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

M. A. Urbin, PhD, Ryan R. Bailey, MS, and Catherine E. Lang, PhD

Background and Purpose: Accelerometers have been used to capture real-world use of the paretic upper extremity in people with stroke. It may be possible to characterize different aspects of the recorded acceleration to gain insight about movement capabilities during task-specific behavior. These measures may be 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 or more poststroke with upper extremity paresis participated. Signals from wrist-worn accelerometers were sampled at 30 Hz during 7 sessions of task-specific training. Paretic upper extremity function was evaluated with the Action Research Arm Test. We used Spearman correlations to examine within-session associations between acceleration metrics and Action Research Arm Test performance. A mixed model was used to determine which metrics were sensitive to within-participant fluctuations in upper extremity function across the 7 training sessions.

Results: Upper extremity function correlated with bilateral acceleration variability and use ratio during 5 and 6 sessions, respectively. Time accelerating between 76% and 100% of peak acceleration correlated with function in 6 sessions. Variability of the paretic upper extremity acceleration and the ratio of acceleration variability between upper extremities were associated with function during all 7 sessions. Variability in both the acceleration of the paretic upper extremity, and acceleration of the paretic and nonparetic extremities combined were sensitive to within-participant fluctuations in function across training sessions.

Discussion and Conclusions: 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.

Video Abstract available for more insights from the authors (see Supplemental Digital Content 1, http://links.lww.com/JNPT/A91).

Key words: *accelerometry, hemiparesis, motor control, neurorehabilitation, practice*

(*JNPT* 2015;39: 111–118)

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 psychological[2] and financial[3] 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 noninvasive 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 after stroke.[4] Previous studies have demonstrated that, early after stroke, people use their paretic upper extremity significantly less than controls over a 24-hour period[5] or longer.[6] In individuals at the chronic stage, the absolute duration of use[7] and the duration of use relative to the nonparetic upper extremity[8,9] have been found to increase after constraint-induced movement therapy. The amount of paretic upper extremity use has also 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 (eg, gait-related arm swing) and task-specific, goal-directed movement (eg, 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 noninvasive 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

---

Program in Physical Therapy (M.A.U., R.R.B., C.E.L.), Program in Occupational Therapy (C.E.L.), and Department of Neurology (C.E.L.), Washington University School of Medicine, St. Louis, Missouri.

This study was supported by the National Institutes of Health (grants T32HD007434 to MAU, TL1 TR000449 to RRB, and R01HD068290 to CEL).

This work has not been presented at any scientific meeting or published previously.

The authors declare no conflicts of interest.

Supplemental digital content is available for this article. Direct URL citation appears in the printed text and is provided in the HTML and PDF versions of this article on the journal's Web site (www.jnpt.org).

Correspondence: M. A. Urbin, PhD, Program in Physical Therapy, Washington University School of Medicine, Campus Box 8502, 4444 Forest Park, St. Louis, MO 63108 (urbinm@wusm.wustl.edu).

ISSN: 1557-0576/15/3902-0111

DOI: 10.1097/NPT.0000000000000085

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 toward 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 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 whether the metrics are responsive to intervention-induced changes in function, particularly in real-world settings.

METHODS

Subjects

Twenty-seven individuals 6 months or more poststroke 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 after 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 to 1 on the consciousness and communication items of the National Institutes of Health Stroke Scale; (c) unilateral upper extremity paresis as defined by a score of 1 to 3 on the arm item of the National Institutes of Health Stroke Scale; (d) movement of the paretic upper extremity as defined by a score of 10 or more 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 neurorehabilitation laboratory for task-specific training, focusing on the identified tasks (Table 1 for examples), 4 times per week for a total of 8 weeks; data reported here are from weeks 2 through 8. Testing took place before the final training session each week. At the beginning of each testing session, wireless devices containing a triaxial, solid-state digital accelerometer (Figure 1; dimensions, 4.6 cm × 3.3 cm × 1.5 cm; weight, 19 g; 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

