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Muscle recruitment and coordination during upper-extremity functional tests

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ABSTRACT

Performance-based tests, such as the Jebsen Taylor Hand Function Test or Chedoke Arm and Hand Activity Inventory, are commonly used to assess functional performance after neurologic injury. However, the muscle activity required to execute these tasks is not well understood, even for unimpaired individuals. The purpose of this study was to evaluate unimpaired muscle recruitment and coordination of the dominant and non-dominant limbs during common clinical tests. Electromyography (EMG) recordings from eight arm muscles were monitored bilaterally for twenty unimpaired participants while completing these tests. Average signal magnitudes, activation times, and cocontraction levels were calculated from the filtered EMG data, normalized by maximum voluntary isometric contractions (MVICs). Overall, performance of these functional tests required low levels of muscle activity, with average EMG magnitudes less than 6.5% MVIC for all tests and muscles, except the extensor digitorum, which had higher activations across all tasks (11.7 ± 2.7% MVIC, dominant arm). When averaged across participants, cocontraction was between 25 and 62% for all tests and muscle pairs. Tasks evaluated by speed of completion, rather than functional quality of movement demonstrated higher levels of muscle recruitment. These results provide baseline measurements that can be used to evaluate muscle-specific deficits after neurologic injury and track recovery using common clinical tests.

1. Introduction

Muscle recruitment and coordination are commonly impaired after stroke and negatively impact function. In the United States alone, over 600,000 people experience their first stroke each year (Go et al., 2013) and 80% of these people experience hemiparesis (Sommerfeld et al., 2004), most commonly impacting arm and hand function (Trombly, 1989). Clinical tests, such as the Jebsen Taylor Hand Function Test (Jebsen et al., 1969) or Chedoke Arm and Hand Activity Inventory (Barreca et al., 2005), are often used to evaluate and track functional recovery of the upper-extremity. While clinical tests provide insight into functional performance (Beebe and Lang, 2009b; Lang et al., 2013), they provide limited insight into changes in neuromuscular control that may be either contributing to or hindering recovery (Okkema and Culler, 1998). Quantifying normative patterns of muscle recruitment and coordination during these common clinical tests may illuminate the neuromuscular demand required for common tasks and provide baselines for evaluating clinical populations.

Electromyographic (EMG) recordings provide a window into the central nervous system to evaluate muscle recruitment and coordination. Surface EMG signals can be non-invasively monitored from many key upper-extremity muscles during dynamic tasks. After stroke, EMG recordings have been used to evaluate synergistic patterns of muscle activity (Clark et al., 2010; Cruz et al., 2005; Dewald et al., 1995), control assistive devices (Ho et al., 2011; Song et al., 2008), guide biofeedback training (Armagan et al., 2003; Huang et al., 2006; Moreland and Thomson, 1994; Woodford and Price, 2007), and inform other applications.

While prior work has demonstrated that EMG recordings can serve as a powerful tool in research, there remains limited use of this tool in the clinic. In research, EMG recordings are often taken in controlled environments, such as protocols that involve specific force profiles (Roh et al., 2013) or movement trajectories (Beer et al., 2000; Chae et al., 2002; Rasool et al., 2017; Sarcher et al., 2017). However, there are few examples of upper-extremity EMG analyses examining muscle function during activity-based or unconstrained tasks of daily living (Jakobi

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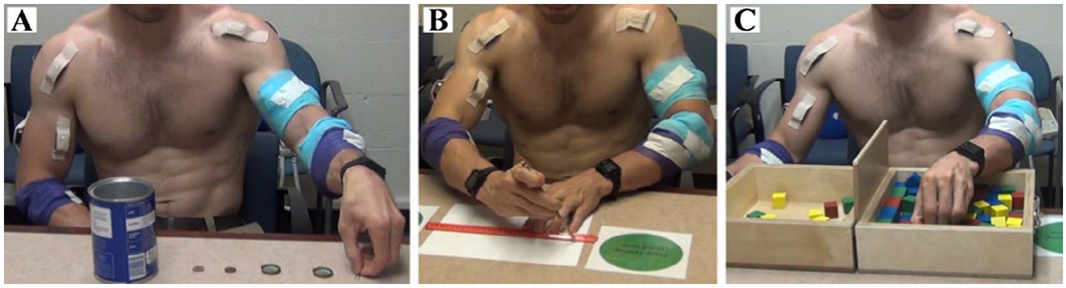

Fig. 1. Three common clinical tests of upper-extremity function were evaluated in this research. (A) The Jebsen Taylor Hand Function Test (JTHF) involves seven unimanual tasks, including moving small common objects in succession into a can. (B) The Chedoke Arm and Hand Activity Inventory Version 13 (CAHAI-13) evaluates bimanual function and was modified to 12 tasks, including drawing a line with a ruler. (C) The Box and Block Test (BBT) assesses unimanual function by asking participants to move as many wooden blocks from one side of a rectangular box to another within one minute.

et al., 2008; Kern et al., 2001). For example, Jakobi et al. (2008) evaluated muscle activity over four hours for one stroke survivor and found notable differences between the affected and unaffected arms; suggesting tracking muscle recruitment may inform clinical evaluation.

While EMG data is not commonly used to evaluate function after neurologic injury, many studies and clinics use performance-based tests to monitor function. A wide variety of clinical tests have been used to evaluate impaired arm function. These tests typically evaluate functional performance as the time to complete a task or successful task completion using unconstrained tasks simulating activities of daily living (Beebe and Lang, 2009b). For example, the Jebsen Taylor Hand Function Test evaluates the time required to complete common one-handed tasks such as writing, eating, or moving small objects, with a faster time indicative of desired performance. Clinical tests and measures are also used extensively in research to assess performance after interventions such as transcranial magnetic stimulation (Gomes-Osman and Field-Fote, 2015; Hummel et al., 2005), robot and gravity-assisting exercises (Krishnaswamy et al., 2016), virtual reality rehabilitation (Shin et al., 2014), or constraint-induced movement therapy (McCall et al., 2011; Gordon et al., 2011). While these tests provide valuable metrics to track and guide rehabilitation, current performance metrics provide limited insight into the mechanisms contributing to the impaired movement. For example, individuals may use compensatory strategies to execute tasks quickly (Lum et al., 2009), but mask deficits that may hinder more complex activities. Without monitoring EMG data during these tests, there is a gap in our understanding of how changes in muscle recruitment and coordination influence functional performance and recovery.

The aim of this research was to evaluate how unimpaired individuals recruit and coordinate their muscles during common upper-extremity clinical tests. Specifically, we evaluated muscle recruitment and coordination from eight upper-extremity muscles during three common activity-based clinical tests: (1) Jebsen Taylor Hand Function Test, (2) Chedoke Arm and Hand Activity Inventory, and (3) Box and Block Test. We evaluated which muscles were used to execute each task, if differences exist between dominant and non-dominant limbs, and whether activation and cocontraction levels were similar across tasks. Establishing normative patterns of recruitment and coordination can assist in understanding the neuromuscular demands of clinical tests and support future evaluations of patient-specific deficits.

