraction (MVC) in a resisted contraction in each of the manual muscle testing positions. Data were sampled in two 3-second trials during manually resisted maximal contractions of each muscle. The highest value (averaged over 1 second) was used as the normalization reference. For all EMG raw data, m-Scope (S & ME Co., Japan) was utilized for recording and analysis. After band pass-filtering between 15–500 Hz and sampling at 1,000 Hz, root mean square (RMS) values were calculated. The MVC values were used to normalize the EMG signal amplitude of the reach-to-grasp movement. The relative value was calculated by dividing the average RMS of the reach-to-grasp movement by the RMS of the MVC value.

The notation A (sampled at 1,000 Hz) is used to refer to the acceleration. The x-axis acceleration was analyzed from the starting point of the reach-to-grasp movement to the second zero point. The velocity was calculated by through time integration of the acceleration.

SPSS software package version 21 was used for all statistical analyses. The calculated percent MVC values of the four muscles were compared during the reach-to-grasp movement. Comparisons of the percent MVC values of the resting seated posture and reach-to-grasp movement phases were performed using repeated-measures analysis of variance. To determine the significance of differences, Tukey's test was used as a post hoc test. The paired-samples t-test was used to test differences between the dominant and non-dominant upper extremities. In all of these tests, the significance level was 0.05.

RESULTS

Figure 1 shows a representative case with corresponding acceleration curves and EMG activities. The acceleration curve was essentially a diphasic complex, as already noted[9]. In the present study, the simple biphasic profile of the reaching movement starting from a value of 0 acceleration (point 0 in Fig. 1) and returning to that from a negative value (point e) was analyzed.

Subjects focused on accelerating the hand in order to reach peak velocity (point a) at approximately one-third of the duration of the movement evaluated here. After the acceleration peak, the acceleration gradually reduced to 0 (point b), where the hand reached peak velocity at half of the duration of the movement. Then, the subjects rapidly decelerated the hand, and after the declaration peak (point c), deceleration rapidly reduced until 0 (point e), where backward movement of the hand reached peak velocity at four-fifths of the duration of the movement. During the reduction phase of the deceleration, hand movement changed smoothly from the forward direction to the backward one at point d, indicating the turning point of the hand movement to the backward direction. This finding, that acceleration was still negative when the velocity value returned to 0, was observed in all subjects. After peak velocity of the backward direction (point e), increase and decrease in acceleration occurred until the next peak velocity of the forward direction (data not shown). Then, the change of acceleration and deceleration, followed by the change in forward and backward directions with a small time lag, were repeated several times with reduction in the lag time; the values of the acceleration and velocity until the point of zero acceleration corresponded to that of velocity, when transportation of the hand toward the object was completed (data not shown). On the basis of the acceleration profile, this reaching movement of the reach-to-grasp task could be divided into four phases: an increasing acceleration (IA) phase, a decreasing acceleration (DA) phase, an increasing deceleration (ID) phase, and a decreasing deceleration (DD) phase.

EMG activities showed different levels and muscle activity patterns among the muscles examined here. Since the pattern of each muscle activity seemed to be associated with the acceleration profile shown in Fig. 1, the muscle activities were analyzed separately in each phase. Interestingly, the active phases of each muscle varied among the muscles examined here (Table 1). Significant increases in the upper trapezius activity were observed in both Phase IA and Phase DD compared with the resting position, by approximately 5- and 3.5-fold, respectively (Table 1). The anterior deltoid muscle was constantly active during all the phases. Furthermore, the activity was gradually augmented and reached approximately 10 times that of the resting position (Table 1). Significant increases in the biceps brachii activity were observed in Phases IA, ID, and DD (Table 1), by approximately 2.5-fold. A significant increase in the triceps brachii muscle activity was observed only in Phase DD, by 1.5-fold (Table 1). There was little difference between the muscle activities of the backward and forward movements in Phase DD (data not shown).

