Archives of Rehabilitation Research and Clinical Translation (2021) 3, 100136

ACRM
AMERICAN CONGRESS OF REHABILITATION MEDICINE

Archives of Rehabilitation Research and Clinical Translation

Archives of Rehabilitation Research and Clinical Translation 2021;3:100136

Available online at www.sciencedirect.com

Original Research

Electromyography Recordings Detect Muscle Activity Before Observable Contractions in Acute Stroke Care

Christina Papazian, MS [a], Nick A. Baicoianu, BS [a], Keshia M. Peters, BS [a], Heather A. Feldner, PT, PhD, PCS [b], Katherine M. Steele, PhD [a]

[a] *Department of Mechanical Engineering, University of Washington, Seattle, WA*
[b] *Department of Rehabilitation Medicine, University of Washington, Seattle, WA*

KEYWORDS
Arm;
Electromyography;
Hemiplegia;
Muscle contraction;
Paresis;
Rehabilitation;
Stroke;
Wearable electronic devices

Abstract *Objective:* To evaluate muscle activity in the arms of adult stroke survivors with limited or no arm movement during acute care.
Design: Prospective observational study.
Setting: Acute care regional stroke center.
Participants: We recruited adults (N=21) who had a stroke within the previous 5 days who were admitted to a level 1 trauma hospital and had a National Institutes of Health Stroke Scale score >1 for arm function at the time of recruitment. A total of 21 adults (13 men, 8 women) with an average age of 60±15 years were recruited an average of 3±1 days after their stroke. Eleven (7 men, 4 women; age, 56±11y) had no observable or palpable arm muscle activity (Manual Muscle Test [MMT]=0) and 10 (6 men, 4 women; age, 64±1y) had detectable activity (MMT>0).
Interventions: Dual mode sensors (electromyography and accelerometry) were placed on the anterior deltoid, biceps, triceps, wrist extensors, and wrist flexors of the impaired arm.
Main Outcome Measures: The number of muscle contractions, as well as average duration, amplitude, and co-contraction patterns were evaluated for each participant.
Results: Muscle contractions were observed in all 5 muscles for all participants using electromyography (EMG) recordings. Contractions were easily identified from 30 minutes of monitoring for participants with an MMT >0, but up to 3 hours of monitoring was required for participants with an MMT=0 to detect contractions in all 5 muscles during standard care. Only the wrist extensors demonstrated significantly larger amplitude contractions for participants with an MMT>0 than those with an MMT=0. Co-contraction was rare, involving less than 10% of contractions. Co-contraction of 2 muscles most commonly aligned with the flexor synergy pattern commonly observed after stroke. For participants with an MMT=0, the number of contractions and maximum amplitude were moderately correlated with MMT scores at follow-up.

List of abbreviations: EMG, electromyography; IPR, inpatient rehabilitation; MMT, manual muscle test.
Supported by the National Institute of Biomedical Imaging and Bioengineering of the National Institutes of Health (award no. R01EB021935).
Disclosures: none.
Cite this article as: Arch Rehabil Res Clin Transl. 2021;3:100136

https://doi.org/10.1016/j.arrct.2021.100136

Conclusions: Muscle activity was detected with surface EMG recordings during standard acute care, even for individuals with no observable activity by clinical examination. Wearable sensors may be useful for monitoring early muscle activity and movement after stroke.

The initial days after stroke are a time of rapid change and uncertainty. Although 80% of stroke survivors initially present with arm or hand impairments,[1] early prognosis for motor recovery remains challenging.[2,3] Clinicians routinely assess these impairments by measuring an individual's ability to volitionally perform a movement.[4] Manual muscle testing (MMT) is recommended for initial assessments because it is quick and provides standardized measures of motor function.[5] However, for individuals with no volitional movement, the MMT alone cannot determine whether muscle activity is present. An MMT score of 0 can indicate severe paresis with no muscle activity, that the muscle activity is below the level necessary to produce observable contractions, or that the patient was unable to fully participate in the assessment. For patients with an MMT of 0, this can be frustrating as the patient and their clinical team take a "wait-and-see" approach to determine whether muscle activity will return.[6,7]

Patterns of recovery can be highly variable during the first week after stroke.[8] Much of our current knowledge of early recovery is still based on Twitchell's observations from the 1950s using surface electromyography (EMG) recordings to monitor muscle activity.[9] He used EMG recordings from major arm muscles to outline common patterns of recovery. He documented that flexor contractions were often first observed and recovery generally progressed from proximal to distal joints, although patterns of recovery were highly variable. Of the 25 patients he followed, 17 could not initially move their arm. In these patients, he often could not detect muscle activity with EMG but only monitored for short periods during specific movements. Whether modern EMG sensors or extended monitoring could identify contractions in this early period after stroke remains unknown.

Despite significant technical advancements, there are still few studies of motor function during the initial weeks after stroke,[10-12] with most relying on clinical tests or observation. The presence of shoulder abduction and finger extension at 72 hours after stroke have been suggested as indicators of good recovery potential, whereas dense hemiplegia is believed to be an indicator of poor long-term recovery.[13,14] However, in 2012, Prager and Lang found that initial paresis at day 3 only accounts for 28% of upper extremity function at 3 months poststroke.[15] Stroke survivors are typically discharged from acute care within 7 days after stroke, which requires clinicians to make decisions about discharge destinations, therapy interventions, and prognosis based on these early assessments.[5,16] This makes the need for more detailed and informative assessments during acute care a priority. At the same time, acute care represents a hectic and uncertain environment where there is limited bandwidth for additional examinations or assessments.

Wearable sensors may provide more detailed quantitative measurements in acute care.[17] Clinicians have recognized the potential of EMG as a prognostic tool, but challenges in evaluating EMG signals and deploying this technology have limited broader use.[18,19] In research, EMG has been shown to be superior to clinical assessments because it can identify changes in patterns of motor function that are not otherwise evident.[20] Accelerometers have also been used extensively to monitor arm movement after stroke, including during inpatient rehabilitation and in the community.[21,22] Although these sensors are useful for monitoring movement, they have limited use before muscle activity can produce movement and provide limited insight into muscle recruitment and coordination. EMG sensors have been developed that can be worn for extended periods and are integrated with accelerometers or inertial measurement units to simultaneously monitor movement.[23-26] These technologies provide promising opportunities to expand upon Twitchell's observations and use wearable sensors to enhance care. Consequently, the goal of this study was to use wearable sensors during standard care in an acute stroke clinic to monitor muscle activity and movement for patients with limited or no arm movement.