2. Methods

2.1. Participants

A convenience sample of 20 unimpaired individuals, including 12 males and 8 females (avg ± std, age 27 ± 5.7 years, height 1.74 ± 0.09 m, mass 72.6 ± 11.0 kg) were recruited to participate in the present study. Participants reported no known neurological, visual, or orthopedic impairments, and were asked to perform three clinical tests while wearing upper-extremity EMG sensors in one test session. The protocol was approved by the University of Washington Institutional Review Board for Human Subjects Research, and all individuals provided informed consent prior to participation.

2.2. Protocol

Functional tests: We selected three common clinical tests of upper-extremity function: the Jebsen Taylor Hand Function Test (JTHF), Chedoke Arm and Hand Activity Inventory Version 13 (CAHAI-13), and Box and Block Test (BBT). These standardized tests evaluate both unimanual (JTHF, BBT) and bimanual (CAHAI-13) tasks and are designed to assess function in people with neurologic or orthopedic conditions impacting arm and hand use.

The JTHF consists of seven tasks that are completed with one arm, including writing, card turning, moving small common objects, simulated feeding, stacking checkers, moving empty food cans, and moving full cans while seated at a standard height table with knees and hips at 90° flexion (Fig. 1A). Task items had a starting position 127mm perpendicular from the edge of the table, save for the simulated feeding task, which places kidney beans approximately 143mm from the edge of the table. The JTHF tasks were completed with both the dominant and non-dominant arms, with the order randomized for which arm performed each task first. Performance on the JTHF was evaluated by the time to complete each of the seven tasks. Jebsen et al. (1969) reported a repeatability of r = 0.92 for the time to complete the JTHFT for individuals with hand impairment from brain injury, stroke, or rheumatoid arthritis.

The CAHAI-13 is a bimanual performance test using common functional activities of daily living, and has shown sensitivity to changes post-intervention (Barreca et al., 2006). Activities of the CAHAI-13 include opening a jar of coffee, dialing a telephone, drawing a line with a ruler, pouring a glass of water, wringing a washcloth, buttoning a shirt, drying the back with a towel, applying toothpaste to a toothbrush, cutting food with knife and fork, zipping up a zipper, cleaning a pair of glasses, and placing a container (4.5kg) on a table (Fig. 1B). Evaluation is based on the level of independence and quality of movement and does not require quick completion of tasks. Note that two modifications were made to the standard CAHAI-13 protocol: (1) since we were focusing on arm function, participants were not asked to carry a bag up the stairs and (2) the pitcher of water contained enough water to fill the cup ¾ full to maintain comparability with clinical protocols. The modified CAHAI-13 was performed once, with each participant using the arm(s) of their choice to execute each task. Note the CAHAI-13 evaluates whether participants can successfully complete each task and is not timed. Barreca et al. (2005) reported a repeatability of 0.98 for the CAHAI-13 for stroke survivors with a minimal detectable score of 6.3 on the CAHAI-13 point scale.

In the BBT, participants are seated and asked to move as many wooden cubes (2.5 cm) in one minute from one side of a rectangular box, over a 19 cm height partition, and into the side of the box opposite the tested arm (Fig. 1C). The BBT was administered three times per arm, with arm order randomized. The number of blocks successfully transferred during each trial was used to evaluate BBT performance. Desrosiers et al. (1994) reported a test-retest reliability of 0.89–0.97 for the BBT among participants with upper-extremity impairment.

Electromyography: Surface EMG data were recorded from eight upper-extremity muscles on each arm: anterior deltoid (AD), posterior deltoid (PD), biceps brachii (Bic), triceps lateral head (Tri), brachioradialis (Br), extensor carpi radialis longus (ECRL), flexor carpi ulnaris (FCU), and extensor digitorum communis (ExtD) using a Trigno Wireless EMG System (Delsys, Boston, MA, USA). EMG data were recorded at 1111 Hz, with an effective EMG signal gain of 909 V/V ± 5%, and hardware signal processing including a band-pass filter (20–460 Hz). Electrodes were placed on each muscle following Surface Electromyography for the Non-Invasive Assessment of Muscles (SENIAM) recommendations for proximal arm muscles, and forearm muscle placements were measured relative to bony landmarks and manual muscle testing. Excessive hair was removed, and skin was abrasively wiped with an alcohol preparation pad and allowed to dry prior to attaching the electrodes with double-sided tape. After the electrode signal quality was assessed, sensor attachments were maintained with a light wrap of Coban™ or tape. Note that data fromfaulty EMG sensors were removed from Participant 2 for the dominant and non-dominant Bic and FCU, Participant 10 from the non-dominant AD and Bic channels, and Participant 13 for the non-dominant AD.

EMG data were processed in MATLAB (MathWorks, Inc., Natick, MA, USA). Each muscle's EMG data were high-pass filtered (40 Hz, 4th order Butterworth), rectified, and low-pass filtered (40Hz, 4th order Butterworth) to calculate the linear envelope describing muscle activation. We selected a cut-off frequency of 40 Hz for the low-pass filter to ensure we maintained signal detail during the quick pace of the tasks in the JTHF and BBT (~1.3 blocks/second). Maximum voluntary isometric contractions (MVICs) were performed for each muscle at the beginning of each data collection to normalize the EMG data. During the MVIC tests, the arm was supported to isolate the distal joint of the muscle being tested. Resistance was applied manually at the distal end of the moving segment, with a static postural hold at or near 50% of the respective joint's active range of motion. The study staff applied resistance matching participants' comfortable force levels. The participants were asked to hold the MVIC for five seconds while strong verbal encouragement was given, with ten seconds of rest between each muscle. The 95th percentile of the filtered EMG data for the MVIC trial of each muscle was used to normalize the EMG data for comparison between participants.

2.3. Analyses

To evaluate muscle recruitment levels during functional tasks, our primary outcome measure was the average magnitude of the EMG signal, normalized to percent of MVIC (%MVIC) for each muscle during each task. This metric was chosen to represent the average muscle recruitment during these common clinical tests. Peak EMG signal magnitude and activation time were also assessed as secondary outcome metrics. For activation time, an activation threshold of 5% MVIC (Fig. 2) was selected to capture the amount of time each muscle had a moderate to intense activity level (Tikkanen et al., 2013). Activation time was expressed as the percent of time the EMG signal was above this threshold for each task. Due to the lag in time between the start of the EMG recording and vocal instruction for the participant to begin each task, the on-board accelerometer (signal gain 2.421 ± 0.233 V/g) of the Bic EMG sensor was used to manually parse the initiation and cessation of each task. Tasks were truncated based on the initial change in signal slope (task start), and last known change in slope (task finished).