Percent MVCs of the dominant and non-dominant upper extremities were compared in the phases in which the muscles were significantly active compared to the resting position (Table 2). These comparisons found there were significant differ-
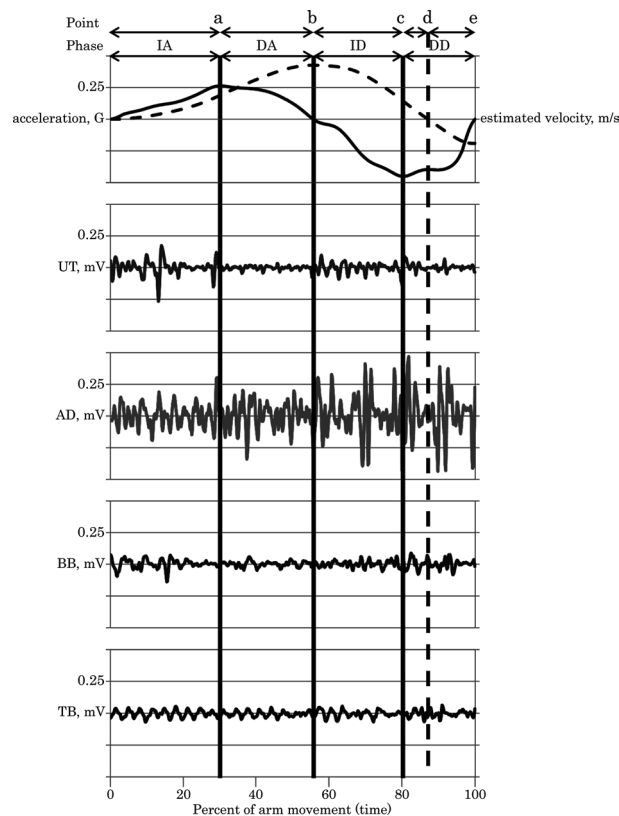
Fig. 1. Patterns of acceleration (solid line), estimated velocity (dotted line), and muscle activation of the upper trapezius (UT), anterior deltoid (AD), biceps brachii (BB), and triceps brachii (TB) muscles during a reach-to-grasp movement for a representative object

Acceleration and estimated velocity of the forward movement along the long axis of the forearm are depicted. IA: increasing acceleration phase, DA: decreasing acceleration phase, ID: increasing deceleration phase, DD: decreasing deceleration phase

ences between the dominant and non-dominant upper extremities in Phases IA and DD for the upper trapezius activity, and in Phases ID and DD for the biceps brachii activity. The percent MVCs of the non-dominant upper extremity in each phase of these muscles were all larger than those of the dominant extremity.

DISCUSSION

Analysis showed the kinematic trajectories of acceleration during a simple biphasic profile of the reaching movement in a reach-to-grasp task could be divided into four phases: increasing acceleration (IA) phase, decreasing acceleration (DA) phase, increasing deceleration (ID) phase, and decreasing deceleration (DD) phase. Muscles around the shoulder showed different activity patterns, which were closely associated with these acceleration phases. Interestingly, significantly smaller muscle activities for the dominant extremity, approximately two-thirds of those of the non-dominant one, were observed in Phases IA and DD for the upper trapezius and Phases ID and DD for the biceps brachii.

There have been few studies evaluating the EMG activity patterns of muscles around the shoulder in association with the kinematics of a reaching movement. Sabatini showed the EMG activities were characterized by phasic drives in some muscles around the shoulder during reaching movement, although what was related to the phasic pattern among the kinematic parameters was not elucidated[10]. Phases divided on the basis of the velocity trajectory, which is bell-shaped[5], might be related to the phasic drives of the muscles' activities. The peak of the velocity profile was reported to divide the reaching movement into a hand acceleration phase (positive values of tangential acceleration) and a hand deceleration phase (negative values of acceleration)[9, 17]. The present study showed that this hand acceleration phase is composed of Phases IA and DA. In the upper trapezius and biceps brachii muscles, EMG activation was observed only in Phase IA. The hand deceleration phase was composed of Phase ID and a part of Phase DD. Similarly, in the upper trapezius and triceps brachii muscles, EMG activation was observed only in Phase DD. These findings indicate that the muscle activities examined here were related to the acceleration profile, but not to the velocity profile of the reaching movement in the reach-to-grasp task. These results suggest the importance of the four phases derived from the acceleration trajectory for the elucidation of the muscular mechanisms

Table 1. Comparison of the muscle activities of the upper trapezius, anterior deltoid, biceps brachii, and triceps brachii muscles in each acceleration phase

	Rest	Acceleration phase		Deceleration phase	
		IA	DA	ID	DD
UT (%MVC)	7.5 ± 6.1	37.7 ± 22.3*	16.8 ± 22.2[a]	20.0 ± 9.2[b]	26.5 ± 16.3*[c, e]
AD (%MVC)	4.3 ± 3.2	30.7 ± 10.3*	33.0 ± 13.3*	37.5 ± 20.8*[b]	42.4 ± 29.6*[c, e]
BB (%MVC)	8.0 ± 11.7	19.5 ± 11.9*	14.3 ± 13.4[a]	20.3 ± 16.4*[d]	21.6 ± 17.9*[e]
TB (%MVC)	14.3 ± 8.2	15.5 ± 7.7	17.2 ± 7.6	19.4 ± 11.9	22.6 ± 13.6*[c, e, f]