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

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

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 5 activities of daily living with this subscale. Scores range from 0 to 100, where 100 indicates normal hand function. Semmes-Weinstein monofilaments[17] were used on each index fingertip to determine sensitivity to light touch, sharp touch, and deep pressure; scores range from 2.83 (ie, normal) to 6.65 (ie, deep pressure sensation only). Severity of paresis was quantified with the Motricity Index[18] a test consisting of 3 upper extremity actions: hand grasp, elbow flexion, and shoulder abduction. Each action is scored on a 0- to 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 4 subscales: grasp, grip, pinch, and gross movement. The test is scored on a 0- to 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 after 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. Before 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 because of 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 3 cardinal planes because most movements 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/s^2 per count), using proprietary software (ActiGraph 6, ActiGraph LLC, Pensacola, FL). Activity counts occurring in each plane were smoothed using a 5-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 (see Table 2). The raw accelerations recorded in each plane for the paretic and nonparetic 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 4 separate categories. The first category reflects ratios of acceleration characteristics between the paretic and nonparetic 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 composed 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.[28] 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 composed 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 Armonk, NY) and SAS version 9.3 (SAS Institute Inc Cary, NC). 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.[30] Within-session correlations were used to determine which metrics were associated with function for each week. These correlations were examined for each of the 7 sessions to assess stability of the within-session relationships over time. On the basis of 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.[31]

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.[32] 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 the 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 $P < 0.05$.

Table 2. Description and Formulae Used to Calculate Acceleration Metrics

Composite Acceleration: Before calculating individual metrics, accelerations of each upper extremity in accelerometer-referenced planes (x, y, z) were combined into one composite value that is calculated as follows:

$$= \sqrt{x^2 + y^2 + z^2}$$

Ratio Acceleration Metrics: These metrics reflect acceleration characteristics of the paretic upper extremity normalized to the nonparetic upper extremity. These metrics were calculated because most task-specific behaviors occur as part of bimanual movement.

Use Ratio: Ratio of total duration of paretic upper extremity activity to total duration of nonparetic upper extremity activity. The use ratio reflects the amount of time the paretic upper extremity is active relative to the amount of time the nonparetic upper extremity is active. Values near 1 indicate the duration of activity is the same between the 2 upper extremities. Values > 1 indicate the paretic upper extremity is used more than the nonparetic upper extremity, whereas values < 1 indicate the paretic upper extremity is used less than the nonparetic upper extremity. Use ratios are in the 0.3-0.5 range in persons with stroke[9] and 0.8-1.0 in controls[29] during real-world monitoring.

$$\sum_{i=1}^{n} \left(\#\text{ of epochs}_i \geq 0.02m/s^2{}_{(\text{paretic})}\right) \Big/ \sum_{i=1}^{n} \left(\#\text{ of epochs}_i \geq 0.02m/s^2{}_{(\text{nonparetic})}\right)$$

Magnitude Ratio: Ratio of the magnitude of paretic upper extremity acceleration to the magnitude of the nonparetic upper extremity acceleration. The magnitude ratio reflects the movement intensity of the paretic upper extremity relative to the movement intensity of the nonparetic upper extremity. Values near 1 indicate the upper extremities are moving at similar magnitudes. Values > 1 indicate the nonparetic 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.)

$$= \sum_{i=1}^{n} \left(\text{epoch value}_{i\ \text{paretic}} + \text{epoch value}_{i\ \text{nonparetic}}\right)$$

$$= \tilde{x}\ (\text{paretic acceleration/paretic acceleration})$$

Variation Ratio: Ratio of the standard deviation of acceleration on the paretic upper extremity to the standard deviation on nonparetic upper extremity. The variation ratio reflects the dynamic movement capabilities of the paretic upper extremity relative to the dynamic movement capabilities of the nonparetic upper extremity. Values near 1 indicate an equal spread of paretic accelerations around the mean paretic acceleration relative to the spread of nonparetic accelerations around the mean nonparetic acceleration. Values > 1 indicate a greater spread of paretic acceleration relative to nonparetic accelerations, whereas values < 1 indicate a tighter spread of paretic acceleration relative to nonparetic accelerations.

$$= \sigma_{(\text{paretic acceleration})}/\sigma_{(\text{nonparetic acceleration})}$$

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.