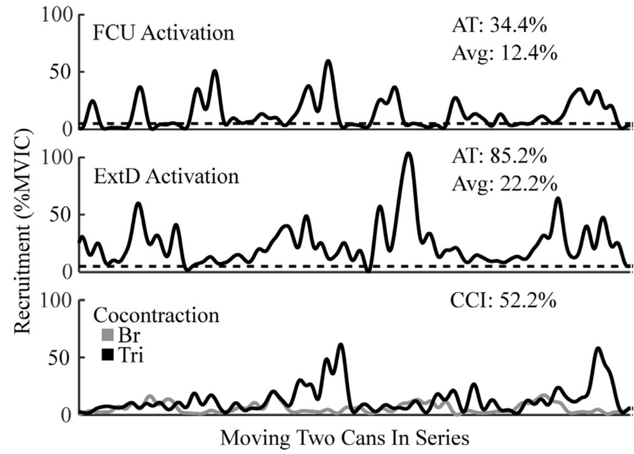

Fig. 2. A sample of the processed EMG data and outcome measures from the dominant arm for one participant during the full cans task of the JTHF. For clarity, the EMG data is shown during the time period required to move two of the five cans during this task. The horizontal dashed line is the threshold (5% MVIC) for activation time (AT). The AT and average recruitment (Avg) were computed for all five cans for the FCU and ExtD (inset values). The cocontraction index (CCI) was calculated by comparing the activation of pairs of muscles. An example of CCI for the brachioradialis (Br) and triceps (Tri) muscle pairing (BrT) is shown. To see more participants or tasks, please view the interactive graphics (https://tableau.washington.edu/views/JEK_MuscleRecCoord/Story_Musc_RecruitmentCoordination).

To evaluate muscle cocontraction, we calculated the percent cocontraction for four muscle pairings: anterior and posterior deltoid (AP), biceps and triceps (BT), brachioradialis and triceps (BrT), and flexor carpi ulnaris and extensor carpi radialis longus (FE). Percent cocontraction (%COCON) was calculated as described by Winters (2009) comparing the overlapping integrated areas of the linear envelopes relative to the total integrated area of both muscles:

$$\%COCON = 2 \times \frac{common\ area\ A\&B}{area\ A + area\ B} \times 100\% \tag{1}$$

where A and B correspond to the linear envelopes of each muscle in the pair.

2.4. Statistics

For each task and muscle, the average and peak EMG magnitude, activation time, and %COCON were calculated for each participant. Paired t-tests with Bonferroni corrections for multiple comparisons were used to evaluate differences in each measure between the dominant and non-dominant arms. Linear regression was used to evaluate whether muscle activity was related to performance by comparing the average EMG magnitude, peak magnitude, activation time, and %COCON of each muscle or muscle pair to performance (time to complete each JTHF task and number of blocks in BBT).

2.5. Repeatability

A convenience sample of three participants (1 female, 2 males) was chosen for intra- and inter-day repeatability analyses. On two consecutive days, MVICs were collected and JTHF and CAHAI-13 were repeated twice. BBT was repeated three times for the 20 participants on the original testing day. Pearson product-moment correlations were calculated to assess the intra-day and inter-day repeatability of the traditional performance metrics and average EMG magnitude for each muscle and task.

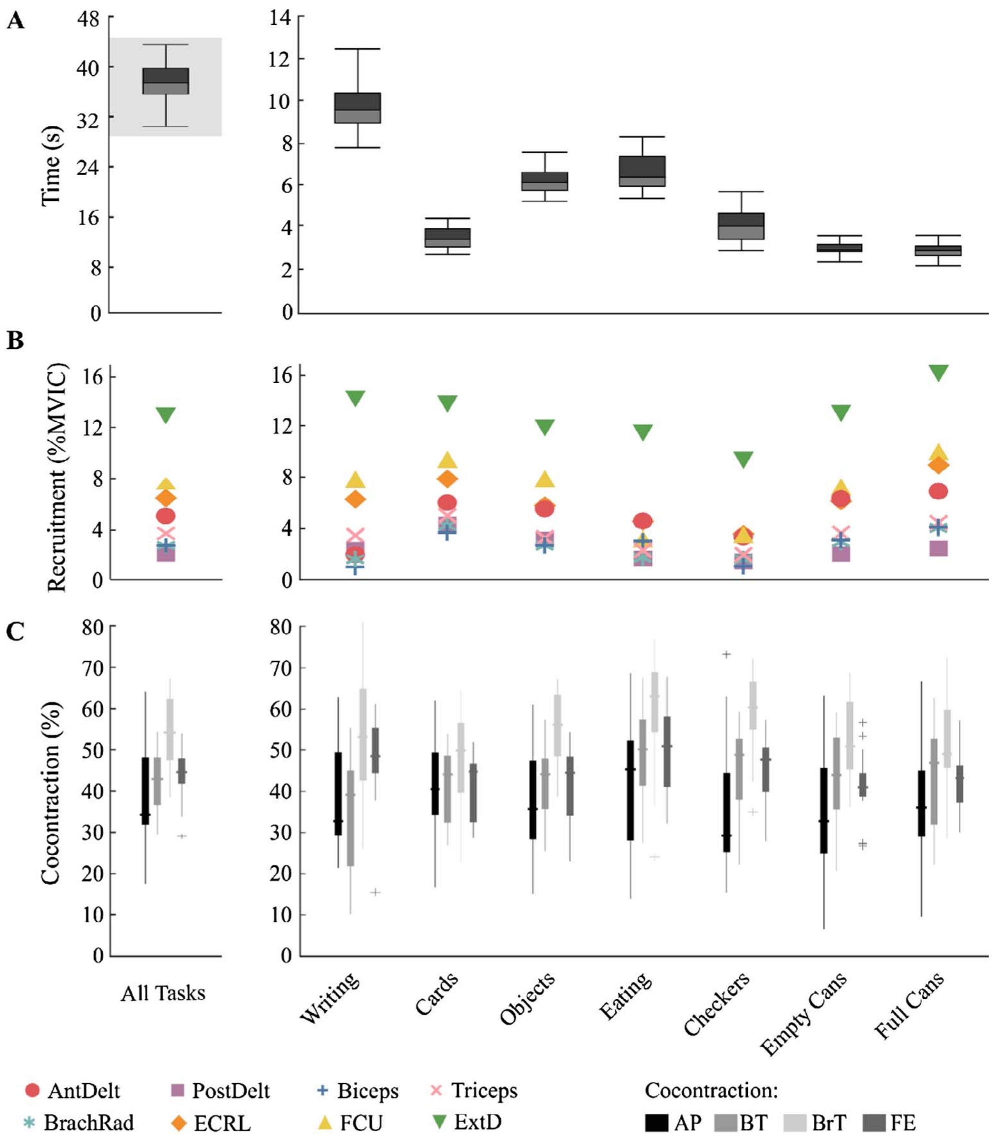

Fig. 3. Performance and muscle activity on the dominant limb during the seven tasks of the JTHF averaged across 20 unimpaired participants. (A) Performance was measured by the time to complete each task. (B) Muscle recruitment was evaluated as the average muscle activity measured for eight dominant arm muscles. (C) Muscle coordination was evaluated by the average cocontraction levels for four muscle pairs: anterior and posterior deltoids (AP), biceps and triceps (BT), brachioradialis and triceps (BrT), and FCU and ECRL (FE). Total time to complete the JTHF (gray band normative values for men and women aged 20–59, Jebsen et al., 1969) and average muscle activity across all tasks are shown in the left column. The right column displays results during each task. Note: To view non-dominant limb results, view the online supplement for interactive graphics.

