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Original Research

Comparing Home Upper Extremity Activity With Clinical Evaluations of Arm Function in Chronic Stroke

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KEYWORDS
Rehabilitation;
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Abstract *Objective:* To determine if clinical evaluations of poststroke arm function correspond to everyday motor performance indexed by arm accelerometers.
Design: Cross-sectional study analyzing baseline data from a larger trial (NCT02665052).
Setting: Outpatient research center.
Participants: Community-dwelling adults (N=20) with chronic arm motor deficits (stroke≥6mo).
Intervention: A total of 72 hours of home wrist-worn accelerometry during normal routine.
Main Outcome Measures: Clinical evaluations included the Fugl-Meyer Assessment (FMA), Action Research Arm Test (ARAT), Wolf Motor Function Test (WMFT), and 2 self-assessments: the Motor Activity Log (MAL) and hand motor subscale of the Stroke Impact Scale (SIS). Accelerometer-derived variables included quantifications of movement intensity (magnitude) and duration of arm use.
Results: Participants had moderate arm impairment (FMA, 36.1±9.4). The accelerometer-derived mean magnitude ratio correlated significantly with the FMA (ρ=0.60, *P*<.01), WMFT functional score (ρ=0.59, *P*<.01), and ARAT (ρ=0.50, *P*<.05). The hours of use ratio correlated with the

List of abbreviations: ADL, activity of daily living; AOU, amount of use; ARAT, Action Research Arm Test; CESD, Center for Epidemiologic Studies Depression; FMA, Fugl-Meyer Assessment; MAL, Motor Activity Log; QOM, quality of movement; SIS, Stroke Impact Scale; UE, upper extremity; WMFT, Wolf Motor Function Test.

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MAL amount of use ($\rho=0.58$, $P<.01$) and quality of movement ($\rho=0.61$, $P<.01$). Total paretic hours did not correlate with the FMA, WMFT, or ARAT, and intensity variables did not correlate with the MAL or SIS.

Conclusions: Participants with higher baseline function had greater intensity of paretic arm movement at home; similarly, those who perceived they had less disability used their paretic arm more relative to their nonparetic arm. However, some participants with higher clinical scores did not exhibit greater arm use in everyday life, possibly because of neglect and learned nonuse. Therefore, individualized home accelerometry profiles could provide valuable insight to better tailor poststroke rehabilitation.

Stroke is the leading cause of long-term disability in the United States, affecting 795,000 people each year.[1] Upper extremity (UE) impairment is the most common consequence and has significant effects on activities of daily living (ADLs) and overall independence.[2] More than 50% of patients have arm deficits 6 months post stroke, and many have residual effects lasting years.[3] While impairment reduction has improved with a variety of rehabilitation techniques,[4,5] restoration of basic function does not always translate into greater everyday use.[6,7]

An important step in improving rehabilitation strategies is better understanding activity patterns outside the clinical setting. The amount and intensity of arm activity in the community setting post stroke is not well understood.[8,9] Clinical outcomes are limited because of their highly structured testing environment and focus on unilateral assessment.[6] Patients are encouraged to give their best effort, which may not reflect normal use. Noninvasive, wearable accelerometers are an emerging technology validated in adults post stroke to quantify intensity and duration of arm use in the home and may provide a more complete picture of recovery.[10-12] This technology gives additional objective data with the potential to assess and monitor progress in home arm use in response to therapy, including changes in complementary bilateral arm activity, which is required for many daily functional tasks.[13] If correlated to clinical assessments, these devices could provide data remotely, which can be further used to individually tailor treatment.

This cross-sectional study examined the relationship of home activity levels, indexed by wrist-worn accelerometer activity counts, among persons with chronic stroke-related arm impairment to conventional clinical evaluations. We also aimed to better understand habitual arm activity in the home setting among this population. We hypothesized that home accelerometer measures would correlate with clinical measures of impairment, performance, and perceived use and that different activity patterns would be seen among patients with dominant vs nondominant arm impairment.

Methods

Participants

Twenty-one community-dwelling adults enrolled in a larger randomized-controlled trial (Translating Intensive Arm Rehabilitation in Stroke to a Telerehabilitation Format; ClinicalTrials.gov NCT02665052) participated from May 2017 to June 2018 (fig 1). This study analyzed preintervention clinical and accelerometer data. Inclusion criteria were (1) age 18 years or older; (2) clinically defined hemiparetic stroke; (3) stroke onset ≥6 months; and (4) moderate arm impairment based on a Fugl-Meyer Assessment (FMA) score of 19-50 of 66.[14] Exclusion criteria were (1) cognitive impairment preventing understanding of the study requirements; (2) concurrent rehabilitation or study enrollment for their stroke-affected arm; and (3) botulinum injection to the stroke-affected arm within 3 months of enrollment. Participants gave informed consent, and this study was approved by the Veterans Affairs Research and Development Committee and its institutional review board. All procedures were in accordance with the ethical standards of the Declaration of Helsinki and Good Clinical Practice. Demographics and stroke-specific information are in table 1.