Methods

We recruited 21 adult stroke survivors who had an upper extremity motor impairment (score≥2 on the National Institutes of Health Stroke Scale for Motor Arm) within the first 5 days after admission to a level 1 trauma hospital (table 1). This included 11 stroke survivors who had an MMT score of 0 and 10 stroke survivors with upper extremity impairment but MMT scores >0. MMT scores range from 0 (no observable or palpable contraction) to 5 (complete range of motion against gravity with full resistance). The participants with no observable muscle activity were aged between 32 and 67 years old and included 6 who had experienced an ischemic stroke and 5 who had experienced an intraparenchymal hemorrhagic stroke. The participants with an MMT score >0 were between 29 and 85 years old and included 8 who had experienced an ischemic stroke and 2 who had experienced an intraparenchymal hemorrhagic stroke. Independent sample *t* tests indicated that the 2 groups were not significantly different by age (P=.26), sex (P=.87), days after stroke (P=.43), length of stay in acute care (P=.58), type of stroke (P=.24), hand dominance (P=.33), or stroke side (P=.84). We obtained approval of the described protocols from the institutional review board, and all participants or their legal authorized representative provided informed consent.

Muscle activity and movement were monitored with wireless sensors placed on the impaired arm. Given the hectic environment during acute care, we prioritized monitoring during standard care to minimize the burden on the patient and clinical team. We used commercially available, dual

Table 1 Participant characteristics

MMT=0

Participant	Age	Data Day	Acute LOS	Final MMT	Sex	Stroke Type	Stroke Location	Dominant Hand	Stroke Side
1	57	1	8	0.3	F	Ischemic	Basal ganglia	Right	Left
2	67	1	3	0.0	M	Ischemic	Basal ganglia	Right	Left
3	50	2	7	4.2	M	IPH	Basal ganglia	Left	Right
4	49	2	7	3.0	F	IPH	Thalamic	Right	Right
5	60	2	8	0.0	M	Ischemic	ACA	Right	Right
6	67	2	10	3.7	F	IPH	Parietal	Right	Right
7	58	3	17	1.8	M	Ischemic	Pontine	Left	Left
8	70	3	13	0.0	M	Ischemic	MCA	Right	Left
9	64	4	5	2.5	F	IPH	Thalamic	Right	Right
10	32	4	8	3.2	M	Ischemic	Insular	Right	Left
11	45	4	8	N/A	M	IPH	Thalamic	Left	Left
Average	56	2.5	8.5	1.9	7 men, 4 women	5 IPH, 6 Ischemic		8 right, 3 left	6 right, 5 left
SD	11	1.1	3.8	1.7					

MMT > 0

	Age	Data Day	Acute LOS	Final MMT	Sex	Stroke Type	Stroke Location	Dominant Hand	Stroke Side
1	85	1	11	1.6	M	Ischemic	MCA	Right	Left
2	67	2	10	2.6	M	Ischemic	MCA/ICA	Right	Left
3	80	2	5	1.8	M	IPH	Basal ganglia	Right	Right
4	71	2	6	3.0	F	Ischemic	Basal ganglia	Right	Left
5	65	2	13	3.0	M	Ischemic	MCA	Left	Right
6	74	3	6	3.6	M	Ischemic	MCA	Right	Right
7	61	4	7	3.0	F	Ischemic	MCA	Right	Left
8	70	4	10	3.0	F	Ischemic	MCA	Right	Right
9	29	5	6	2.0	F	IPH	Basal ganglia	Right	Right
10	36	5	3	4.5	M	Ischemic	Putamen	Right	Left
Average	64	3.0	7.7	2.8	6 men, 4 women	2IPH, 8 ischemic		9 right, 1 left	5 right, 5 left
SD	18	1.4	3.1	0.9					

NOTE. Data Day indicates the number of days after stroke that data collection occurred. MMT indicates the average score. Final indicates the follow-up MMT score.
Abbreviations: ACA, anterior cerebral artery; ICA, internal carotid artery; IPH, intraparenchymal hemorrhage; LOS, length of stay; MCA, middle cerebral artery.

sensors that simultaneously monitor muscle activity from EMG recordings and movement from accelerometers (BioStamp RC Sensors[a]).[27-30] The Bluetooth interface and low profile (measuring 3.4 × 6.6 × 0.3cm) also made these sensors appealing for extended monitoring without interfering with care. We placed 5 sensors on the anterior deltoid, biceps, triceps, wrist flexors, and wrist extensors of the impaired upper extremity using Surface Electromyography for Non-Invasive Assessment of Muscles guidelines and palpation (fig 1). The sensor area on the upper extremity was shaved, if necessary. The sensors were secured to the skin with manufacturer-provided double-sided tape, and a strip of Tegaderm[b] transparent dressing was placed over each sensor in addition to Coban[c] self-adherent wrap around the arm to ensure that the sensors would not fall off or move during clinical care.

For participants with an MMT of 0, after the EMG sensors were placed, we also performed an MMT examination to confirm the clinician's documented assessment. The researcher asked the participant to attempt to move their arm. If no movement or contraction by palpation was detected, the researcher then performed a passive range of motion examination, repeatedly moving the shoulder, elbow, and wrist sequentially through their range of motion 3 times. The passive range of motion examination was only completed on 9 of the 11 participants with an MMT of 0 due to clinical constraints. After completing these assessments, the sensors were left on for 3-4 hours, during which the participant continued with standard care. Because we sought to capture muscle activity without other interventions or specific activities to minimize interruptions in acute care, we focused on recording during standard clinical activities. An activity check was performed every 30 minutes to briefly document activity (eg, sleeping, eating, working with nurse, watching TV). Times when the participants were sleeping were not used in subsequent analyses.

Raw EMG data were recorded at 1000 Hz. EMG data were processed using a fourth-order Butterworth bandpass filter between 20 and 400 Hz. Outlier data were discarded to remove high-magnitude hardware artifacts. Rectified EMG data were then smoothed using a moving median. The smoothed signal was used to manually identify contractions. For each participant, the EMG and accelerometer recordings from all muscles were evaluated concurrently in 5- to 10-