$$\text{Median} = \tilde{x}_{(\text{paretic acceleration})}$$

$$\text{Maximum} = \max_{(\text{paretic acceleration})}$$

$$\text{Variability} = \sigma_{(\text{paretic acceleration})}$$

Bilateral Acceleration Metrics: These metrics reflect acceleration characteristics of the paretic upper extremity and nonparetic upper extremity combined. The accelerations of corresponding paretic and nonparetic upper extremity epochs are summed together. The median, maximum, and standard deviation of the resulting array are then used to calculate each metric.

$$= \sum_{i=1}^{n} \left(\text{epoch value}_{i\ \text{paretic}} + \text{epoch value}_{i\ \text{nonparetic}}\right)$$

$$\text{Median} = \tilde{x}_{(\text{bilateral acceleration})}$$

$$\text{Maximum} = \max_{(\text{bilateral acceleration})}$$

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

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.

$$= \sum_{i=1}^{n} \left(\text{epochs value}_i \geq x\,\% \leq x\,\%_{\text{peak paretic}}\right) \Big/ \sum_{i=1}^{n} \left(\text{epochs value}_i \geq 0.02m/s^2{}_{\text{ paretic}}\right)$$

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 were 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 7 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 7 sessions, indicating more paretic upper extremity use and greater paretic movement intensity compared with the nonparetic limb. In addition, the variation ratio was very close to 1 for all 7 sessions. These values are expected since training emphasized the paretic upper extremity. Across the 7 weeks, less time was spent in higher normalized acceleration ranges. For example, across the 7 sessions, the paretic upper extremity accelerated an average of approximately 54%, 16%,

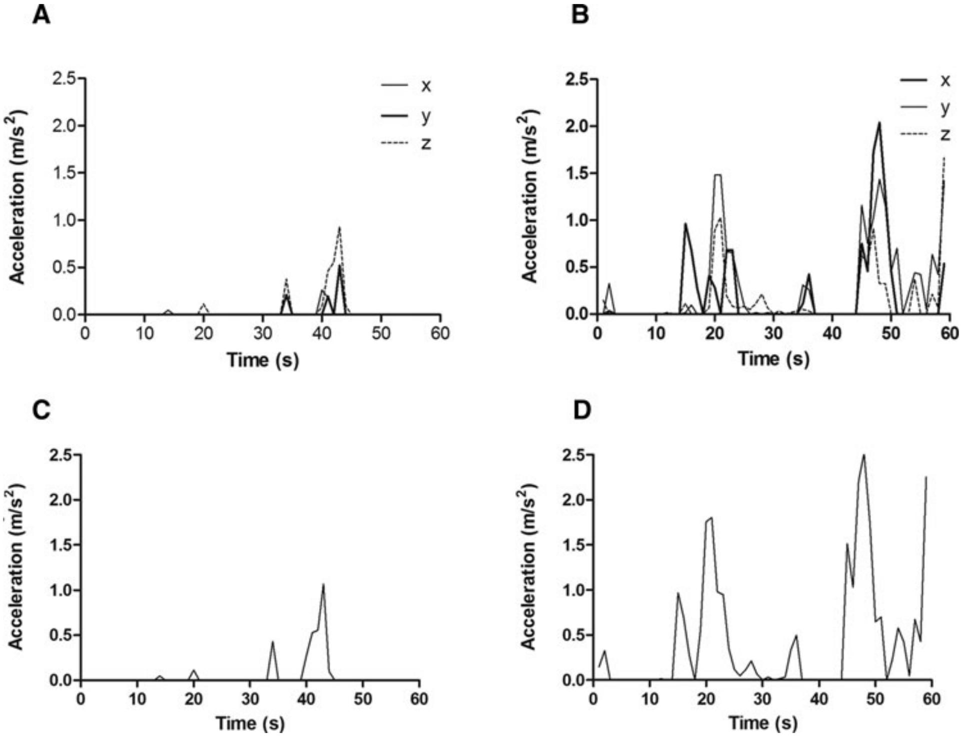

Figure 2. Accelerations in each device-referenced plane for the (A) paretic and (B) nonparetic upper extremities during 60 seconds of task-specific training. Accelerations in each cardinal plane were combined into a composite acceleration for the (C) paretic and (D) non-paretic upper extremities.