3. Results

3.1. Jebsen Taylor Hand Function Test

Performance: The average time to complete the JTHF was 37.5 ± 3.1 seconds for the dominant arm and 52.2 ± 6.2 seconds for the non-dominant arm, within the range expected for unimpaired individuals (Fig. 3A, Jebsen et al., 1969). The writing task took the longest time for all participants and was the only task performed significantly faster by the dominant arm than the non-dominant arm ($p < .001$), with an average of 9.9 ± 1.1 s for the dominant arm and 23.2 ± 4.7 s for the non-dominant arm. The can tasks took the shortest time to complete for all participants (3.2 ± 0.5 s averaged across arms), with no significant difference in time between the empty and full cans for dominant and non-dominant arms.

Recruitment: Average EMG magnitudes during the JTHF were generally < 10% MVIC for the muscles monitored in this study (Fig. 3B), except for the ExtD, which exhibited an average magnitude of 13.5 ± 2.2% and 13.0 ± 2.2% MVIC across tasks and participants for the dominant and non-dominant arms, respectively. The Tri, Br, and PD muscles exhibited the lowest activation levels, with average magnitudes on the dominant arm of 3.8 ± 1.1%, 3.0 ± 1.1%, and 2.8 ± 1.0% MVIC, respectively. The full cans task required the greatest muscle recruitment for the majority of muscles, except the PD and Tri, which had the greatest average recruitment during the cards task. Peak EMG magnitude exhibited trends similar to average EMG magnitude. Muscles acting on the wrist displayed higher peak values (51.5–76.2% MVIC) than muscles primarily acting on the elbow or shoulder (22.7–44.3% MVIC). In addition to exhibiting the greatest average EMG magnitude, the ExtD also demonstrated the greatest activation time relative to other muscles during all tasks. In descending order of activation time, ExtD, ECRL, AD, and FCU were moderately active (dominant 67.6 ± 4.3%, 37.5 ± 7.4%, 32.9 ± 10.9%, 23.4 ± 7.1%), while the Bic, Tri, PD, Br (dominant 15.0 ± 6.6%, 12.8 ± 4.7%, 9.5 ± 4.4%, 9.5 ± 4.5%) had lower activation times during the JTHF tasks. No significant differences in the average or peak EMG magnitudes or activation times were found between the dominant and non-dominant arms during the JTHF tasks. Average EMG magnitude was only weakly correlated with time to complete each task ($-0.57 < r < 0.55$, $r^2 < 0.34$) for the dominant and non-dominant arms.

Coordination: When averaged across participants, levels of cocontraction were similar across tasks during the JTHF (Fig. 3C), ranging between 25 and 62% for all muscle pairings on the dominant and non-dominant arms. Average dominant arm cocontraction levels across tasks were 35.8 ± 3.3%, 44.0 ± 3.3%, 55.1 ± 4.5%, and 44.0 ± 3.3% for the AP, BT, BrT, and FE, respectively. The non-dominant arm had no significant differences in cocontraction levels compared to the dominant arm, with averages of 32.2 ± 3.9%, 43.7 ± 2.5%, 55.2 ± 4.6%, and 42.6 ± 4.5% COCON for the AP, BT, BrT, and FE. The shoulder (AP) had lower cocontraction levels than the distal muscle pairings during the checkers and empty cans tasks. The Tri and Br (BrT) had greater levels of contraction than other muscle pairs during the eating, objects, and checker tasks. Cocontraction was mildly correlated with time to complete each task for the dominant and non-dominant arms ($-0.52 < r < 0.62$, $r^2 < 0.39$).

Repeatability: Intra-day average EMG magnitude was moderate to strong for both limbs, with a median Pearson correlation coefficient of 0.84 and 0.89 ($0.45 < r < 1.00$). Inter-day recruitment was also moderate to strong with a median coefficient between 0.82 and 0.88; however, one modest correlation was found (dominant arm, Tri), out of the 48 correlation coefficients across all muscles and tasks ($0.22 < r < 1.00$). Similar to prior research, time to complete the tasks had strong inter- and intra-day repeatability for both limbs ($r > 0.92$).

3.2. Chedoke Arm and Hand Activity Inventory

Performance: All participants scored a 7 on each task, showing unimpaired function and complete independence.

Recruitment: Average EMG magnitudes during the CAHAI-13 were generally < 6% MVIC for the muscles monitored in this study (Fig. 4A), except for the ExtD, with averages of 10.2 ± 2.3% and 9.6 ± 2.2% MVIC for the dominant and non-dominant arms, and AD with an average of 6.2 ± 2.6% MVIC on the dominant side. The ExtD and AD also demonstrated the greatest activation time across tasks (dominant 60.9 ± 8.0%, 42.4 ± 19.4%). Conversely, the Tri, Br, and PD muscles exhibited the lowest average EMG magnitudes across tasks, with averages on the dominant arm of 1.5 ± 0.7%, 1.4 ± 0.5%, and 1.0 ± 0.6% MVIC, respectively. As expected, proximal muscles responsible for extension (PD and Tri) had the largest average EMG magnitudes during tasks requiring participants to manipulate or perform activities in a posterior space, such as drying their back with a towel, but were otherwise mildly active. Peak EMG magnitudes displayed similar trends to average EMG magnitude. The Tri, Br, and PD had low peak EMG values across tasks (13.8–23.2% MVIC), while muscles acting about the wrist had higher peak recruitment values (38.6–61.4% MVIC). Muscle recruitment was not significantly different between the dominant and non-dominant arms when completing the CAHAI-13 for average or peak EMG magnitude; however, activation time was different between limbs for the FCU when drawing a line with a ruler (non-dominant > dominant arm, $p < .0003$) and pouring a glass of water (dominant > non-dominant arm, $p < .0002$).

Cocontraction: Levels of cocontraction were similar across tasks during the CAHAI-13 (Fig. 4B), with an average across participants of 26–56% for all tasks. Average dominant arm cocontraction levels across tasks were 32.3 ± 7.3%, 45.3 ± 5.5%, 55.3 ± 5.6%, and 44.6 ± 4.2% COCON for the AP, BT, BrT, and FE, respectively. The non-dominant arm had no significant differences in cocontraction compared to the dominant arm, with averages of 26.6 ± 8.5%, 43.5 ± 4.5%, 55.5 ± 4.9%, and 42.9 ± 4.5% COCON for the AP, BT,

