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Validity of Body-Worn Sensor Acceleration Metrics to Index Upper Extremity Function in Hemiparetic Stroke

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Abstract

Background and Purpose—In people with stroke, real-world use of the paretic upper extremity influences function. Therefore, measures of real-world use are of value for guiding rehabilitation. We undertook a study to identify the acceleration characteristics that have a stable association with upper extremity function and sensitivity to within-participant fluctuations in function over multiple sessions of task-specific training.

Methods—Twenty-seven adults > 6 months post stroke with upper extremity paresis participated. Signals from wrist-worn accelerometers were sampled at 30 Hz during seven sessions of task-specific training. Paretic upper extremity function was evaluated with the Action Research Arm Test (ARAT). We used Spearman correlations to examine within-session associations between acceleration metrics and ARAT performance. A mixed model was used to determine which metrics were sensitive to within-participant fluctuations in upper extremity function across the seven training sessions.

Results—Upper extremity function correlated with bilateral acceleration variability and use ratio during five and six session, respectively. Time accelerating between 76-100% of peak acceleration correlated with function in six sessions. Variability of the paretic upper extremity acceleration and the ratio of acceleration variability between upper extremities were associated with function during all seven sessions. Variability in both the acceleration of the paretic upper extremity, and acceleration of the paretic and non-paretic extremities combined were sensitive to within-participant fluctuations in function across training sessions.

Conclusion—Multiple features of the acceleration profile track with upper extremity function within and across sessions of task-specific training. It may be possible to monitor these features with accelerometers to index upper extremity function outside of clinical settings.

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INTRODUCTION

Effective rehabilitation of movement disorders is predicated on sufficient restoration of function to allow the individual to engage in everyday tasks outside of the clinic in their real-world environment. Greater than 50% of persons with stroke experience upper extremity disability.¹ This disability results in a loss of independent living and productivity leading to psychological² and financial³ hardship for stroke survivors and family members providing care. The amount of real-world paretic upper extremity use, therefore, is thought to be an indicator of real-world function.

Body-worn sensors, such as accelerometers, provide a non-invasive means for monitoring activity outside of the clinic. Accelerometry is a valid and reliable index of upper extremity use in people with hemiparesis at varying time-points following stroke.⁴ Previous studies have demonstrated that, early after stroke, people use their paretic upper extremity significantly less than controls over a 24-hour period⁵ or longer.⁶ In individuals at the chronic stage, the absolute duration of use⁷ and the duration of use relative to the non-paretic upper extremity^{8,9} have been found to increase following constraint-induced movement therapy. The amount of paretic upper extremity use also has been reported to increase as a function of stroke chronicity.¹⁰

One limitation associated with accelerometer-derived measures of upper extremity use in the abovementioned studies is that they do not differentiate between general movement (e.g., gait-related arm swing) and task-specific, goal-directed movement (e.g., reaching and grasping an object). More sophisticated, somewhat cumbersome monitoring systems have been developed to categorize real-world upper extremity use in different body postures,¹¹ allowing for this differentiation. There is a need, however, to make body-worn sensors non-invasive and practical for wear during everyday life. If the purpose of these devices is to index upper extremity function outside of tightly controlled clinical settings, then an alternative approach moving forward may involve identifying acceleration characteristics that provide insight into upper extremity function. Recording these characteristics via wrist-worn accelerometers and quantifying specific metrics from the monitoring period could offer clinicians a more objective basis for selecting and adapting rehabilitation protocols.

The purpose of the current study is to establish the convergent validity of specific acceleration metrics, quantified from a period of task-specific training in controlled, clinical settings, with a widely used clinical assessment of upper extremity function.¹² This study represents an initial effort directed towards identifying which acceleration characteristics are associated with function in chronic stroke hemiparesis. The primary purpose of this exploratory study was to identify acceleration metrics that have a stable association with a performance on a standardized assessment of function. The secondary purpose was to determine which acceleration metrics can detect within-subject fluctuations in upper extremity function. With these purposes satisfied, future work will be in a position to examine if the metrics are responsive to intervention-induced changes in function, particularly in real-world settings.