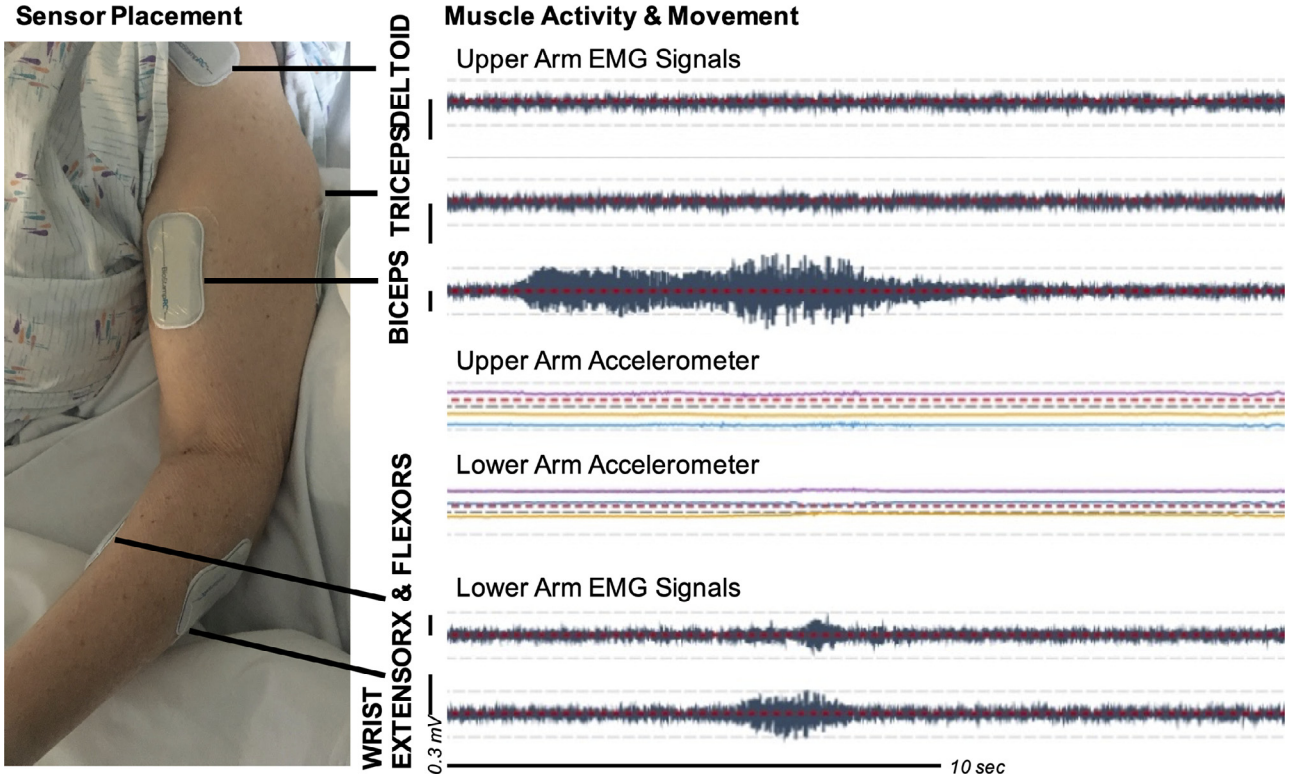

Fig 1 The dual mode sensors were placed on 5 muscles—the anterior deltoid, biceps, triceps, wrist flexors, and wrist extensors—of the affected arm. Each sensor monitored muscle activity with EMG recordings and movement with a triaxial accelerometer. An example contraction is shown for one of the participants with an MMT of 0 while they were watching TV in their hospital room. Accelerometer recordings from the upper arm and forearm show no movement, and the biceps had an extended contraction with some wrist flexor and extensor activity.

second windows, and the start and end times of each contraction were manually identified when the EMG signal's magnitude exceeded baseline noise. For each participant, baseline noise was assessed by evaluating signal magnitude and the frequency spectrum across multiple periods of rest. The concurrent raw accelerometer data were also used to classify whether movement of the arm was present during each contraction. Specifically, the triaxial accelerometer data were viewed for all sensors during each contraction to determine which body segments were moving. If no movement was detected from any of the sensors, the contraction was labeled as no movement. Contractions were also labeled based on the confidence during manual identification (1, high confidence to 3, low confidence) and evaluated by the research team. No significant differences in contraction characteristics were identified across participants between contractions identified with high or low confidence, and thus all contractions were included in subsequent analyses.

For all participants, contractions were identified during a 30-minute period during standard care when the participant was awake and not involved in therapy (as documented from activity checks). Additional 30-minute periods were evaluated until contractions were identified from all 5 muscles or no data remained for analysis. The number of contractions was reported for each participant as a count of the number of contractions divided by the number of 30-minute time windows analyzed for that participant.

For each contraction, we calculated the maximum amplitude, median amplitude, and duration from the manually identified start and end times. For each muscle, the average amplitude and duration of contractions were then calculated for each participant. Although amplitudes are commonly normalized to a maximum voluntary contraction or other action, these participants could not perform these actions and we chose to evaluate and report absolute amplitudes. For each participant, the average duration and maximum and median amplitude was calculated across all identified contractions with or without movement. We compared the contractions identified with and without movement for each group using unadjusted nonparametric Wilcoxon signed-rank tests (2-sided). We compared contractions between participants with MMT of 0 and MMT >0 using unadjusted nonparametric Wilcoxon rank sum tests (2-sided).

Regression analyses were also used to evaluate factors that may influence contraction characteristics during acute care. Given the limited number of participants, these were exploratory analyses. For each group, linear regression was used to evaluate associations between the number, duration, and magnitude of contractions. For the participants with an MMT >0, linear regression was also used to compare the number of contractions with or without movement to their average MMT score (see table 1, acute MMT).

We also evaluated co-contraction by evaluating whether multiple muscles were active at the same time. Co-