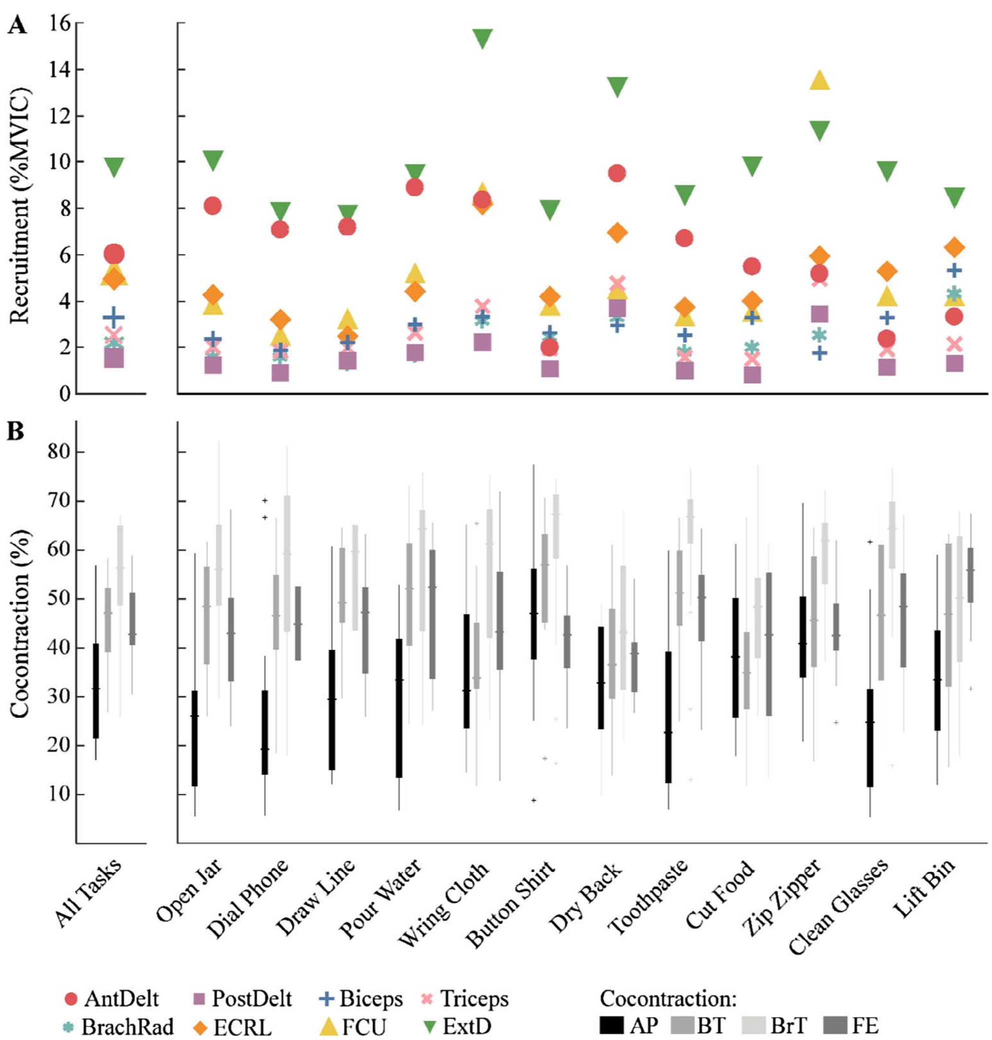

Fig. 4. Muscle recruitment and coordination of the dominant arm during the twelve tasks of the modified CAHAI-13 averaged across 20 unimpaired participants. (A) Average muscle recruitment for eight dominant arm muscles. (B) Cocontraction for four muscle pairs: anterior and posterior deltoids (AP), biceps and triceps (BT), brachioradialis and triceps (BrT), and FCU and ECRL (FE). Averages across all tasks are shown in the left column, while the right column displays each task individually. To view non-dominant limb results, view the online supplement for interactive graphics.

BrT, and FE. The FE and BrT pairings had the least amount of cocontraction during the back-drying task for both sides, while the upper arm (BT) had the lowest levels during the zipper task. On both sides, the shoulder had lower cocontraction when dialing a phone, and the greatest cocontraction when buttoning a shirt.

Repeatability: Intra-day analyses of average EMG magnitude exhibited moderate to strong Pearson correlations across both limbs (median r = 0.84; 0.90); however, slight to moderate correlations were calculated for one participant. This participant also reported altering his strategy for CAHAI-13 tasks (*e.g.* "I've learned to cut [*the medium resistance putty*] differently"). Inter-day repeatability on the dominant side was strong to moderate ($0.61 < r < 0.99$), while the non-dominant side had slight to strong repeatability with a median r = 0.85 ($0.16 < r < 0.99$). Traditional performance metrics (*i.e.,* completion of tasks) did not change between trials or days.

3.3. Box and Block Test

Performance: Participants moved an average of 78.1 ± 7.2 blocks with their dominant arm and 74.2 ± 7.4 blocks with their non-dominant arm during the 60-second BBT, similar to previously reported normative data (Fig. 5A, Mathiowetz et al., 1985). Across three trials, performance increased by an average of 6.1 blocks for the dominant arm, and 7.6 blocks for the non-dominant arm.

Recruitment: Average EMG magnitudes during the BBT were generally < 9% MVIC for the muscles monitored (Fig. 5B), except for the AD with an average EMG magnitude of 9.1 ± 0.2% and 9.2 ± 0.2% MVIC for the dominant and non-dominant arms, and the ExtD with an average EMG magnitude of 13.7 ± 0.0% and 13.0 ± 0.3% MVIC for the dominant and non-dominant arms. The Tri and Br muscles exhibited the lowest activation levels across trials, with average EMG magnitudes on the dominant arm of 2.9 ± 0.1% and 1.7 ± 0.1% MVIC, respectively. The activation time was also greatest for the ExtD and AD (dominant arm: 72.5 ± 0.3% and 55.9 ± 0.6% MVIC), and lowest for the Tri and Br (dominant arm: 17.7 ± 0.6% and 10.0 ± 0.7% MVIC). Peak EMG magnitude ranged from 117.8% MVIC for the dominant ExtD to 26.3% MVIC for the non-dominant Br muscle. When averaged across trials, peak muscle recruitment ranged from 68.6–117.8% MVIC for the ECRL, FCU, and ExtD while Tri and Br had peak levels between 26.3 and 41.8% MVIC. Peak and average EMG magnitudes and activation time were not significantly different between the dominant and non-dominant arms when completing the BBT trials. Average EMG magnitude was only weakly correlated with the number of blocks transferred ($-0.42 < r < 0.46$, $r^2 < 0.22$) on the dominant and non-dominant arms, suggesting that greater muscle activation was not strongly associated with better performance on the BBT.

Cocontraction: Cocontraction ranged between 36 and 53% for all muscle pairs on the dominant and non-dominant arms during the BBT (Fig. 5C). Average dominant arm cocontraction levels across the three trials were 41.2 ± 0.1%, 42.6 ± 0.3%, 51.2 ± 0.7%, and 36.3.0 ± 0.3% for the AP, BT, BrT, and FE, respectively. The non-dominant arm had no significant differences in cocontraction levels to the dominant arm, with averages of 38.7 ± 0.6%, 42.3 ± 3.5%, 52.1 ± 0.3%, and 36.6 ± 0.4% COCON across tasks for AP, BT, BrT, and FE. Cocontraction was weakly associated with performance ($-0.46 < r < 0.32$, $r^2 < 0.22$).

Repeatability: Average EMG magnitude ($r > 0.89$, $r^2 > 0.79$) and the number of blocks transferred ($r > 0.81$, $r^2 > 0.66$) were strongly correlated between trials for all participants.