4%, and 1% of the time in each respective range from 1% to 25% to 76% to 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 the ARAT score during 6 and 3 sessions, respectively. The variation ratio was moderately correlated with the ARAT score in 4 sessions, with strong correlations observed in the remaining 3 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 the ARAT score at 2 of the 7 time points. Variability in the paretic upper extremity acceleration had a consistent, moderate correlation with the ARAT score across all weeks. Bilateral acceleration variability had a moderate and strong correlation during 4 sessions and 1 session, respectively. The time spent at 1% to 25% and 26% to 50% of peak accelerations was not correlated with the ARAT score during any session. Moderate correlations were observed in 4 and 6 sessions for time spent within 51% to 75% and 76% to 100% ranges, respectively.

Across-Sessions Association

A total of 189 observations (7 sessions × 27 participants) were entered into the mixed model. The model demonstrated the strongest model fitness ($\chi^2 = 470$; $P < 0.001$) 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 nonparetic extremities combined was sensitive to within-subject fluctuations in function across the 7 sessions. Figure 3 depicts corresponding within-subject fluctuations in paretic upper extremity acceleration variability (Figure 3A) and bilateral acceleration variability (Figure 3B) for 2 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 range of task-specific behaviors that are performed daily. Findings of the current study indicate that multiple acceleration characteristics can index upper extremity function poststroke. Metrics pertaining to acceleration variability appear to be valid indicators of paretic upper extremity movement capabilities during task-specific trainin.

Of all 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 7 training sessions; the relationship with variability of the bilateral acceleration was not as consistent. Variability reflects how far each sampled acceleration deviates from the mean acceleration, on average, during the monitoring period. Thus, a greater range of accelerations around the mean is associated with better upper extremity function. 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 nonparetic extremity. The within-subject fluctuations in acceleration variability of the paretic upper extremity and both upper extremities combined corresponded to variations in function across the 7 sessions. Thus, these metrics seem 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 nonparetic upper extremity (ie, use ratio) has been used as a marker of recovery after stroke in real-world settings.[8,9] The vast majority of normal use[29] and paretic upper extremity use[11] occurs as part of bimanual movement. Previously reported use ratios in free-living environments are in the 0.3 to 0.5 range in persons with stroke[9] and 0.8 to 1.0 in controls.[29] Data from the current study indicate that the paretic upper extremity was used more than the nonparetic upper extremity (ie, use ratio > 1). Participants in this study were forced to engage the paretic upper extremity while undergoing

Table 3. Participant and Paretic Upper Extremity Characteristics at the Initial Evaluation (n = 27).

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

Abbreviation: SD, standard deviation.