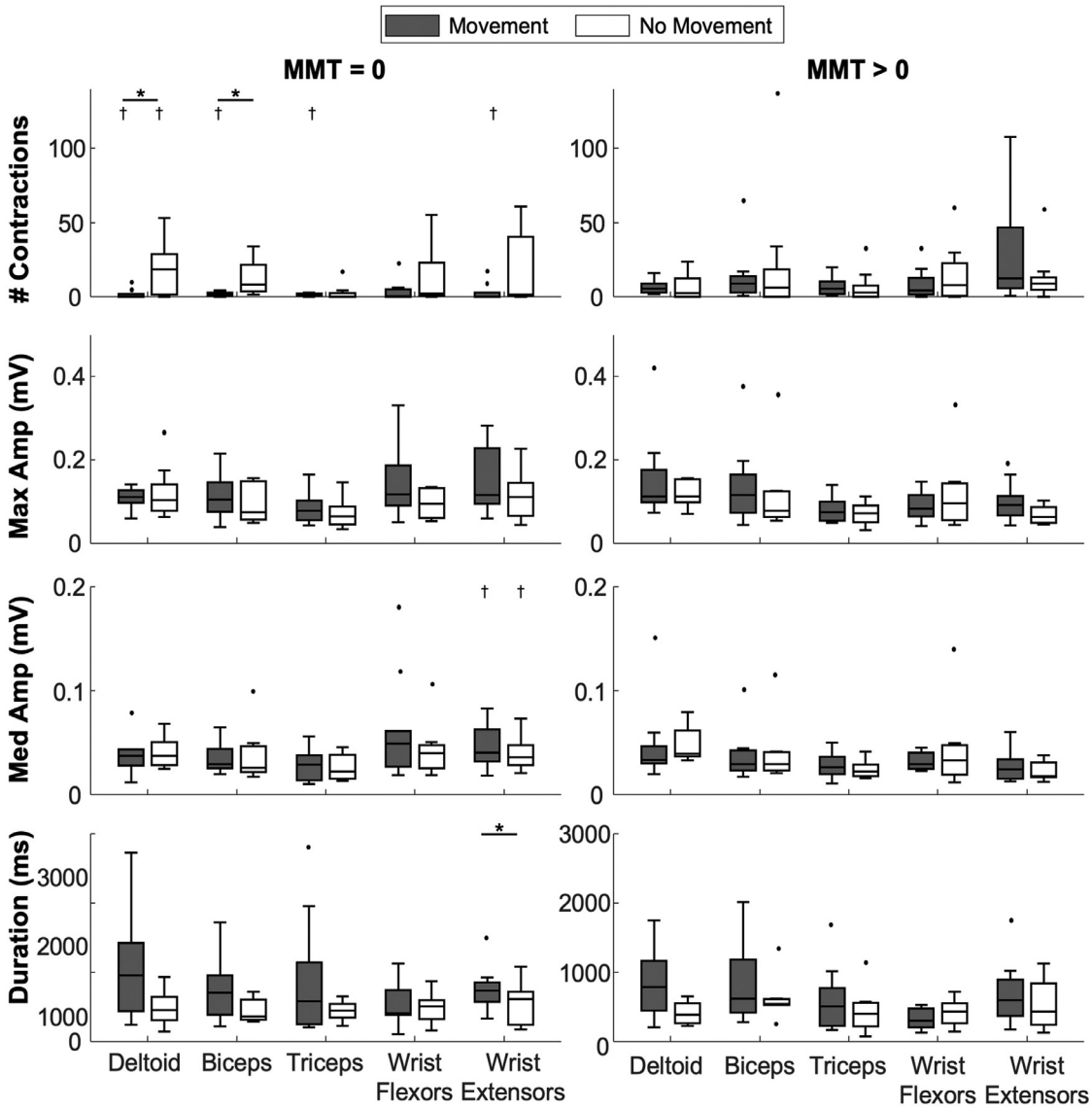

Fig 2 Contractions identified from EMG recordings for participants with no observable muscle activity (MMT=0) and participants with some arm movement (MMT >0). The number of contractions per 30-minute time window, maximum amplitude, median amplitude, and contraction duration are shown for contractions with or without movement. For each participant, the average duration and maximum and median amplitudes were calculated across all identified contractions. Bars represent the median value, with black dots showing individual participants. All participants had contractions in all 5 muscles, although not all participants had contractions both with and without movement. *Significant difference between contractions with or without movement. †Significant difference between participants with an MMT of 0 and an MMT >0.

contraction was defined as any overlap in the start and end time between muscles. For each contraction, periods of overlap were identified and classified based on the number of muscles active. For 5 muscles, there are 21 potential co-contraction combinations: 10 pairs of muscles, 10 sets of 3 muscles, 5 sets of 4 muscles, or all 5 muscles.

All of the participants with an MMT of 0 continued to inpatient rehabilitation (IPR) after acute care. MMT scores at IPR discharge and follow-up were also collected for these participants and used for exploratory analyses comparing contraction characteristics to MMT at follow-up. One participant did not return for follow-up. Univariate linear regression was used to compare the number, duration, and maximum amplitude of contraction with average MMT score at follow-up (see table 1, final MMT). Only 4 of the participants with an MMT>0 continued to IPR. Owing to the limited number and ceiling effect of MMT (ie, scores of 4+ at IPR discharge), these exploratory analyses were only conducted with the group with MMT of 0.

Results

Contractions were identified from the EMG recordings for all 5 muscles in all participants during standard care (fig 2). For the participants with observable muscle activity (MMT >0), contractions were identified from all muscles in just 30 minutes of monitoring while awake in their hospital room.

For 5 of the participants with no observable muscle activity (MMT=0), we were also able to identify contractions from a single 30-minute period. The other participants with an MMT of 0 (n=6) required monitoring for an additional 30-150 minutes before contractions were identified in all 5 muscles, with the biceps and triceps typically requiring the longest time periods to identify contractions.

Most contractions for the participants with no observable muscle activity (MMT=0) were during times of no movement. Participants with observable muscle activity (MMT >0) had significantly more contractions with movement than participants with an MMT of 0 for all muscles except the wrist flexors (*P*=.003-0.01; *P*=.07 for wrist flexors). For these participants (MMT >0), the majority of contractions occurred with movement (59%-66% of contractions, but 45% for the wrist flexors); higher MMT scores were modestly associated with more contractions with movement (r^2=0.16-0.42).

The maximum and median amplitudes of contractions were similar across muscles and between participants with and without observable muscle activity, with the average maximum amplitude between 0.03 and 0.42 mV and median amplitude between 0.01 and 0.18 mV (see fig 2). Only the wrist extensors demonstrated significantly larger median amplitudes (*P*=.02) for participants with an MMT>0 than those with an MMT of 0. There were no significant differences in maximum (*P*=.08-0.99) or median (*P*=.16-0.81) amplitudes between contractions with or without movement. Durations of contractions were also not significantly different between groups, with most contractions lasting less than 1 second. We also evaluated the correlation between the number of contractions, amplitude, and duration. For the participants with an MMT of 0, individuals with more contractions had greater maximum amplitude (r^2=0.16-0.62) and longer duration (r^2=0.16-0.83) contractions. We observed weak or no correlation between the number of contractions, amplitude, and duration for participants with observable muscle activity (MMT >0).

The participants with an MMT of 0 were also monitored during the MMT and passive range of motion assessments (n=9) (fig 3). Although the MMT examination confirmed no muscle activity via observed movement or palpation, we identified contractions from EMG during these activities. At the beginning of the examination, when asked if they could move their arm, we identified muscle contractions among 4 of the participants, even though the examiner observed no movement or muscle activity. During the passive range of motion tests, muscle contractions were identified in all 9 participants during elbow range of motion and in 7 participants during both shoulder and wrist range of motion examinations. As would be expected from reflexes, the deltoid was only active during attempted movement or shoulder range of motion.

Co-contraction was rare for all participants. For the participants with an MMT of 0, more than 90% of contractions involved only a single muscle (fig 4). Co-contraction was significantly more common during contractions with movement (*P*=.003). Three of the 4 most common co-contraction patterns observed among the participants with an MMT of 0 aligned with a flexion synergy, involving activation of the deltoid and wrist flexors (17% of co-contractions), biceps and wrist flexors (16% of co-contractions), or deltoid and biceps (11% of co-contractions). There were no co-contractions aligned with the extension synergy among participants with an MMT of 0. Co-contraction was significantly more common among the participants with an MMT>0 than those with an MMT of 0. For participants with an MMT>0, co-contraction was more common during contractions with movement (*P*=.048); the most common co-contractions were activation of the biceps and wrist extensors (23% of co-contractions) and activation of the wrist flexors and extensors (17% of co-contractions).