4. Discussion

This study quantified unimpaired muscle recruitment and coordination during three common upper-extremity clinical tests: the unimanual Jebsen Taylor Hand Function Test (JTHF) and Box and Block Test (BBT), as well as the bimanual Chedoke Arm and Hand Activity Inventory Version 13 (CAHAI-13). Even when trying to complete tasks "as quickly as possible," unimpaired individuals could complete these tests with minimal muscle recruitment. Average magnitudes of muscle recruitment were low across all tests, generally < 10% MVIC, highlighting that minimal muscle force is required to perform these activity-based tests that incorporate tasks of daily living. The magnitude of EMG data was similar between dominant and non-dominant arms across tasks; however, there were greater differences in activation times between arms, especially during the bimanual tasks in the CAHAI-13. The magnitude of muscle activity was greater during the unimanual JTHF compared to the bimanual CAHAI-13 for the majority of muscles, suggesting these tasks may be of more assistance in clinical evaluations of strength or muscle demand. Similarly, the BBT required the greatest demand of proximal muscles, similar to prior studies (Silva

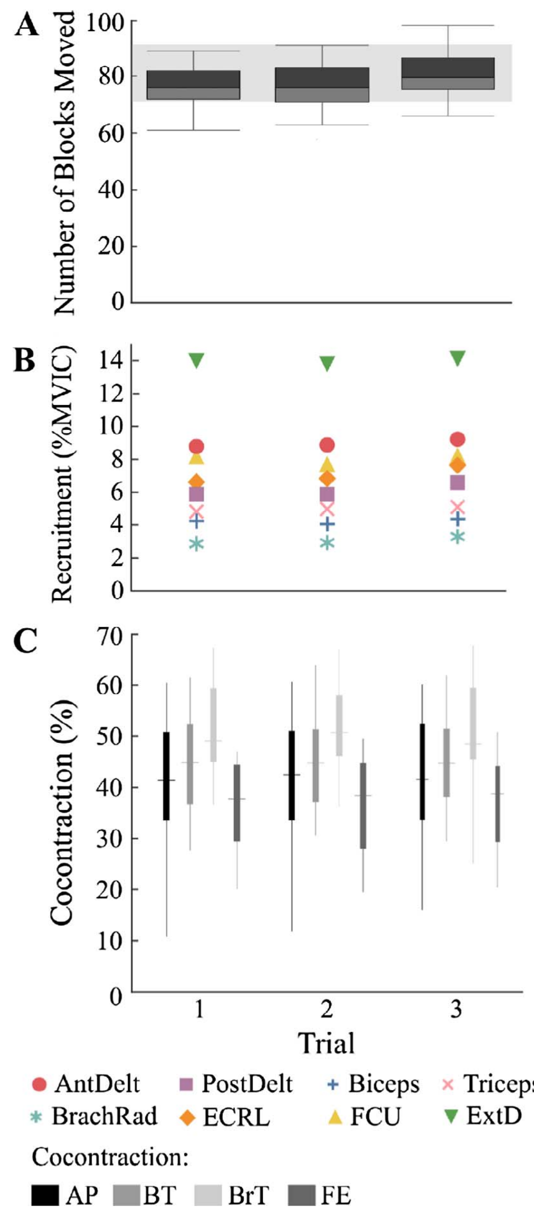

Fig. 5. Performance and muscle activity during the three trials of the Box and Block Test averaged across 20 unimpaired participants. (A) Performance was measured by the number of blocks transferred in one minute. The gray band represents normative values for men and women aged 40–44 (Mathiowetz et al., 1985). (B) Average muscle recruitment was measured for eight dominant arm muscles. (C) Average cocontraction levels for four muscle pairings: anterior and posterior deltoids (AP), biceps and triceps (BT), brachioradialis and triceps (BrT), and FCU and ECRL (FE). To view non-dominant limb results, view the online supplement for interactive graphics.

et al., 2017), and may be most useful for clinical evaluations of the activation and coordination of these muscles. Including analyses of EMG data during these common clinical tests can help clinicians evaluate and monitor patient-specific recruitment and coordination strategies.

Cocontraction levels were also similar across tests, ranging from 25–60% across all antagonist muscle pairs. The levels of cocontraction reported in this study are similar to prior analyses of unimpaired limbs (Dewald et al., 1995); however, to our knowledge, cocontraction levels have not been previously reported for these clinical tests. Cocontraction provides insight into the coordination patterns required to execute a task. In unimpaired individuals, cocontraction of antagonist muscles is often critical to maintaining proper levels of joint stiffness to stabilize the limb during complex tasks (Hogan, 1984). It is important to recognize that high levels of cocontraction can be due to either a high or low level of overlapping muscle activity. High %COCON does not necessarily indicate high muscle force or activity level, but rather coordinated recruitment. For example, in this study, putting toothpaste on a toothbrush required low muscle recruitment (< 4% MVIC) from the ECRL and FCU forearm muscles, but high cocontraction of these muscles (48.1 ± 10.0% COCON). These distinctions highlight the importance of evaluating both the magnitude of muscle recruitment and cocontraction patterns to understand the dynamics and control required to execute a task. In this research, we used Winter's method to calculate %COCON, which evaluates overlapping periods of muscle activation for pairs of muscles. For clinical populations, evaluating more global coordination patterns (*i.e.,* muscle synergies, Roh et al., 2013; Cheung et al., 2012) or quantifying inappropriate cocontraction that hinders task execution (Dewald et al., 2001) may provide additional insights into deficits that hinder movement.

Tracking muscle activity during these clinical tests in unimpaired individuals can also provide insight into mechanisms that may influence recovery after neurologic injury. For example, active range of motion in finger extension has been shown to predict recovery after stroke (Fritz et al., 2005; Beebe and Lang, 2009a). In the current study, the ExtD was found to have the greatest activation levels across all tasks, denoting the muscle's importance for common tasks. However, the ExtD is commonly impaired after stroke (Trombly, 1989), emphasizing the need to target the ExtD during rehabilitation to recover function required for activities of daily living. Evaluating muscle recruitment during clinical tests could help to track recovery of the ExtD or other muscles, but also identify compensatory mechanisms (Lum et al., 2009) used to overcome deficits and guide treatment planning (Cramer, 2008). Surprisingly, there were only low correlations between performance and muscle recruitment and coordination during the tasks evaluated in this research. We expected better performance (*i.e.,* faster performance on JTHF test or number of blocks transferred) would correspond to higher levels of muscle recruitment; however, this was not the case and there were only weak and variable correlations between muscle activity and performance. Our study population was relatively homogeneous in their performance and higher correlations may be present when evaluating individuals after neurologic injury. The variability in muscle recruitment and coordination do suggest that unimpaired participants used different strategies to execute the tests included in this study, which may also impact correlations between muscle activity and performance.

Beyond clinical tests, evaluating muscle recruitment and coordination during functional tasks provides insight into the neuromuscular control strategies and muscular demands that can inform other applications. Since these clinical tests are also commonly used in research to track recovery or responses to interventions, including EMG data may provide more sensitive measures and insight into patient-specific responses than performance metrics alone. Further, these results can inform the levels of muscle demand required for functional tasks to inform assistive device design, such as for upper-extremity prostheses or exoskeletons. EMG signals are increasingly being used to control myoelectric devices, and this study highlights the low-levels of EMG signals that need to be detected and processed for many tasks of daily living (Cipriani et al., 2008; Farina et al., 2014). Similar methods could also be used to evaluate performance of athletes (Huston and Wojtys, 1996; Krommes et al., 2017) or other groups who are executing complex dynamic tasks.