Table 4. Mean ± Standard Deviation and Spearman Correlation (With Action Research Arm Test) 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 ± 0.2	1.1 ± 0.3	1.2 ± 0.4	1.2 ± 0.4	1.3 ± 0.5	1.2 ± 0.4	1.3 ± 0.4
ρ	0.43[a]	0.15	0.39[a]	0.43[a]	0.56[a]	0.57[a]	0.51[a]
Magnitude, %	1.4 ± 1.2	1.6 ± 1.6	2.4 ± 4.6	2.5 ± 4.6	5.4 ± 10.7	2.9 ± 3.7	2.9 ± 4.3
ρ	0.31	0.11	0.32	0.25	0.55[a]	0.46[a]	0.41[a]
Variation, %	0.92 ± 0.29	0.96 ± 0.39	0.92 ± 0.28	0.90 ± 0.21	1.0 ± 0.35	0.99 ± 0.39	0.93 ± 0.33
ρ	0.58[a]	0.68[a]	0.65[a]	0.45[a]	0.66[a]	0.56[a]	0.56[a]
Paretic							
Median, m/s^2	0.7 ± 0.4	0.6 ± 0.3	0.6 ± 0.3	0.7 ± 0.3	0.7 ± 0.3	0.8 ± 0.5	0.8 ± 0.4
ρ	0.04	0.06	0.23	0.13	0.25	0.32	0.37
Maximum, m/s^2	4.9 ± 1.4	4.5 ± 1.1	4.4 ± 1.1	4.7 ± 1.3	4.9 ± 1.2	5.1 ± 1.3	4.9 ± 1.2
ρ	0.08	0.49[a]	0.17	0.13	0.31	0.41[a]	0.33
Variability, m/s^2	0.8 ± 0.3	0.8 ± 0.4	0.8 ± 0.3	0.7 ± 0.3	0.8 ± 0.4	0.8 ± 0.4	0.8 ± 0.3
ρ	0.55[a]	0.55[a]	0.56[a]	0.59[a]	0.53[a]	0.46[a]	0.59[a]
Bilateral							
Median, m/s^2	1.5 ± 0.6	1.4 ± 0.5	1.3 ± 0.6	1.3 ± 0.4	1.3 ± 0.5	1.5 ± 0.6	1.5 ± 0.7
ρ	−0.14	0.05	0.03	−0.11	0.00	0.05	0.06
Maximum, m/s^2	7.8 ± 1.7	7.9 ± 1.7	7.5 ± 1.5	7.9 ± 1.9	7.7 ± 1.8	8.2 ± 2.0	8.2 ± 2.1
ρ	0.35	0.24	0.19	0.40[a]	0.19	0.47[a]	0.17
Variability, m/s^2	1.3 ± 0.4	1.3 ± 0.5	1.2 ± 0.3	1.2 ± 0.4	1.2 ± 0.4	1.3 ± 0.4	1.3 ± 0.4
ρ	0.54[a]	0.61[a]	0.34	0.56[a]	0.37	0.42[a]	0.46[a]
Normalized range							
1%-25% peak	56.3 ± 13.4	55.7 ± 11.3	48.3 ± 18.0	55.2 ± 15.2	55.1 ± 15.4	53.0 ± 17.8	51.5 ± 17.1
ρ	−0.36	0.13	−0.09	−0.16	−0.11	−0.05	−0.13
26%-50% peak	16.3 ± 9.5	17.1 ± 8.5	12.3 ± 5.7	15.2 ± 7.9	16.8 ± 10.6	16.1 ± 9.3	16.2 ± 9.5
ρ	0.04	−0.19	0.06	−0.13	−0.17	0.03	−0.02
51%-75% peak	4.2 ± 3.9	5.5 ± 5.2	4.3 ± 4.4	3.3 ± 3.3	4.2 ± 3.5	3.8 ± 4.0	4.9 ± 6.2
ρ	0.51[a]	0.31	0.40	0.34	0.38[a]	0.38[a]	0.40[a]
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
ρ	0.46[a]	0.35	0.51[a]	0.55[a]	0.53[a]	0.54[a]	0.41[a]

[a] $P < 0.05$.