All of the participants with an MMT of 0 continued to IPR. At IPR discharge (range, 13-35d after stroke), 7 of the 11 participants still had an MMT score of 1 or less for all

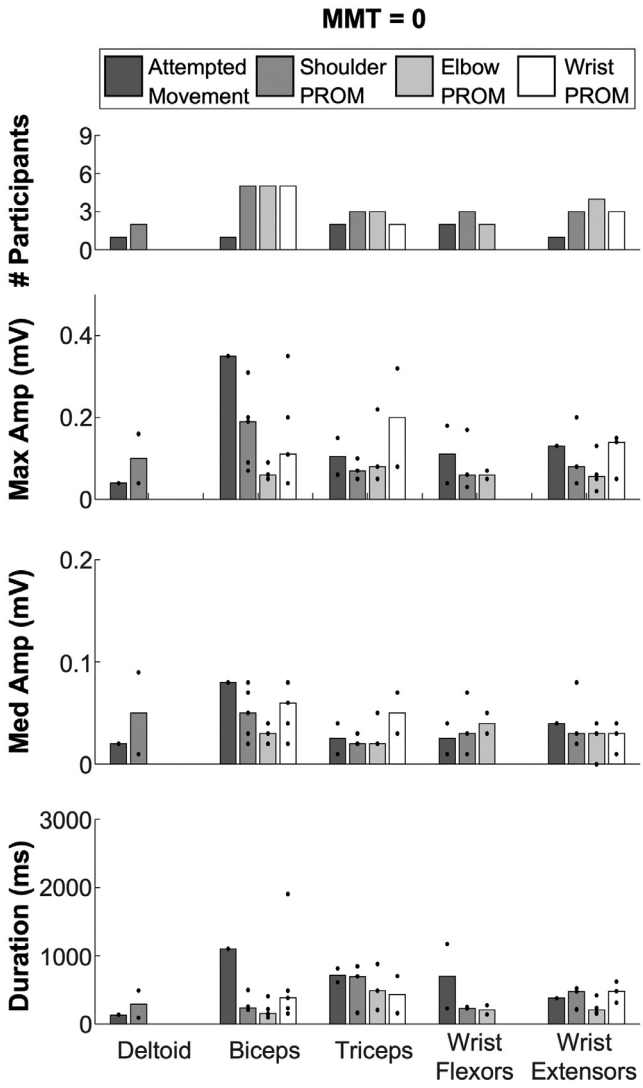

Fig 3 Contractions during the MMT and passive range of motion (PROM) assessments for the participants with an MMT of 0. EMG recordings were collected for 9 participants during these assessments. The number of participants who had identifiable contractions, as well as the maximum amplitude, median amplitude, and duration of contractions are shown for each muscle. Bars represent the median amplitude and duration across participants, with the black dots showing the median for individual participants.

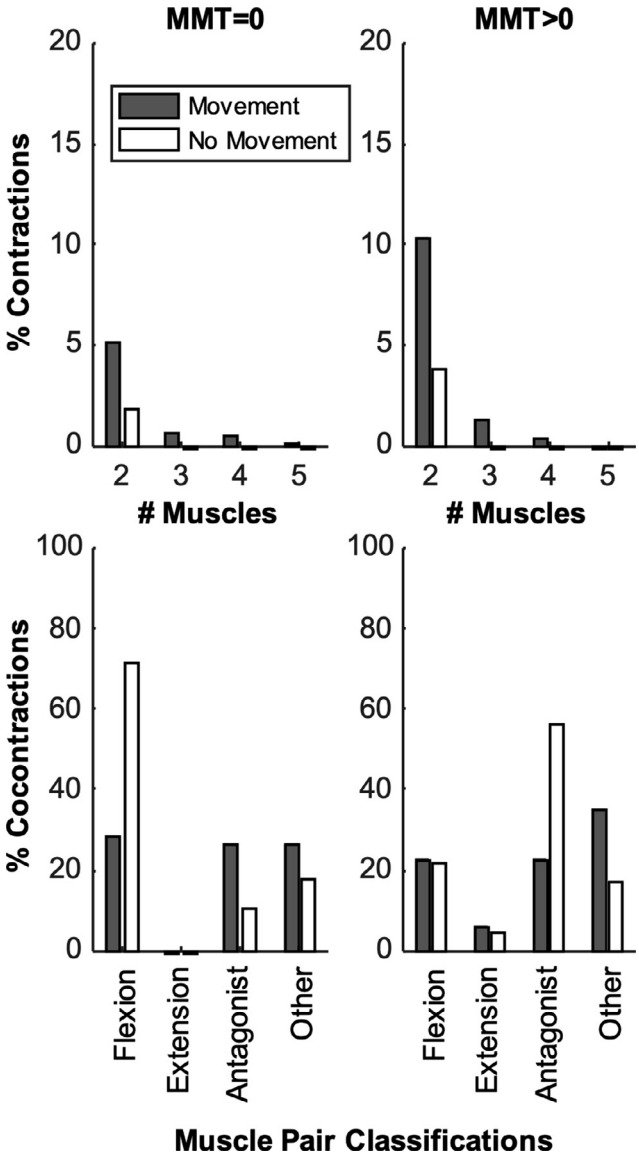

Fig 4 (A) Co-contractions (percent of total number of contractions) were rare among participants without (MMT=0) and with (MMT >0) observable muscle activity. (B) Co-contraction involving 2 muscles were classified as aligning with the flexion or extensor synergy, antagonist pairs, or other patterns. The flexion synergy includes co-contraction of the deltoid, biceps, and wrist flexors. The extension synergy includes co-contraction of the triceps and wrist extensors.

muscles. At follow-up (range, 1-12mo after stroke; average, 5mo), 5 participants had regained some arm function with MMT scores greater than 2. The number of contractions and maximum amplitude at the initial evaluation were associated with MMT scores at follow-up for the biceps, triceps, and wrist flexors (fig 5). Participants with fewer contractions and lower maximum amplitude in acute care had greater MMT scores at IPR follow-up. The wrist extensors showed the opposite trends, in which the few participants with more contractions, greater maximum amplitude, and longer duration contractions in acute care demonstrated the greatest improvements in MMT at follow-up.

Discussion

We found that monitoring muscle activity with dual mode sensors during acute care could detect contractions in the major arm muscles of stroke survivors, even among those who had no observable activity from clinical examination. We did not detect large differences in contraction characteristics—number of contractions, amplitude, or duration—between muscles or participants with varying arm function. This may reflect the wide variety of contractions that are captured when monitoring while a patient is in their hospital room, or that our signal quality was not good enough to detect more subtle differences. Regardless, the presence of contractions among all participants with MMT scores of 0 indicates that EMG may help clinicians and patients evaluate muscle activity that is currently not observable with other methods to inform care and recovery. Wearable sensors facilitated deployment in acute care, which represents a challenging environment; similar methods may further support care when deployed in inpatient, outpatient, or other rehabilitation settings.

For the participants with an MMT of 0, the majority of contractions occurred without movement detected from the accelerometers. This aligns with expectations because these participants have no voluntary movement. Whether these contractions represent volitional muscle activity or random activity remains unknown. After stroke, the upper motor neuron lesion can cause random signals to be sent to the lower motor neurons. The observed contractions without movement may reflect this random, uncontrolled muscle activity. Contractions during times of movement among participants with an MMT of 0 likely reflect events when someone else was moving their arm (eg, nurse repositioning in bed). This movement may have triggered reflex activity or some voluntary activity when the patient was trying to assist. During the passive range of motion tests, we also observed contractions for all participants with an MMT of 0, which supports the hypothesis that some of this activity represents reflex activity. Co-contraction was also significantly more common during contractions with movement, which may also reflect reflex activity when the arm was moved. Spasticity is generally assumed to start 1-6 weeks after stroke. Because our participants were monitored in the first 5 days after stroke, these contractions may reflect reflex activity or early signs of spasticity. Future research during controlled activities or with sensors that enable frequency spectrum or motor unit analyses could provide greater insight into the origin of these contractions.