There are several important limitations in this work that can impact future research and clinical use of our results. Due to experimental constraints, we selected a small set of clinical tests and muscles to monitor with surface EMG sensors. We chose the clinical tests to align with current standards in our local clinics while including both unimanual and bimanual activity-based tests. Similarly, we selected proximal and distal muscle groups that can be effectively monitored with surface EMG and which have previously been used in research studies of neuromuscular control after stroke (Roh et al., 2013; Cheung et al., 2012; Steele et al., 2013; Ellis et al., 2005). The limited repeatability analysis on three participants demonstrated that EMG-based metrics of recruitment have inter-day and intra-day repeatability similar to prior reports of the performance-based metrics traditionally used to evaluate these tests (Jebsen et al., 1969; Barreca et al., 2005; Desrosiers et al., 1994). An additional limitation of this study was the convenience sample of unimpaired individuals. Determining whether there are differences in muscle recruitment among older adults or adults with varying levels of daily sedentary activity represent interesting areas for future investigation. Kinematics were not included in this study due to the unstructured nature of the tasks included in the selected clinical tests. While kinematics may provide further insight into whether muscle recruitment is related to efficient or compensatory actions, the analysis and processing time of current methods makes these analyses infeasible in most clinical environments. Future studies that incorporate additional clinical tests, kinematic evaluations, or an expanded set of muscles can expand our understanding of muscle recruitment and coordination required for functional recovery.

5. Conclusion

Limited evidence existed that documented muscle recruitment and coordination during activity-based or unconstrained tasks of daily living commonly used in clinical evaluations. The findings in this research suggest individuals with no prior neurologic injuries require relatively low muscle recruitment levels and moderate cocontraction values to complete tasks simulating activities of daily living. To inform future studies, an interactive graphic that provides the data supporting this research and which illustrates the muscle recruitment and coordination across all participants and tests included in this study is provided online [*https://tableau.washington.edu/views/JEK_MuscleRecCoord/Story_Musc_RecruitmentCoordination*]. These baseline measurements among unimpaired individuals can be used to evaluate muscle-specific deficits after neurologic injury, track recovery, and guide future clinical and research applications.

Conflict of interest

We confirm that there are no known conflicts of interest associated with this publication.

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Appendix A. Supplementary material

Supplementary material associated with this article can be found, in the online version, at https://doi.org/10.1016/j.jelekin.2017.12.002.

References

Armagan, O., Tascioglu, F., Oner, C., 2003. Electromyographic biofeedback in the treatment of the hemiplegic hand: a placebo-controlled study. Am. J. Phys. Med. Rehabil. 82 (11), 856–861.

Barreca, S.R., Stratford, P.W., Lambert, C.L., Masters, L.M., Streiner, D.L., 2005. Test-retest reliability, validity, and sensitivity of the Chedoke arm and hand activity inventory: a new measure of upper-limb function for survivors of stroke. Arch. Phys. Med. Rehabilit. 86 (8), 1616–1622.

Barreca, S.R., Stratford, P.W., Masters, L.M., Lambert, C.L., Griffiths, J., 2006. Comparing 2 versions of the chedoke arm and hand activity inventory with the action research arm test. Phys. Therapy 86 (2), 245.

Beebe, J.A., Lang, C.E., 2009a. Active range of motion predicts upper extremity function 3 months after stroke. Stroke 40 (5), 1772–1779.

Beebe, J.A., Lang, C.E., 2009b. Relationships and responsiveness of six upper extremity function tests during the first 6 months of recovery after stroke. J. Neurol. Phys. Therapy: JNPT 33 (2), 96.

Beer, R.F., Dewald, J.P.A., Rymer, W.Z., 2000. Deficits in the coordination of multijoint arm movements in patients with hemiparesis: evidence for disturbed control of limb dynamics. Exp. Brain Res. 131 (3), 305–319.

Chae, J., Yang, G., Park, B.K., Labatia, I., 2002. Muscle weakness and cocontraction in upper limb hemiparesis: relationship to motor impairment and physical disability. Neurorehabilit. Neural Repair 16 (3), 241–248.

Cheung, V.C., Turolla, A., Agostini, M., Silvoni, S., Bennis, C., Kasi, P., et al., 2012. Muscle synergy patterns as physiological markers of motor cortical damage. Proc. Natl. Acad. Sci. 109 (36), 14652–14656.

Cipriani, C., Zaccone, F., Micera, S., Carrozza, M.C., 2008. On the shared control of an EMG-controlled prosthetic hand: analysis of user–prosthesis interaction. IEEE Trans. Rob. 24 (1), 170–184.

Clark, D.J., Ting, L.H., Zajac, F.E., Neptune, R.R., Kautz, S.A., 2010. Merging of healthy motor modules predicts reduced locomotor performance and muscle coordination complexity post-stroke. J. Neurophys. 103 (2), 844–857.

Cramer, S.C., 2008. Repairing the human brain after stroke II. Restorative therapies. Ann. Neurol. 63 (5), 549–560.

Cruz, E.G., Waldinger, H.C., Kamper, D.G., 2005. Kinetic and kinematic workspaces of the index finger following stroke. Brain 128 (5), 1112–1121.

Desrosiers, J., Bravo, G., Hébert, R., Dutil, É., Mercier, L., 1994. Validation of the Box and Block Test as a measure of dexterity of elderly people: reliability, validity, and norms studies. Arch. Phys. Med. Rehabilit. 75 (7), 751–755.

Dewald, J.P.A., Pope, P.S., Given, J.D., Buchanan, T.S., Rymer, W.Z., 1995. Abnormal muscle coactivation patterns during isometric torque generation at the elbow and shoulder in hemiparetic subjects. Brain 118 (2), 495–510.

Dewald, J.P.A., Sheshadri, V., Dawson, M.L., Beer, R.F., 2001. Upper-limb discoordination in hemiparetic stroke: implications for neurorehabilitation. Top. Stroke Rehabilit. 8 (1), 1–12.

Ellis, M.D., Holubar, B.G., Acosta, A.M., Beer, R.F., Dewald, J., 2005. Modifiability of abnormal isometric elbow and shoulder joint torque coupling after stroke. Muscle Nerve 32 (2), 170–178.

Farina, D., Jiang, N., Rehbaum, H., Holobar, A., Graimann, B., Dietl, H., et al., 2014. The extraction of neural information from the surface EMG for the control of upper-limb prostheses: emerging avenues and challenges. IEEE Trans. Neural Syst. Rehabil. Eng. 22 (4), 797–809.

Fritz, S.L., Light, K.E., Patterson, T.S., Behrman, A.L., Davis, S.B., 2005. Active finger extension predicts outcomes after constraint-induced movement therapy for individuals with hemiparesis after stroke. Stroke 36 (6), 1172–1177.