Methods

Subjects

Twenty-seven individuals 6 months post stroke with upper extremity paresis were recruited to participate as part of an ongoing clinical trial (NCT 01146379). The purpose of the trial is to determine the optimal dose of progressive task-specific training required to enhance upper extremity function following stroke. Individuals were included in the trial if they had: (a) clinical diagnosis of ischemic or hemorrhagic stroke as determined by a stroke neurologist; (b) cognitive functioning as defined by a score of 0–1 on the consciousness and communication items of the NIH Stroke Scale (NIHSS); (c) unilateral upper extremity paresis as defined by a score of 1–3 on the arm item of the NIHSS; (d) movement of the paretic upper extremity as defined by a score of 10 on the Action Research Arm Test (ARAT); and (e) ability to provide informed consent. Individuals were excluded from the trial if they had: (a) history of neurosurgical intervention; (b) psychiatric diagnosis; (c) other neurological diagnoses; or (d) were pregnant. All participants provided informed consent according to procedures established and approved by the Washington University Institutional Review Board and were compensated for their time.

Procedure

Upon enrolling in the study, participants identified multiple task-specific behaviors they struggled to perform, including self-care, household, workplace, and/or leisure activities (Table 1). Participants were also evaluated on measures of spasticity, self-perceived hand function, somatosensation, and paretic severity on the paretic side (explained below). Participants presented to the neurorhabilitation laboratory for task-specific training, focusing on the identified tasks (see Table 1 for examples), 4 times per week for a total of 8 weeks; data reported here are from weeks two through eight. Testing took place prior to the final training session each week. At the beginning of each testing session, wireless devices containing a tri-axial, solid-state digital accelerometer (see Figure 1, dimensions: 4.6cm×3.3cm×1.5 cm, weight: 19 grams, range: +/-6 g) were strapped to the dorsal side of both wrists just proximal to the radial and ulnar styloid processes. Accelerations were recorded during assessments of upper extremity function and paretic severity, and continued while participants engaged in individualized, task-specific training according to a previously established protocol.¹³ Task difficulty was graded to motor capabilities and progressed over the course of the 7 weeks.

Clinical Measures

Spasticity of the elbow flexor muscles was evaluated with the Modified Ashworth Scale.¹⁴ The scores on the scale range from 0 to 4, where 0 equates to normal muscle tone and 4 equates to complete rigidity. Self-perceived hand function was evaluated using the Hand Function Subscale of the Stroke Impact Scale.^{15, 16} Participants rated their ability to use their paretic upper extremity in five activities of daily living with this subscale. Scores range from 0 – 100, where 100 indicates normal hand function. Semmes-Weinstein monofilaments¹⁷ were used on each index fingertip to determine sensitivity to light touch, sharp touch, and deep pressure; scores range from 2.83 (i.e., normal) to 6.65 (i.e., deep pressure sensation only). Severity of paresis was quantified with the Motricity Index¹⁸ a test consisting of three

upper extremity actions: hand-grasp, elbow flexion and shoulder abduction. Each action is scored on a 0–33 point scale (+1 point), to achieve a maximum of 100 points, and measures the extent to which muscle groups of the upper extremity can be activated to move a body segment through a range of motion and withstand external resistance. The Motricity Index is strongly correlated with dynamometer-derived estimates of force production in persons with stroke.¹⁸

Upper extremity function was evaluated with the ARAT, which consists of 19 items divided into four subscales: grasp, grip, pinch, and gross movement. The test is scored on a 0–57 point scale, with higher scores indicating better upper extremity function. The ARAT is a valid and reliable test of upper extremity movement capabilities^{19–21} and is responsive to change following stroke.^{20, 22–24} The ARAT is also strongly correlated with other accepted assessments of upper extremity function.^{25, 26} The same blinded rater did not always administer the ARAT for each participant and for each testing session. Prior to being a blinded rater for the trial, each individual underwent a standardized training protocol that included education about and observation of test protocol administration. The individual then had to pass a written test to ensure competence with test administration. All assessments were video-recorded and videos are randomly monitored to ensure fidelity of the testing protocol.