Data presented as mean ± SD. UT: upper trapezius, AD: anterior deltoid, BB: biceps brachii, TB: triceps brachii
IA: increasing acceleration, DA: decreasing acceleration, ID: increasing deceleration, DD: decreasing deceleration, SD: standard deviation. *Significant ($p < 0.01$) difference between rest and movement phases, respectively; [a]Significant ($p < 0.01$) difference between IA and DA; [b]Significant ($p < 0.01$) difference between IA and ID; [c]Significant ($p < 0.01$) difference between IA and DD; [d]Significant ($p < 0.01$) difference between DA and ID; [e]Significant ($p < 0.01$) difference between DA and DD; [f]Significant ($p < 0.05$) difference between ID and DD

Table 2. Comparison of percent MVC of the dominant and non-dominant upper extremities in the phases in which muscle were significantly active compared to the resting position

(%MVC)		Dominant	Non-dominant
UT	Phase IA	37.7 ± 22.3	49.7 ± 33.1 *
	Phase DD	26.5 ± 16.3	33.3 ± 17.3 *
AD	Phase IA	30.7 ± 10.3	32.6 ± 10.7
	Phase DA	33.0 ± 13.3	32.0 ± 9.9
	Phase ID	37.5 ± 20.8	38.6 ± 17.6
	Phase DD	42.4 ± 29.6	43.0 ± 25.8
BB	Phase IA	19.5 ± 11.9	18.5 ± 7.9
	Phase ID	20.3 ± 16.4	26.2 ± 14.8 *
	Phase DD	21.6 ± 17.9	35.8 ± 23.8 *
TB	Phase DD	22.6 ± 13.6	30.1 ± 33.6

Data presented as mean ± SD. UT: upper trapezius, AD: anterior deltoid, BB: biceps brachii, TB: triceps brachii, IA: increasing acceleration, DA: decreasing acceleration, ID: increasing deceleration, DD: decreasing deceleration, SD: standard deviation. *Significant ($p < 0.05$) difference between percent MVC of dominant and non-dominant upper extremities

which regulate and coordinate the muscles around the shoulder in reaching movements.

It is interesting and unexpected that hand movement changed smoothly from the forward to the backward direction during Phase DD, the reduction phase of deceleration. Similar findings that the acceleration value was still negative when the velocity value returned to 0 were reported by Supuk et al[9]. In the present study, several repeated cycles of acceleration and deceleration in a short period followed the period analyzed here. It is possible that there is a precise regulatory mechanism when the palm approaches the target. Careful and precise examination will be needed to elucidate the possible factors contributing to the delicate kinematics operating in this late stage of the reach-to-grasp task, which might correspond to the phase of final closure of the fingers as reported by Supuk et al[9]. On the other hand, there was little difference in the muscular activity of backward and forward movements in Phase DD, confirming that the muscle activities examined here were related to the acceleration profile, but not the velocity profile.

The upper trapezius was activated during Phases IA and DD (Table 1). Muscle activity of the upper trapezius was more frequently present during the early acceleration phase. Since the arm is not supported against gravity, a component of the upper trapezius activity is tonic, and results from holding the limb up against the force of gravity, particularly in the last period of the reaching movement[10]. The muscle activity has also been shown to be characterized by phasic drives that occur at the movement onset and at the time when the object is grasped[10]. The upper trapezius was active in elevating the arm at the start of reaching and in appropriately positioning the scapula during the movements[11]. The upper trapezius' primary capability was elevation[18]. The upper trapezius acts to resist the downward rotation torques believed to occur via the reverse action of the glenohumeral muscles, including the deltoid, cuff muscles, and triceps brachii, acting on the scapula[19]. Together, these results suggest that the role of the upper trapezius activity may be to hold up the limb against the force of gravity during Phase IA, and reverse the action of the deltoid and triceps brachii muscles for fine control of transportation of the hand toward the

object by stabilizing the scapula in Phase ID. The muscle may also play a reverse role to the deltoid muscle and biceps brachii in scapular stabilization in Phase IA.