The patterns of muscle activity we observed in acute care reflected those documented by Twitchell and others.[8,31-33] Like Twitchell's observations,[9] we saw wide variety in muscle activity after stroke, reflecting the unique deficits and recovery of each brain injury. Twitchell observed shoulder flexion emerging 6-38 days after stroke, with elbow and wrist flexion following shortly after. We also observed a large number of deltoid and biceps contractions in the first 5 days after stroke, which may precede the return of shoulder and elbow flexion. Flexor activity was more prevalent than extensor activity, which may reflect greater reliance and activity from the rubrospinal tract.[34-36] Patterns of co-contraction were also similar to previously documented

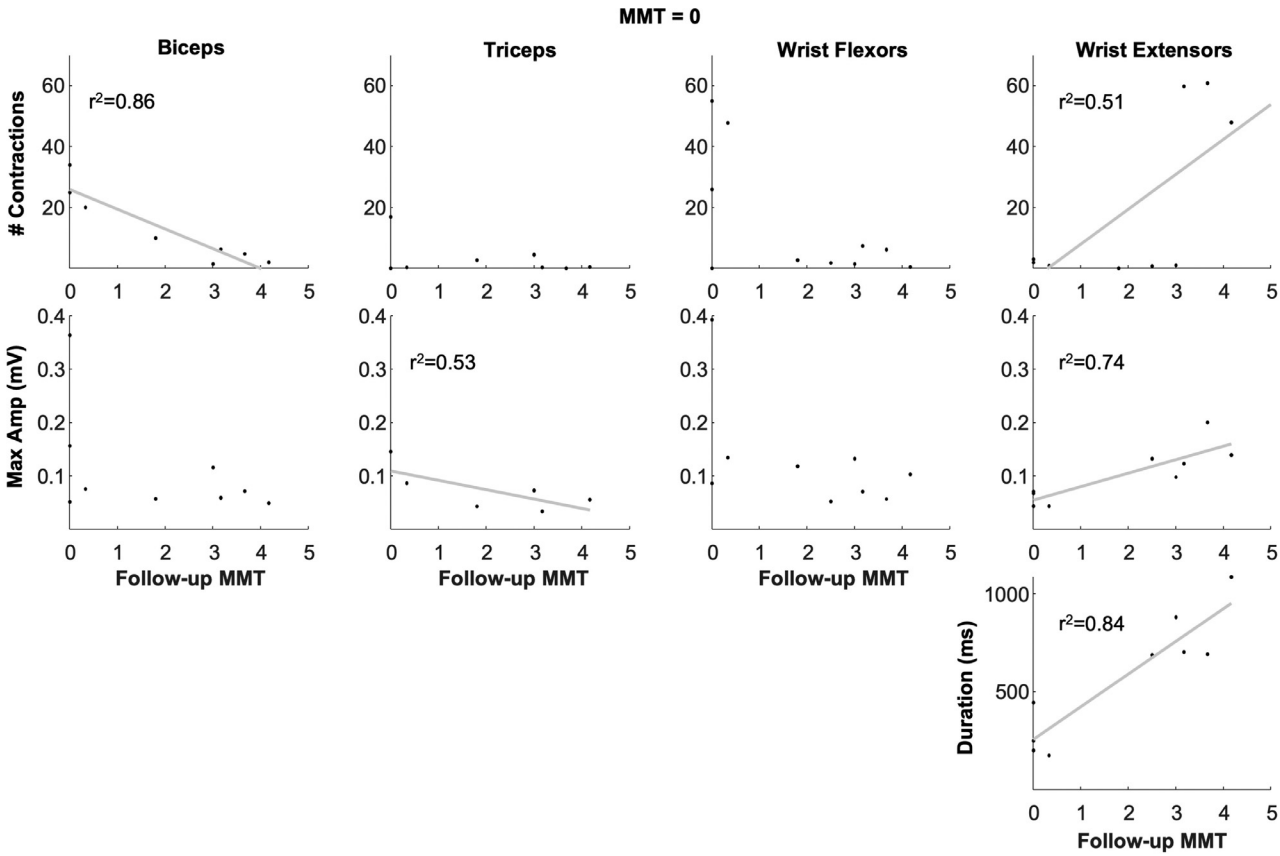

Fig 5 Exploratory analyses were conducted to evaluate whether contraction characteristics during contractions without movement were associated with MMT scores at follow-up (1-12mo after stroke) among the participants with an MMT=0. R^2 values are shown for correlations >0.5. For the biceps, triceps, and wrist flexors, fewer contractions and lower maximum amplitudes in acute care were associated with greater improvement at follow-up. The wrist extensors had the opposite trend, showing that more contractions, higher amplitudes, and longer durations during acute care were associated with higher MMT scores at follow-up.

patterns.[37-40] The flexion synergy and antagonist co-contraction were the most prevalent patterns. Participants with an MMT of 0 demonstrated no contractions aligning with the extensor synergy, which is generally believed to appear later in recovery.

Adopting wearable sensors in acute care will ultimately require that these sensors provide unique and valuable insights that are not available with current methods.[41,42] Detecting muscle activity alone may be sufficient to address a patient's question of whether or not their muscles are firing or to give therapists a tool to plan and evaluate their training sessions. For example, using EMG during the MMT or other clinical examinations may help patients and clinicians see activity, encourage engagement, and give clinicians confidence in their assessment. Beyond detecting muscle activity, longitudinal evaluations will determine the diagnostic and prognostic value of EMG in acute care. Predicting future function has been attempted by many researchers.[43-46] In our exploratory analyses, we found modest correlations between contraction characteristics and future function for the participants with an MMT of 0. Surprisingly for the biceps, triceps, and wrist flexors more and larger amplitude contractions were associated with worse outcomes at follow-up. These may reflect involuntary, reflex-driven contractions, but larger longitudinal studies will be required to link EMG-based measures with neurophysiology and recovery. Identifying opportunities for integrating wearable sensors into acute care can help support translation of this technology to the clinic.

Study limitations

For this research, we recruited a convenience sample with broad inclusion criteria to test the deployment of wearable sensors in acute stroke care. Evaluating specific types of stroke or groups with specific movement deficits may elucidate differences in contraction characteristics between individuals. We also relied on the MMT to evaluate arm function, which only provides a coarse ordinal scale that lacks the sensitivity to detect subtle improvements in strength.[47-49] We chose to use this examination because it is conducted multiple times per day to evaluate function and inform clinical decision-making. Other examinations, such as the Fugl-Meyer Assessment,[50] could provide more detailed measures, but are not commonly used in acute care. To minimize disruption to care, we also chose to passively monitor with EMG, vs having the participant attempt to complete specific activities or observing their activities. EMG amplitude is usually normalized by maximum voluntary contractions or other

controlled activities, which our participants could not perform. This limited the types of analyses and normalizations we could perform on the EMG data; motivating our choice to report absolute amplitudes (mV) and focus on number and duration of contractions. More detailed records of the activities they were performing could further help decode and classify different types of contractions.