Data Processing and Calculation of Accelerometer Metrics

The duration of each session varied within participants due to the nature of the task, fatigue, etc. and varied across participants due to the presence/severity of apraxia and other cognitive deficits, but the duration was always 90 minutes or longer. Raw accelerometer data, therefore, were truncated to 90 minutes for each session. Accelerations were sampled at 30 Hz in all three cardinal planes because most movement during activities of daily living are well below this frequency.²⁷ The accelerations occurring across all 30 samples were summed together into 1-second epochs and quantified as activity counts (0.016318 m/s² per count), using proprietary software (ActiGraph 6, ____). Activity counts occurring in each plane were smoothed using a five-second running average first and then combined into a single composite measure for each upper extremity by summing the squares of activity counts in each plane and taking the square root of the resulting value ($= \sqrt{x^2 + y^2 + z^2}$). The raw accelerations recorded in each plane for the paretic and non-paretic upper extremities during task-specific training are illustrated in Figure 2; the bottom panels depict the accelerations for each upper extremity after being combined into the composite measure.

Custom software was written in MATLAB (Mathworks, Inc. R2012a, Natick, MA) to calculate multiple acceleration metrics classified into four separate categories. The first category reflects ratios of acceleration characteristics between the paretic and non-paretic upper extremities, which include the use, magnitude, and variation ratios. Metrics that capture how one extremity moves compared to the other are important because of differences in movement capabilities that exist between individuals. The second and third categories are comprised of acceleration characteristics specific to the paretic upper extremity and both upper extremities combined. Paretic and bilateral accelerations are indices of the paretic-upper extremity acceleration magnitude and the combined acceleration

magnitude of both extremities, respectively. Bilateral acceleration characteristics were examined because many activities of daily living involve both upper extremities.³¹ Median values for both metrics were examined, as outliers made the mean value less representative of the data. Both the maxima and standard deviations of these parameters were calculated to characterize peak magnitudes and spread of accelerations around the mean acceleration magnitude. The fourth category is comprised of normalized acceleration ranges, reflecting the time distribution of paretic upper extremity movement intensity relative to each participant's peak acceleration. The acceleration magnitudes of the paretic extremity were normalized to each participant's peak acceleration to account for differences in participant capabilities and tasks performed. Descriptions of the metrics and the formulae used to calculate them are provided in Table 2.

Statistical Analyses

Statistical analyses were conducted using SPSS version 20 (IBM Statistics) and SAS version 9.3 (SAS Institute Inc.). Spearman correlations were used to examine the within-session association between upper extremity function, as measured by total ARAT, and acceleration metrics because the ARAT is scored on an ordinal scale.³² Within-session correlations were used to determine which metrics were associated with function for each week. These correlations were examined for each of the seven sessions to assess stability of the within-session relationships over time. Based on the sample size, correlation coefficients greater than 0.38 were significant at $p < 0.05$ and coefficients greater than 0.48 were significant at $p < 0.01$. The strength of correlation coefficients was considered weak at 0.29 or below, moderate at 0.30 to 0.59, and strong at 0.60 or greater.³³

A mixed model with a compound symmetry covariance structure was used to examine which acceleration metrics were sensitive to within-subject variation in ARAT scores across testing sessions.³⁴ This analysis captures how fluctuations in each variable correspond to one another across individual participants. Initially, all acceleration metrics were entered into the model as predictor variables and ARAT score as the response variable. The least significant variable was removed from the model using a stepwise modeling procedure. The model fit was evaluated at each step. Variables were entered and removed until the greatest model fit was achieved. Significance for this model was set at $p < 0.05$.