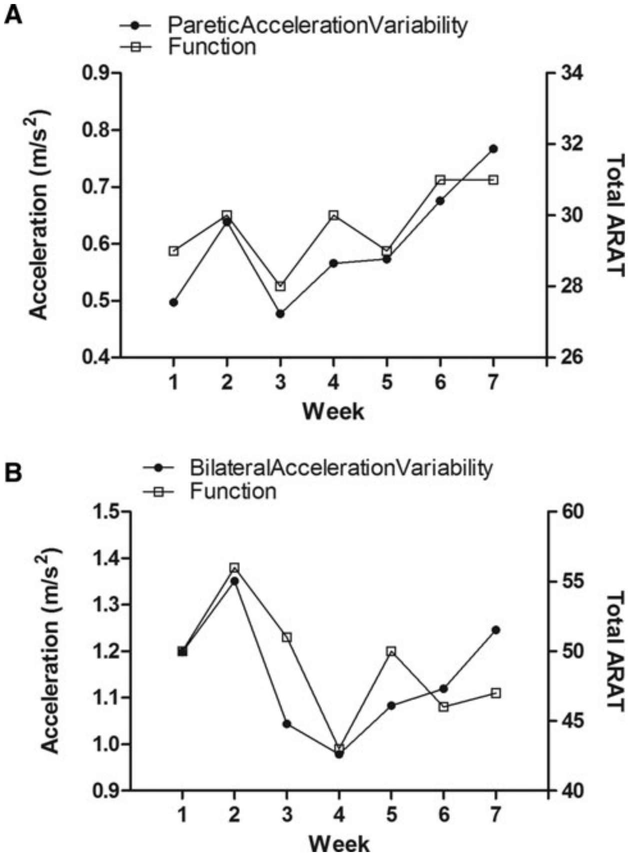

Figure 3. Correspondence between actual values for acceleration metrics and the ARAT score across the 7 sessions of task-specific training in 2 example participants: (A) variability of the paretic upper extremity acceleration and (B) variability of the bilateral acceleration.

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, acceleration of the paretic upper extremity may be associated with 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,[33–35] 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. The relationship between this metric and upper extremity function was likely influenced by the demands of the task-specific training context. It does seem, 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 accelerated within 76% to 100% of peak acceleration. Thus, movement intensity of the paretic upper extremity can index function when normalized to its own highest movement intensity, not when normalized to the nonparetic upper extremity's highest movement intensity.

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 occurred 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.

REFERENCES

1. Han CE, Arbib MA, Schweighofer N. Stroke rehabilitation reaches a threshold. *Plos Comput Biol.* 2008;4:e1000133.
2. White JH, Magin P, Attia J, Sturm J, Carter G, Pollack M. Trajectories of psychological distress after stroke. *Ann Fam Med.* 2012;10:435-442.
3. Essue BM, Hackett M, Li Q, Glozier N, Lindley R, Jan S. How are household economic circumstances affected after a stroke? The Psychosocial Outcomes in StrokE POISE Study. *Int J Stroke.* 2012;7:36-36.
4. Uswatte G, Giuliani C, Winstein C, Zeringue A, Hobbs L, Wolf SL. Validity of accelerometry for monitoring real-world arm activity in patients with subacute stroke: evidence from the extremity constraint-induced therapy evaluation trial. *Arch Phys Med Rehab.* 2006;87:1340-1345.
5. Lang CE WJ, 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.
6. Seitz RJ, Hildebold T, Simeria K. Spontaneous arm movement activity assessed by accelerometry is a marker for early recovery after stroke. *J Neurol.* 2011;258:457-463.