Go, A.S., Mozaffarian, D., Roger, V.L., Benjamin, E.J., Berry, J.D., Borden, W.B., et al., 2013. Heart disease and stroke statistics-2013 update. Circulation 127 (1).

Gomes-Osman, J., Field-Fote, E.C., 2015. Improvements in hand function in adults with chronic tetraplegia following a multi-day 10Hz rTMS intervention combined with repetitive task practice. J. Neurol. Phys. Therapy: JNPT 39 (1), 23.

Gordon, A.M., Hung, Y.-C., Brandao, M., Ferre, C.L., Kuo, H.-C., Friel, K., et al., 2011. Bimanual Training and Constraint-Induced Movement Therapy in children with hemiplegic cerebral palsy: a randomized Trial. Neurorehabilit. Neural Repair 25 (8), 692–702.

Ho, N., Tong, K., Hu, X., Fung, K., Wei, X., Rong, W., et al., editors. An EMG-driven exoskeleton hand robotic training device on chronic stroke subjects: task training system for stroke rehabilitation. Rehabilitation Robotics (ICORR), 2011 IEEE International Conference on IEEE, 2011.

Hogan, N., 1984. Adaptive control of mechanical impedance by coactivation of antagonist muscles. IEEE Trans. Autom. Control 29 (8), 681–690.

Huang, H., Wolf, S.L., He, J., 2006. Recent developments in biofeedback for neuromotor rehabilitation. J. Neuroeng. Rehabilit. 3 (1), 11.

Hummel, F., Celnik, P., Giraux, P., Floel, A., Wu, W.-H., Gerloff, C., et al., 2005. Effects of non-invasive cortical stimulation on skilled motor function in chronic stroke. Brain 128 (3), 490–499.

Huston, L.J., Wojtys, E.M., 1996. Neuromuscular performance characteristics in elite female athletes. Am. J. Sports Med. 24 (4), 427–436.

Jakobi, J.M., Edwards, D.L., Connelly, D.M., 2008. Utility of portable electromyography for quantifying muscle activity during daily use. Gerontology 54 (5), 324–331.

Jebsen, R.H., Taylor, N., Trieschmann, R., Trotter, M.J., Howard, L.A., 1969. An objective and standardized test of hand function. Arch. Phys. Med. Rehabilit. 50 (6), 311–319.

Kern, D.S., Semmler, J.G., Enoka, R.M., 2001. Long-term activity in upper-and lower-limb muscles of humans. J. Appl. Physiol. 91 (5), 2224–2232.

Krishnaswamy, S., Coletti, D.J., Berlin, H., Friel, K., 2016. Feasibility of using an arm weight–supported training system to improve hand function skills in children with hemiplegia. Am. J. Occup. Ther. 70 (6) 7006220050p1-p7.

Krommes, K., Bandholm, T., Jakobsen, M.D., Andersen, L.L., Serner, A., Hölmich, P., et al., 2017. Dynamic hip adduction, abduction and abdominal exercises from the holmich groin-injury prevention program are intense enough to be considered strengthening exercises–a cross-sectional study. Int. J. Sports Phys. Therapy 12 (3), 371.

Lang, C.E., Bland, M.D., Bailey, R.R., Schaefer, S.Y., Birkenmeier, R.L., 2013. Assessment of upper extremity impairment, function, and activity following stroke: foundations for clinical decision making. J. Hand Therapy: Off. J. Am. Soc. Hand Therap. 26 (2), 104–115.

Lum, P.S., Mulroy, S., Amdur, R.L., Requejo, P., Prilutsky, B.I., Dromerick, A.W., 2009. Gains in upper extremity function after stroke via recovery or compensation: potential differential effects on amount of real-world limb use. Top. Stroke Rehabilit. 16 (4), 237–253.

Mathiowetz, V., Volland, G., Kashman, N., Weber, K., 1985. Adult norms for the box and block test of manual dexterity. Am. J. Occup. Ther. 39 (6), 386–391.

McCall, M., McEwen, S., Colantonio, A., Streiner, D., Dawson, D.R., 2011. Modified constraint-induced movement therapy for elderly clients with subacute stroke. Am. J. Occup. Ther. 65 (4), 409–418.

Moreland, J., Thomson, M.A., 1994. Efficacy of electromyographic biofeedback compared with conventional physical therapy for upper-extremity function in patients following stroke: a research overview and meta-analysis. Phys. Ther. 74 (6), 534–543.

Okkema, K.A., Culler, K.H., 1998. Functional evaluation of upper extremity use following stroke: a literature review. Top. Stroke Rehabilit. 4 (4), 54–75.

Rasool, G., Afsharipour, B., Suresh, N., Rymer, W.Z., 2017. Spatial analysis of multichannel surface EMG in hemiplegic stroke. IEEE Trans. Neural Syst. Rehabil. Eng.

Roh, J., Rymer, W.Z., Perreault, E.J., Yoo, S.B., Beer, R.F., 2013. Alterations in upper limb muscle synergy structure in chronic stroke survivors. J. Neurophys. 109 (3), 768–781.

Sarcher, A., Raison, M., Leboeuf, F., Perrouin-Verbe, B., Brochard, S., Gross, R., 2017. Pathological and physiological muscle co-activation during active elbow extension in children with unilateral cerebral palsy. Clin. Neurophysiol. 128 (1), 4–13.

Shin, J.H., Ryu, H., Jang, S.H., 2014. A task-specific interactive game-based virtual reality rehabilitation system for patients with stroke: a usability test and two clinical experiments. J. Neuroeng. Rehabilit. 11 (1), 32.

Silva, N.S., de Almeida, P.H.T.Q., Mendes, P.V.B., Komino, C.S.M., Jùnior, J.M.N., Da Cruz, D.M.C., 2017. Electromyographic activity of the upper limb in three hand function tests. Hong Kong J. Occupat. Ther. 29, 10–18.

Sommerfeld, D.K., Eek, E.U.-B., Svensson, A.-K., Holmqvist, L.W., von Arbin, M.H., 2004. Spasticity after stroke. Stroke 35 (1), 134–139.

Song, R., Tong, K.-y., Hu, X., Li, L., 2008. Assistive control system using continuous myoelectric signal in robot-aided arm training for patients after stroke. IEEE Trans. Neural Syst. Rehabil. Eng. 16 (4), 371–379.

Steele, K.M., Tresch, M.C., Perreault, E.J., 2013. The number and choice of muscles impact the results of muscle synergy analyses. Front. Comput. Neurosci. 7, 105.

Trombly, C.A., 1989. Stroke. Occupational Therapy for Physical Dysfunction. Williams & Wilkins, Baltimore, MD.

Tikkanen, O., Haakana, P., Pesola, A.J., Häkkinen, K., Rantalainen, T., Havu, M., Pullinen, T., Finni, T., 2013. Muscle activity and inactivity periods during normal daily life. PloS One 8 (1), e52228.

Winter, D.A., 2009. Biomechanics and Motor Control of Human Movement. John Wiley & Sons.

Woodford, H.J., Price, C.I., 2007. EMG Biofeedback for the Recovery of Motor Function after Stroke. The Cochrane Library, pp. 1.