Results

Descriptive measures for the 27 participants with chronic hemiparesis included in the study are given in Table 3. Overall, the sample consisted of middle-aged individuals with long-standing stroke who had sufficient motor abilities in the paretic extremity to participate in a task-specific training program. Most participants were male (74%) and affected on their right side (63%); the same proportion of participants was affected on their dominant side (63%, 3 left, 14 right). Paretic severity was mild-to-moderate at the initial evaluation (Motricity Index = 74 ± 14.5). This was accompanied by little or no spasticity, relatively intact somatosensation, and a moderate self-perception of the ability to use the paretic upper extremity.

Within Session Associations

Paretic and bilateral upper extremity acceleration metrics were fairly consistent for the sample as a whole over the seven testing sessions as illustrated in Table 4; in this Table the first row for each metric contains its mean and standard deviation during each session. Use and magnitude ratios were greater than 1 for all seven sessions, indicating more paretic upper extremity use and greater paretic movement intensity compared to the non-paretic limb. Additionally, the variation ratio was very close to 1 for all seven sessions. These values are expected since training emphasized the paretic upper extremity. Across the seven weeks, less time was spent in higher normalized acceleration ranges. For example, across the seven sessions, the paretic upper extremity accelerated an average of approximately 54%, 16%, 4%, and 1% of the time in each respective range from 1–25% to 76–100%, respectively.

Spearman coefficients for ARAT-acceleration metric correlations are presented in Table 4, in the second row for each metric. The use and magnitude ratios were moderately correlated with ARAT score during six and three sessions, respectively. The variation ratio was moderately correlated with ARAT score in four sessions, with strong correlations observed in the remaining three sessions. The median paretic and bilateral acceleration did not correlate with ARAT score at any session. The maximum paretic and bilateral acceleration were both moderately correlated with ARAT score at two of the seven time points. Variability in the paretic upper extremity acceleration had a consistent, moderate correlation with ARAT score across all weeks. Bilateral acceleration variability had a moderate and strong correlation during four sessions and one session, respectively. The time spent at 1–25% and 26–50% of peak accelerations were not correlated with ARAT score during any session. Moderate correlations were observed in four and six sessions for time spent within 51–75% and 76–100% ranges, respectively.

Across Sessions Association

A total of 189 observations (7 sessions×27 participants) were entered into the mixed model. The model demonstrated strongest model fitness ($\chi^2 = 470$, $p < .001$) when it was reduced to the variability of both the paretic-upper extremity acceleration ($F_{1,160}=5.19$, $p = 0.02$) and bilateral acceleration ($F_{1,160} = 6.12$, $p = 0.01$). These findings indicate that variability in both the acceleration of the paretic upper extremity and paretic and non-paretic extremities combined were sensitive to within-subject fluctuations in function across the seven sessions. Figure 3 depicts corresponding within-subject fluctuations in paretic upper extremity acceleration variability (Figure 3A) and bilateral acceleration variability (Figure 3B) for two example participants.

Discussion

The primary and secondary purposes of this exploratory study were to determine which acceleration characteristics occurring during task-specific behaviors have a stable association with upper extremity function and can detect within-subject fluctuations in function. Accelerations were recorded from a wide range of upper extremity tasks to increase the likelihood that the results would generalize to a wide range of task-specific

behaviors that are performed daily. Findings of the current study indicate that multiple acceleration characteristics can index upper extremity function post stroke. The metrics pertaining to acceleration variability appear to be particularly valid indicators of the paretic upper extremity's movement capabilities.