There were also numerous technical challenges that limited the methods we could use to process and evaluate the EMG data. The wearable sensors had an excellent form factor for use in the clinic, but had several limitations compared with research-grade systems that affected signal quality.[51] In particular, there was hardware interference in the sensor board design that introduced noise, which made traditional processing techniques challenging. We attempted to use filtering and automated contraction classification methods extensively.[52-56] Contractions could be identified manually from amplitude and frequency analyses, but this process was incredibly time intensive and severely limits clinical translation. The interelectrode distance was also wide, which increased crosstalk and limited our ability to target specific muscles.[57] Although these sensors work well for large muscles, we report wrist flexor and extensor group activity. We are confident these technical limitations can be overcome, which will increase the potential effect of wearable sensors in acute care and rehabilitation.

Conclusions

Muscle activity is present in the first week after stroke, even among participants with no signs of muscle activity during traditional examinations. We were able to use dual mode sensors to monitor and detect muscle activity for 21 stroke survivors with impaired arm function during acute care. Whether these contractions represent voluntary activity or random events remains unknown and represents an interesting area for future inquiry, especially with higher fidelity EMG sensors. Our exploratory analyses identified modest correlations between contraction characteristics and future function for individuals with an MMT of 0. Whether or not EMG can be used to predict future function represents an important area for further research. Using EMG to detect contractions, evaluate common synergistic patterns, and track changes during routine care may provide new pathways to support recovery of stroke survivors.

Suppliers

a. BioStamp RC Sensors; MC10, Inc.
b. Tegaderm; 3M Corp.
c. Coban; 3M Corp.

Corresponding author

Katherine M. Steele, PhD, Department of Mechanical Engineering University of Washington, 3900 E Stevens Way NE, Box 352600, Seattle, WA 98195. *E-mail address:* kmsteele@uw.edu.

Acknowledgments

We thank the clinical staff for their time and engagement with this research. We also thank Momona Yamagami, MS, and Ivana Milovanovic, PhD, for their early support in launching this research.

References

1. Langhorne P, Coupar F, Pollock A. Motor recovery after stroke: a systematic review. Lancet Neurol 2009;8:741–54.
2. Wade DT, Hewer RL. Functional abilities after stroke: measurement, natural history and prognosis. J Neurol Neurosurg Psychiatry 1987;50:177–82.
3. Katrak P, Bowring G, Conroy P, Chilvers M, Poulos R, McNeil D. Predicting upper limb recovery after stroke: the place of early shoulder and hand movement. Arch Phys Med Rehabil 1998;79:758–61.
4. Sathian K, Buxbaum LJ, Cohen LG, Krakauer JW, Lang CE, Corbetta M, Fitzpatrick SM. Neurological principles and rehabilitation of action disorders: common clinical deficits. Neurorehabil Neural Repair 2011;25(5 suppl):21S–32S.
5. Winstein CJ, Stein J, Arena R, et al. Guidelines for adult stroke rehabilitation and recovery: a guideline for healthcare professionals from the American Heart Association/American Stroke Association. Stroke 2016;47:e98–169.
6. Wiles R, Ashburn A, Payne S, Murphy C. Patients' expectations of recovery following stroke: a qualitative study. Disabil Rehabil 2002;24:841–50.
7. Feldner HA, Papazian C, Peters K, Steele KM. It's all sort of cool and interesting. . . but what do I do with it?" A qualitative study of stroke survivors' perceptions of surface electromyography. Front Neurol 2020;11:1037.
8. Kwakkel G, Kollen B, Lindeman E. Understanding the pattern of functional recovery after stroke: facts and theories. Restor Neurol Neurosci 2004;22:281–99.
9. Twitchell TE. The restoration of motor function following hemiplegia in man. Brain 1951;74:443–80.
10. Stinear C, Ackerley S, Byblow W. Rehabilitation is initiated early after stroke, but most motor rehabilitation trials are not: a systematic review. Stroke 2013;44:2039–45.
11. Bernhardt J, Hayward KS, Kwakkel G, et al. Agreed definitions and a shared vision for new standards in stroke recovery research: the stroke recovery and rehabilitation roundtable taskforce. Int J Stroke 2017;12:444–50.
12. Gregson JM, Leathley MJ, Moore AP, Smith TL, Sharma AK, Watkins CL. Reliability of measurements of muscle tone and muscle power in stroke patients. Age Ageing 2000;29:223.
13. Winters C, Kwakkel G, Nijland R, Van Wegen E, Consortium ES. When does return of voluntary finger extension occur post-stroke? A prospective cohort study. PLoS One 2016;11:e0160528.
14. Stinear CM, Byblow WD, Ackerley SJ, Smith MC, Borges VM, Barber PA. Proportional motor recovery after stroke: implications for trial design. Stroke 2017;48:795–8.
15. Prager EM, Lang CE. Predictive ability of 2-day measurement of active range of motion on 3-mo upper-extremity motor function in people with poststroke hemiparesis. Am J Occup Ther 2012;66:35–41.
16. Lang CE, Bland MD, Bailey RR, Schaefer SY, Birkenmeier RL. Assessment of upper extremity impairment, function, and activity after stroke: foundations for clinical decision making. J Hand Ther 2013;26:104–15.
17. Bolek JE. Quantitative surface electromyography: applications in neuromotor rehabilitation. Biofeedback 2012;40:47–56.