7. Page SJ, Sisto SA, Levine P. Modified constraint-induced therapy in chronic stroke. *Am J Phys Med Rehab.* 2002;81:870-875.
8. Uswatte G, Foo WL, Olmstead H, Lopez K, Holand A, Simms LB. Ambulatory monitoring of arm movement using accelerometry: an objective measure of upper-extremity rehabilitation in persons with chronic stroke. *Arch Phys Med Rehab.* 2005;86:1498-1501.
9. Taub E, Uswatte G, Bowman MH, et al. Constraint-induced movement therapy combined with conventional neurorehabilitation techniques in chronic stroke, patients with plegic hands: a case series. *Arch Phys Med Rehab.* 2013;94:86-94.
10. Reiterer V, Sauter C, Klosch G, Lalouschek W, Zeitlhofer J. Actigraphy—a useful tool for motor activity monitoring in stroke patients. *Eur Neurol.* 2008;60:285-291.
11. Michielsen ME, Selles RW, Stam HJ, Ribbers GM, Bussmann JB. Quantifying nonuse in chronic stroke patients: a study into paretic, nonparetic, and bimanual upper-limb use in daily life. *Arch Phys Med Rehab.* 2012;93:1975-1981.
12. Portney LG WM. *Foundations of Clinical Research: Applications to Clinical Practice*. 2nd ed. Upper Saddle River, New Jersey: Prentice Hall; 2000.
13. Birkenmeier RL, Prager EM, Lang CE. Translating animal doses of Task-Specific training to people with chronic stroke in 1-hour therapy sessions: a proof-of-concept study. *Neurorehabil Neural Repair.* 2010;24:620-635.
14. Bohannon RW, Smith MB. Interrater reliability of a modified Ashworth scale of muscle spasticity. *Phys Ther.* 1987;67:206-207.
15. Duncan PW, Wallace D, Lai SM, Johnson D, Embretson S, Laster LJ. The stroke impact scale version 2.0. Evaluation of reliability, validity, and sensitivity to change. *Stroke.* 1999;30:2131-2140.
16. Lai SM, Studenski S, Duncan PW, Perera S. Discriminant validity of the Stroke Impact Scale. *Stroke.* 2001;32:361-361.
17. JA B-K. Light touch - deep pressure testing using Semmes-Weinstein monofilaments. In: Hunter JM SL, Mackin EJ, Callahan AD, eds. *Rehabilitation of the Hand: Surgery and Therapy*. St. Louis, MO: Mosby Co; 1990:585-593.
18. Bohannon R. Motricity index scores are valid indicators of paretic upper extremity strength following stroke. *J Phy Ther Sci.* 1999;11:59-61.
19. Van der Lee JH, De Groot V, Beckerman H, Wagenaar RC, Lankhorst GJ, Bouter LM. The intra- and interrater reliability of the action research arm test: a practical test of upper extremity function in patients with stroke. *Arch Phys Med Rehab.* 2001;82:14-19.
20. Hsieh CL, Hsueh IP, Chiang FM, Lin PH. Inter-rater reliability and validity of the action research arm test in stroke patients. *Age Ageing.* 1998;27:107-114.
21. Lyle RC. A Performance-test for assessment of upper limb function in physical rehabilitation treatment and research. *Int J Rehabil Res.* 1981;4:483-492.
22. Beebe JA, Lang CE. Relationships and responsiveness of six upper extremity function tests during the first six months of recovery after stroke. *J Neurol Phys Ther.* 2009;33:96-103.
23. Lang CE, Wagner JM, Dromerick AW, Edwards DF. Measurement of upper-extremity function early after stroke: properties of the action research arm test. *Arch Phys Med Rehab.* 2006;87:1605-1610.
24. van der Lee JH, Beckerman H, Lankhorst GJ, Bouter LM. The responsiveness of the action research arm test and the Fugl-Meyer Assessment scale in chronic stroke patients. *J Rehabil Med.* 2001;33:110-113.
25. 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;26:104-114.
26. Connell LA, Tyson SF. Clinical reality of measuring upper-limb ability in neurologic conditions: a systematic review. *Arch Phys Med Rehab.* 2012;93:221-228.
27. Winter DA. *Biomechanics and Motor Control of Human Movement*. 2nd ed. Canada: John Wiley & Sons, Inc; 1990.
28. Waller SM, Whitall J. Bilateral arm training: why and who benefits? *Neurorehabilitation.* 2008;23:29-41.
29. Bailey RR, Lang CE. Upper-limb activity in adults: referent values using accelerometry. *J Rehabil Res Dev.* 2013;50:1213-1222.
30. Koh CL, Hsueh IP, Wang WC, et al. Validation of the action research arm test using item response theory in patients after stroke. *J Rehabil Med*. 2006;38:375-380.
31. Cohen J. *Statistical Power Analysis for the Behavioral Sciences.* 2nd ed. ed. Hillsdale NJ: L. Erlbaum Associates; 1988.
32. Fiscella K, Volpe E, Winters P, Brown M, Idris A, Harren T. A novel approach to quality improvement in a safety-net practice: concurrent peer review visits. *J Natl Med Assoc.* 2010;102:1231-1236.
33. de Niet M, Bussmann JB, Ribbers GM, Stam HJ. The stroke upper-limb activity monitor: Its sensitivity to measure hemiplegic upper-limb activity during daily life. *Arch Phys Med Rehabil*. 2007;88:1121-1126.
34. van der Pas SC, Verbunt JA, Breukelaar DE, van Woerden R, Seelen HA. Assessment of arm activity using triaxial accelerometry in patients with a stroke. *Arch Phys Med Rehab.* 2011;92:1437-1442.
35. Gebruers N, Truijen S, Engelborghs S, Nagels G, Brouns R, De Deyn PP. Actigraphic measurement of motor deficits in acute ischemic stroke. *Cerebrovasc Dis.* 2008;26:533-540.