Of all the metrics examined in the current study, acceleration variability was most closely associated with upper extremity function. The magnitude of the relationship with variability of the paretic upper extremity acceleration was fairly consistent over the seven training sessions; the relationship with variability of the bilateral acceleration was not as consistent. Acceleration variability reflects the average distance of the sampled accelerations from the mean acceleration. Findings reported here indicate that a greater spread of acceleration around the mean acceleration relates to the capabilities of the paretic upper extremity during task-specific training. Moderate-to-strong associations were observed for the variation ratio across all training sessions, suggesting that higher function can be inferred when acceleration variability in the paretic extremity more closely approximates or surpasses that of the non-paretic extremity. The stability of these associations aside, within-subject fluctuations in acceleration variability of the paretic upper extremity and both upper extremities combined corresponded to variations in function across the seven sessions. Thus, these metrics appear sensitive to the subtle shifts in performance on the standardized assessment of function.

The amount of paretic-upper extremity use relative to that of the non-paretic upper extremity (i.e., use ratio) has been used as a marker of recovery following stroke in real-world settings.^{8,9} The vast majority of normal use³⁵ and paretic upper extremity use¹¹ occurs as part of bimanual movement. Previously reported use ratios in free-living environments are in the 0.3 – 0.5 range in persons with stroke⁹ and 0.8 – 1.0 in controls.³⁵ Data from the current study indicate that the paretic upper extremity was used more than the non-paretic upper extremity (i.e., use ratio > 1). Participants in this study were forced to engage the paretic upper extremity while undergoing high-volume task-specific training, which likely accounts for the disparity between the values reported here and previous estimates. Thus, the lack of a consistent association between upper extremity function and the use ratio does not preclude the possibility that the relationship would be more stable if this metric were quantified from a period of monitoring outside of clinical settings.

The use ratio reflects the relative amount or time of paretic upper extremity use but does not indicate the extent to which it contributes to the activity. Without an index of the acceleration's magnitude, an individual's level of function may be overestimated. For example, the paretic upper extremity acceleration may be acceleration due to object stabilization rather than object manipulation. The magnitude ratio, therefore, was developed to account for the contribution of the paretic upper extremity. Previous work has reported the intensity of movement and the ratio of movement intensity between extremities over the entire period of monitoring,^{28–30} which is different from the second-to-second calculation used in the current study. This difference complicates a straightforward comparison of previous estimates to the values reported here. Nevertheless, the relationship between this metric and upper extremity function was likely influenced by the demands of the task-specific training context. It does appear, however, that the ability to maintain higher

movement intensities of the paretic upper extremity is an effective indicator of function in this context. There was a relatively stable association between function and time the paretic upper extremity accelerated within 76–100% of peak acceleration. Thus, movement intensity of the paretic upper extremity can index function when normalized to its own potential for intense movement, not when normalized to the potential of the non-paretic upper extremity.

Study Limitations

Two main limitations need to be considered when interpreting these data. First, participants were recruited as part of an ongoing clinical trial. The criteria for participating in this trial excluded individuals with severe paresis, making the findings reported here generalizable to the subset of the stroke population with chronic, mild-to-moderate paresis. Second, accelerations were recorded in a controlled, clinical setting where participants were required to engage the paretic upper extremity. Although this was a necessary first step to verify accelerations occurring as part of task-specific behaviors, results should be interpreted with caution. It is possible that people with stroke perform task-specific behaviors differently in a monitored, high-repetition intervention than in their everyday lives. Future work is needed to investigate this possibility and implications that may exist for monitoring individuals outside of clinical settings via the metrics examined in the current study.

Conclusions

The current study establishes the convergent validity of multiple acceleration metrics derived from body-worn sensors with a widely used assessment of upper extremity function. Acceleration variability of the paretic upper extremity and the ratio of acceleration variability between the paretic and non-paretic upper extremities exhibited a stable relationship with function over time. Within-subject variations in function corresponded to fluctuations in acceleration variability of the paretic upper extremity and bilateral acceleration. Further research is needed to replicate these findings. Specifically, future research should examine whether the metrics reported here are responsive to intervention-induced changes in upper extremity function, particularly during periods of real-world monitoring.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1.
Wrist-worn accelerometer devices (ActiGraph LLC, 49 East Chase Street, Pensacola, FL 32502; <http://www.actigraphcorp.com/>).