18. Feldner HA, Howell D, Kelly VE, McCoy SW, Steele KM. Look, your muscles are firing!": a qualitative study of clinician perspectives on the use of surface electromyography in neurorehabilitation. Arch Phys Med Rehabil 2019;100:663–75.
19. Shea PA, Woods WW. Electromyography as an aid in clinical diagnosis. AMA Arch Intern Med 1955;96:787–93.
20. Hesam-Shariati N, Trinh T, Thompson-Butel AG, Shiner CT, McNulty PA. A longitudinal electromyography study of complex movements in poststroke therapy. 1: heterogeneous changes despite consistent improvements in clinical assessments. Front Neurol 2017;8:340.
21. Lang CE, Wagner JM, Edwards DF, Dromerick AW. Upper extremity use in people with hemiparesis in the first few weeks after stroke. J Neurol Phys Ther 2007;31:56–63.
22. Waddell KJ, Strube MJ, Bailey RR, et al. Does task-specific training improve upper limb performance in daily life poststroke? Neurorehabil Neural Repair 2017;31:290–300.
23. Yamagami M, Peters KM, Milovanovic I, et al. Assessment of dry epidermal electrodes for long-term electromyography measurements. Sensors 2018;18:1269.
24. Zhang X, Chen X, Li Y, Lantz V, Wang K, Yang J. A framework for hand gesture recognition based on accelerometer and EMG sensors. IEEE Trans Syst Man Cybern Syst Hum 2011;41:1064–76.
25. Giuffrida JP, Lerner A, Steiner R, Daly J. Upper-extremity stroke therapy task discrimination using motion sensors and electromyography. IEEE Trans Neural Syst Rehabil Eng 2008;16:82–90.
26. Jeong JW, Yeo WH, Akhtar A, et al. Materials and optimized designs for human-machine interfaces via epidermal electronics. Adv Mater 2013;25:6839–46.
27. Doheny EP, Goulding C, Flood MW, Mcmanus L, Lowery MM. Feature-based evaluation of a wearable surface EMG sensor against laboratory standard EMG during force-varying and fatiguing contractions. IEEE Sensors J 2019;20:2757–65.
28. Lonini L, Shawen N, Ghaffari R, Rogers J, Jayarman A. Automatic detection of spasticity from flexible wearable sensors. In: Lee SC, Takayama L, Truong K, eds. Proceedings of the 2017 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2017 ACM International Symposium on Wearable Computers, New York, NY: ACM; September 11-15, 2017.
29. Liu Y, Tian L, Raj MS, et al. Intraoperative monitoring of neuromuscular function with soft, skin-mounted wireless devices. NPJ Digital Med 2018;1:1–10.
30. Gurchiek RD, Choquette RH, Beynnon BD, et al. Remote gait analysis using wearable sensors detects asymmetric gait patterns in patients recovering from ACL reconstruction. In: 2019 IEEE 16th International Conference on Wearable and Implantable Body Sensor Networks (BSN), New York, NY: IEEE; May 19-22, 2019.
31. Sukal TM, Ellis MD, Dewald JP. Shoulder abduction-induced reductions in reaching work area following hemiparetic stroke: neuroscientific implications. Exp Brain Res 2007;183:215–23.
32. De Weerdt W, Harrison M. Measuring recovery of arm-hand function in stroke patients: a comparison of the Brunnstrom-Fugl-Meyer test and the Action Research Arm test. Physiother Can 1985;37:65–70.
33. Verheyden G, Nieuwboer A, De Wit L, et al. Time course of trunk, arm, leg, and functional recovery after ischemic stroke. Neurorehabil Neural Repair 2008;22:173–9.
34. Owen M, Ingo C, Dewald J. Upper extremity motor impairments and microstructural changes in bulbospinal pathways in chronic hemiparetic stroke. Front Neurol 2017;8:257.
35. McPherson JG, Chen A, Ellis MD, Yao J, Heckman C, Dewald JP. Progressive recruitment of contralesional cortico-reticulospinal pathways drives motor impairment post stroke. J Physiol 2018;596:1211–25.
36. Ramos-Murguialday A, García-Cossio E, Walter A, et al. Decoding upper limb residual muscle activity in severe chronic stroke. Ann Clin Translat Neurol 2015;2:1–11.
37. Roh J, Rymer WZ, Perreault EJ, Yoo SB, Beer RF. Alterations in upper limb muscle synergy structure in chronic stroke survivors. J Neurophys 2013;109:768–81.
38. Dewald JP, Sheshadri V, Dawson ML, Beer RF. Upper-limb discoordination in hemiparetic stroke: implications for neurorehabilitation. Top Stroke Rehabil 2001;8:1–12.
39. Gowland C, deBruin H, Basmajian JV, Plews N, Burcea I. Agonist and antagonist activity during voluntary upper-limb movement in patients with stroke. Phys Ther 1992;72:624–33.
40. Canning CG, Ada L, O'Dwyer NJ. Abnormal muscle activation characteristics associated with loss of dexterity after stroke. J Neurol Sci 2000;176:45–56.
41. Moskowitz A, McSparron J, Stone DJ, Celi LA. Preparing a new generation of clinicians for the era of big data. Harv Med Stud Rev 2015;2:24–7.
42. Steele KM, Papazian C, Feldner HA. Muscle activity after stroke: perspectives on deploying surface electromyography in acute care. Front Neurol 2020;11:576757.
43. Adams HP, Davis P, Leira E, et al. Baseline NIH Stroke Scale score strongly predicts outcome after stroke: a report of the Trial of Org 10172 in Acute Stroke Treatment (TOAST). Neurology 1999;53:126–31.
44. Loewen SC, Anderson BA. Predictors of stroke outcome using objective measurement scales. Stroke 1990;21:78–81.
45. Morris JH, Van Wijck F, Joice S, Donaghy M. Predicting health related quality of life 6 months after stroke: the role of anxiety and upper limb dysfunction. Disabil Rehabil 2013;35:291–9.
46. Schlegel D, Kolb SJ, Luciano JM, et al. Utility of the NIH Stroke Scale as a predictor of hospital disposition. Stroke 2003;34:134–7.
47. Schwartz S, Cohen ME, Herbison GJ, Shah A. Relationship between two measures of upper extremity strength: manual muscle test compared to hand-held myometry. Arch Phys Med Rehabil 1992;73:1063–8.
48. Bohannon RW. Manual muscle testing: does it meet the standards of an adequate screening test? Clin Rehabil 2005;19:662–7.
49. Cuthbert SC, Goodheart Jr. GJ. On the reliability and validity of manual muscle testing: a literature review. Chiropr Osteopat 2007;15:4.
50. Gladstone DJ, Danells CJ, Black SE. The Fugl-Meyer assessment of motor recovery after stroke: a critical review of its measurement properties. Neurorehabil Neural Repair 2002;16:232–40.
51. Hermens HJ, Freriks B, Disselhorst-Klug C, Rau G. Development of recommendations for SEMG sensors and sensor placement procedures. J Electromyogr Kinesiol 2000;10:361–74.
52. Solnik S, DeVita P, Rider P, Long B, Hortobágyi T. Teager–Kaiser Operator improves the accuracy of EMG onset detection independent of signal-to-noise ratio. Acta Bioeng Biomech 2008;10:65–8.
53. Arjunan SP, Kumar DK. Fractal based modelling and analysis of electromyography (EMG) to identify subtle actions. Conf Proc IEEE Eng Med Biol Soc 2007;2007:1961–4.
54. Chowdhury RH, Reaz MB, Ali MABM, Bakar AA, Chellappan K, Chang TG. Surface electromyography signal processing and classification techniques. Sensors (Basel) 2013;13:12431–66.
55. Li X, Zhou P, Aruin AS. Teager-Kaiser energy operation of surface EMG improves muscle activity onset detection. Ann Biomed Eng 2007;35:1532–8.
56. Micera S, Sabatini AM, Dario P. An algorithm for detecting the onset of muscle contraction by EMG signal processing. Med Eng Phys 1998;20:211–5.
57. De Luca CJ, Kuznetsov M, Gilmore LD, Roy SH. Inter-electrode spacing of surface EMG sensors: reduction of crosstalk contamination during voluntary contractions. J Biomech 2012;45:555–61.