The anterior deltoid was activated and gradually augmented over the whole duration of the movement. The anterior deltoid has been shown to be active to maintain a certain degree of shoulder abduction and to anteflex the shoulder during reaching movements[11]. The deltoid muscle activity reaches an initial peak at 110 degrees when the arm is fully elevated above the head[20]. It is conceivable that anterior deltoid muscle may produce shoulder flexion force with increasing shoulder moment to suspend the upper arm against the force of gravity, which may result in the continuous increase in its muscle activity seen throughout the reaching movement.

The biceps brachii was activated in Phases IA, ID, and DD. The biceps brachii is active in lifting and holding the lower arm above the table and aids the anteflexion of the shoulder[11]. In the elbow flexors, electrical neuromuscular stimulation of the biceps brachii induced the motion of flexion and supination[21]. Thus, the biceps brachii may lift and hold the lower arm above the table during the early acceleration phase. It is interesting that the muscle was not activated in Phase DA, suggesting that the moment of lifting the forearm may not be due to muscle activity but to inertia in this phase. On the other hand, the muscle was active in the deceleration phase, the phase when braking of the movement's velocity occurs. The biceps brachii muscle's activity may play a role in braking elbow extension, resulting in reduction in the speed of reaching.

Significantly lower muscle activity of the triceps brachii was observed in Phase DD. The muscle activity of the triceps brachii has been shown to be very low, sometimes nearly absent, in the extension of the elbow towards the target[11]. It should be noted that the precise muscle regulatory mechanism, when the palm closely approaches the target with repeated forward and backward movements, may start in Phase DD. Therefore, it is possible that the purpose of the triceps brachii activity may be fine control of transportation of the hand, coordinated with the antagonistic biceps brachii, close to the object during Phase DD.

The possible roles of the muscles examined here may be summarized in each phase as follows: the upper trapezius elevates and stabilizes the shoulder girdle, the anterior deltoid produces the moment of shoulder flexion, which initiates forward movement of the upper arm, and the biceps brachii lifts the lower arm above the table during Phase IA; in Phase DA, the anterior deltoid keeps producing the power for shoulder flexion with increasing shoulder moment to suspend the upper arm against the force of gravity, while the other muscles are inactive, suggesting reduction of acceleration; in Phase ID, the biceps brachii acts as a braking mechanism by resisting elbow extension. Finally, in Phase DD, the biceps brachii acts as a brake, the anterior deltoid is still active to keep the upper arm suspended against the force of gravity, and in response to these muscles' activities, the triceps brachii is activated to achieve delicate and fine control of transportation of the hand toward the object when it is very close to it, resulting in the reduction of deceleration. In response to these glenohumeral muscles' activities, upper trapezius activity is induced to stabilize the scapula against downward movement.

Significantly smaller muscle activities of the upper trapezius and biceps brachii muscles of the dominant extremity were observed in the deceleration phase. Annett et al. examined the control of movement in the dominant and non-dominant hands, and reported that non-dominant arm motor output was subject to increased variability, which necessitated a greater number of corrective movements[12]. Recent research investigating the dominant arm advantage of the finger in 15-cm-long movements on a table has indicated that the dominant arm consistently uses more torque-efficient patterns for movements that were made with similar speeds and accuracy than the non-dominant arm movements, since muscle torque impulses were substantially lower at the shoulder of the dominant arm[14]. The authors proposed that distinct neural control mechanisms are employed for dominant and non-dominant arm movements[14]. This suggests that the dominant arm may use more torque-efficient patterns in both the shoulder and elbow joints than the non-dominant arm. On the other hand, it is unclear why muscle activities of the upper trapezius in the IA and DD phases, and the biceps brachii in the ID and DD phases, reduced in association with the putative neural control mechanism. The usual roles of these muscle activities may be the regulation of arm reaching, action to counter glenohumeral activity, and braking action against forward movement of the arm, respectively. Bagesteiro and Sainburg demonstrated a significant difference in direction error and deviation from linearity between dominant and non-dominant arm movements[14], implying excessive motion in non-dominant arm movement. Over-activation of regulatory muscles such as the upper trapezius and biceps brachii may be elicited by responding to possibly inefficient direction error, but not a less efficient torque strategy of the non-dominant arm.

There were several limitations to this study. The velocity was calculated through time integration of the acceleration. To elucidate the correlation between velocity and acceleration precisely, direct measurement of velocity and acceleration will be necessary. Also, the present study focused on only four muscles around the shoulder. Other muscles should be examined on the basis of the acceleration phases presented here so that the role of each muscle in concert with the others can be elucidated.

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