Figure 2. Accelerations in each cardinal plane for the A) paretic and B) non-paretic upper extremity during 60 seconds of task-specific training. Accelerations in each cardinal plane were combined into a composite acceleration for the C) paretic and D) non-paretic upper extremity.

A

B

Figure 3.

Correspondence between actual values for acceleration metrics and ARAT score across the seven sessions of task-specific training in two example participants: A) variability of the paretic-upper extremity acceleration and B) variability of the bilateral acceleration.

Table 1

Examples of task-specific behaviors performed during training.

Self-Care	Household	Workplace	Leisure
Brushing teeth	Cutting food	Handwriting	Shuffling playing cards
Washing body	Folding laundry	Picking up coins	Reeling fishing pole
Applying hand lotion	Wiping table	Latching locks	Sewing
Shaving	Drying pots and pans	Sanding wall	Cross-stitching
Applying make-up	Hanging clothes	Turning pages	Stringing beads
Combing hair	Turning on faucet	Assembling nut/bolt	Drawing

Table 2

Description and formulae used to calculate acceleration metrics.

<p>Composite Acceleration: before calculating individual metrics, the accelerations of each upper extremity in each cardinal plane (x, y, z) were combined into one composite value that is calculated as follows:</p> $= \sqrt{x^2 + y^2 + z^2}$
<p>Ratio Acceleration Metrics: these metrics reflect acceleration characteristics of the paretic upper extremity normalized to the non-paretic upper extremity. These metrics were calculated because most task-specific behaviors occur as part of bimanual movement.</p> <p><i>Use Ratio:</i> ratio of total duration of paretic upper extremity activity to total duration of non-paretic upper extremity activity. The use ratio reflects the amount of time the paretic upper extremity is active relative to the amount of time the non-paretic upper extremity is active. Values near 1 indicate the duration of activity is the same between the two upper extremities. Values >1 indicate the paretic upper extremity is used more than the non-paretic upper extremity, whereas values <1 indicate the paretic upper extremity is used less than the non-paretic upper extremity. Use ratios are in the 0.3 – 0.5 range in persons with stroke⁹ and 0.8 – 1.0 in controls³⁵ during real-world monitoring.</p> $= \frac{\sum_{i=1}^n (\# \text{ of epochs}_i \cdot 0.02m/s^2)_{(paretic)}}{\sum_{i=1}^n (\# \text{ of epochs}_i \cdot 0.02m/s^2)_{(non-paretic)}}$ <p><i>Magnitude Ratio:</i> ratio of the magnitude of paretic upper extremity acceleration to the magnitude of the non-paretic upper extremity acceleration. The magnitude ratio reflects the movement intensity of the paretic upper extremity relative to the movement intensity of the non-paretic upper extremity. Values near 1 indicate the upper extremities are moving at similar magnitudes. Values > 1 indicate the non-paretic upper extremity is moving at higher magnitudes, whereas values < 1 indicate the paretic upper extremity is moving at lesser magnitudes. (The median magnitude ratio is reported in the current study).</p> $= \frac{\sum_{i=1}^n (\text{epoch value}_{i \text{ paretic}} + \text{epoch value}_{i \text{ non-paretic}})}{n} = \frac{\sum_{i=1}^n (\text{paretic acceleration})}{\sum_{i=1}^n (\text{paretic acceleration})}$ <p><i>Variation Ratio:</i> ratio of the standard deviation of acceleration on the paretic upper extremity to the standard deviation on non-paretic upper extremity. The variation ratio reflects the dynamic movement capabilities of the paretic upper extremity relative to the dynamic movement capabilities of the non-paretic upper extremity. Values near 1 indicate an equal spread of paretic accelerations around the mean paretic acceleration relative to the spread of non-paretic accelerations around the mean non-paretic acceleration. Values > 1 indicate a greater spread of paretic acceleration relative non-paretic accelerations, whereas values < 1 indicate a tighter spread of paretic acceleration relative to non-paretic accelerations.</p> $= \frac{\sigma_{(paretic \text{ acceleration})}}{\sigma_{(non-paretic \text{ acceleration})}}$
<p>Paretic Acceleration Metrics: these metrics reflect acceleration characteristics of the paretic upper extremity. The median and maximum accelerations are indicative of the typical and maximum accelerations over the entire monitoring period, respectively. Acceleration variability is indicative of the spread of accelerations around the mean acceleration during the monitoring period.</p> $\text{Median} = x_{(paretic \text{ acceleration})}$ $\text{Maximum} = \max_{(paretic \text{ acceleration})}$ $\text{Variability} = \sigma_{(paretic \text{ acceleration})}$
<p>Bilateral Acceleration Metrics: these metrics reflect acceleration characteristics of the paretic upper extremity and non-paretic upper extremity combined. The accelerations of corresponding paretic and non-paretic upper extremity epochs are summed together. The median, maximum, and standard deviation of the resulting array is then used to calculate each metric.</p>

$$= \frac{n}{i=1} (epoch\ value_i_{paretic} + epoch\ value_i_{non-paretic})$$

$$Median = x_{(bilateral\ acceleration)}$$

$$Meximum = max_{(bilateral\ acceleration)}$$

$$Variability = \sigma_{(bilateral\ acceleration)}$$

Normalized Range Acceleration Metrics: these metrics reflect the percent of time the paretic upper extremity accelerates within specified percentages of the peak acceleration exhibited over the entire period of monitoring. Higher values in higher ranges indicate a greater amount of sustained paretic upper extremity movement intensity.

$$= \frac{n}{i=1} (epoch\ value_i \quad x\% \quad x\%_{peak\ paretic}) \left| \frac{n}{i=1} (epoch\ value_i \quad 0.02m/s^2_{paretic}) \right.$$

Table 3

Participant and paretic upper extremity characteristics at the initial evaluation (n=27).

Parameter	Mean $\pm$ SD	Range/Percentage
Age, years	62 $\pm$ 9.4	46–81
Gender	20 males 7 females	74% 26%
Time since stroke (months) to initial visit	31 $\pm$ 47.5	6–221
Lesion type	22 Ischemic 2 Hemorrhagic	82% 7%
Number of strokes	1.3 $\pm$ 0.5	1–3
Affected upper extremity	17 Right 10 Left	63% 37%
Dominant upper extremity	21 Right 6 Left	78% 22%
Dominant upper extremity affected	14 Right 3 Left	52% 11%
Motricity Index	74 $\pm$ 14.5	40–100
Action Research Arm Test	30.3 $\pm$ 12.3	10–47
Modified Ashworth Scale	1.4 $\pm$ 1.2	0–4
Somatosensation	3.6 $\pm$ 1.1	2.8–6.7
Stroke Impact Scale Hand Function Subscale	42.0 $\pm$ 22.0	0–90

Table 4

Mean $\pm$ standard deviation and Spearman correlation (with ARAT) coefficients for acceleration metrics, arranged by category.

Metric Category	Session 1	Session 2	Session 3	Session 4	Session 5	Session 6	Session 7
Ratio							
Use (%)	1.1 $\pm$ 0.2	1.1 $\pm$ 0.3	1.2 $\pm$ 0.4	1.2 $\pm$ 0.4	1.3 $\pm$ 0.5	1.2 $\pm$ 0.4	1.3 $\pm$ 0.4
ρ	.43*	.15	.39*	.43*	.56*	.57*	.51*
Magnitude (%)	1.4 $\pm$ 1.2	1.6 $\pm$ 1.6	2.4 $\pm$ 4.6	2.5 $\pm$ 4.6	5.4 $\pm$ 10.7	2.9 $\pm$ 3.7	2.9 $\pm$ 4.3
ρ	.31	.11	.32	.25	.55*	.46*	.41*
Variation (%)	.92 $\pm$.29	.96 $\pm$.39	.92 $\pm$.28	.90 $\pm$.21	1.0 $\pm$.35	.99 $\pm$.39	.93 $\pm$.33
ρ	.58*	.68*	.65*	.45*	.66*	.56*	.56*
Paretic							
Median (m/s ²)	0.7 $\pm$ 0.4	0.6 $\pm$ 0.3	0.6 $\pm$ 0.3	0.7 $\pm$ 0.3	0.7 $\pm$ 0.3	0.8 $\pm$ 0.5	0.8 $\pm$ 0.4
ρ	.04	.06	.23	.13	.25	.32	.37
Maximum (m/s ²)	4.9 $\pm$ 1.4	4.5 $\pm$ 1.1	4.4 $\pm$ 1.1	4.7 $\pm$ 1.3	4.9 $\pm$ 1.2	5.1 $\pm$ 1.3	4.9 $\pm$ 1.2
ρ	.08	.49*	.17	.13	.31	.41*	.33
Variability (m/s ²)	0.8 $\pm$ 0.3	0.8 $\pm$ 0.4	0.8 $\pm$ 0.3	0.7 $\pm$ 0.3	0.8 $\pm$ 0.4	0.8 $\pm$ 0.4	0.8 $\pm$ 0.3
ρ	.55*	.55*	.56*	.59*	.53*	.46*	.59*
Bilateral							
Median (m/s ²)	1.5 $\pm$ 0.6	1.4 $\pm$ 0.5	1.3 $\pm$ 0.6	1.3 $\pm$ 0.4	1.3 $\pm$ 0.5	1.5 $\pm$ 0.6	1.5 $\pm$ 0.7
ρ	-.14	.05	.03	-.11	.00	.05	.06
Maximum (m/s ²)	7.8 $\pm$ 1.7	7.9 $\pm$ 1.7	7.5 $\pm$ 1.5	7.9 $\pm$ 1.9	7.7 $\pm$ 1.8	8.2 $\pm$ 2.0	8.2 $\pm$ 2.1
ρ	.35	.24	.19	.40*	.19	.47*	.17
Variability (m/s ²)	1.3 $\pm$ 0.4	1.3 $\pm$ 0.5	1.2 $\pm$ 0.3	1.2 $\pm$ 0.4	1.2 $\pm$ 0.4	1.3 $\pm$ 0.4	1.3 $\pm$ 0.4
ρ	.54*	.61*	.34	.56*	.37	.42*	.46*
Normalized Range							
1–25% Peak	56.3 $\pm$ 13.4	55.7 $\pm$ 11.3	48.3 $\pm$ 18.0	55.2 $\pm$ 15.2	55.1 $\pm$ 15.4	53.0 $\pm$ 17.8	51.5 $\pm$ 17.1
ρ	-.36	.13	-.09	-.16	-.11	-.05	-.13
26–50% Peak	16.3 $\pm$ 9.5	17.1 $\pm$ 8.5	12.3 $\pm$ 5.7	15.2 $\pm$ 7.9	16.8 $\pm$ 10.6	16.1 $\pm$ 9.3	16.2 $\pm$ 9.5
ρ	.04	-.19	.06	-.13	-.17	.03	-.02
51–75% Peak	4.2 $\pm$ 3.9	5.5 $\pm$ 5.2	4.3 $\pm$ 4.4	3.3 $\pm$ 3.3	4.2 $\pm$ 3.5	3.8 $\pm$ 4.0	4.9 $\pm$ 6.2

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Metric Category	Session 1	Session 2	Session 3	Session 4	Session 5	Session 6	Session 7
p	.51*	.31	.40	.34	.38*	.38*	.40*
76–100% Peak	0.6±0.9	1.0±1.4	1.0±0.9	1.0±1.8	0.9±1.2	0.6±0.6	0.7±1.1
p	.46*	.35	.51*	.55*	.53*	.54*	.41*

* (p < .05)