Clinical assessments

An occupational therapist trained in all outcome measures completed 3 baseline evaluations using the FMA, Wolf Motor Function Test (WMFT), and Action Research Arm Test (ARAT). The FMA is a stroke-specific arm impairment measure examining reflexes, sensation, and abnormal synergies. A higher score indicates less impairment (max=66).[14] The WMFT assesses task performance time, quality, and strength with high reliability and consistency. All 15 tasks are performed as quickly as possible with a maximum of 120 seconds each. The natural log of the time was taken to prevent a positively skewed distribution.[15] The ARAT is a reliable assessment of one's ability to manipulate objects of different size, shape and weight.[16] Three sets of evaluations were spaced 1 week apart, and the results were averaged. Participants completed self-reports using the Motor Activity Log (MAL) and Stroke Impact Scale (SIS). The MAL is a structured interview quantifying the participant's perception of the quality of movement (QOM) and amount of use (AOU) of their paretic arm for ADLs.[17] The SIS is a structured interview quantifying the change in quality of life post stroke in 8 domains, one of which is the hand subscale.[18] A measure of depression was collected using the Center for Epidemiologic Studies Depression (CESD) Scale,[19] and insight into visuospatial neglect was collected using the box and clock-drawing portions of the Montreal Cognitive Assessment.[20]

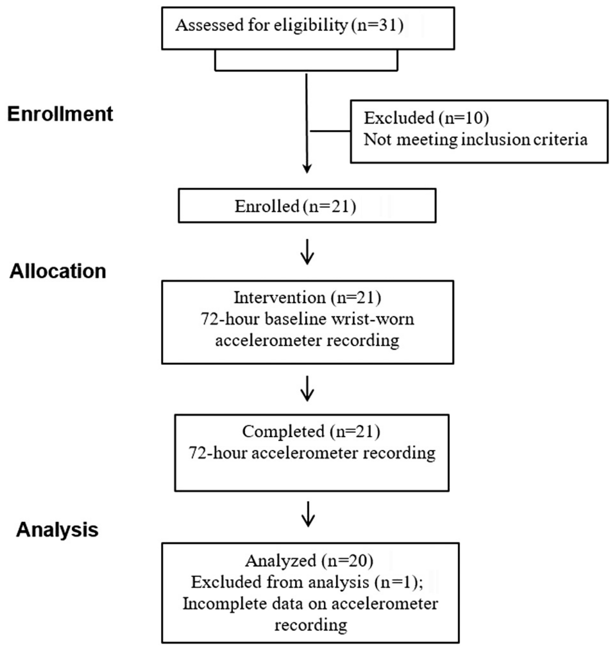

Fig 1 Study flow CONSORT diagram. Abbreviation: CONSORT, Consolidated Standards of Reporting Trials.

Accelerometry data

On completion of all 3 sets of clinic-based evaluations, accelerometers (GT3X+ Activity Monitors, Actigraph, Pensacola, FL)[21] representing different aspects of movement intensity were calculated. The first, vector magnitude, quantifies the total intensity of unilateral UE activity by combining second-by-second accelerations in all dimensions.[22]

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

The second, bilateral magnitude, quantifies intensity of UE activity across both arms by summing vector magnitudes for each. It distinguishes between low- and high-intensity activities. Zero represents no movement and increasing values indicate more intense movements. Higher values are associated with tasks requiring larger and faster movements.[22]

$$\text{Bilateral magnitude} = \sqrt{x^2 + y^2 + z^2}_{paretic} + \sqrt{x^2 + y^2 + z^2}_{non-paretic}$$

The magnitude ratio assesses the contribution of each limb to overall activity by dividing paretic magnitude by nonparetic magnitude. The natural log was taken to prevent skewness of ratios >1. A negative value indicates greater nonparetic activity, and a positive value indicates greater paretic activity. A ratio of 0 indicates equal arm contribution.[22]

$$\text{Magnitude ratio} = \ln\left(\frac{\sqrt{x^2+y^2+z^2}_{paretic}}{\sqrt{x^2+y^2+z^2}_{non-paretic}}\right)$$

Accelerometer-derived duration variables

Variables representing arm movement duration were collected: (1) independent hours of use, the time when 1 arm is used without the other[8]; (2) simultaneous hours of use, the time when both arms are active together[8]; (3) total paretic hours use, the combination of unilateral paretic and simultaneous hours use[8]; (4) total nonparetic hours use, the combination of unilateral nonparetic and simultaneous hours use[8]; and (5) the use ratio, defined below to assess the contribution of each limb to the overall active time. A use ratio close to 1 indicates nearly equal durations of activity from both arms. A value <1 indicates greater nonparetic activity.[10]

$$\text{Use ratio} = \frac{\text{Total paretic hours use}}{\text{Total non-paretic hours use}}$$

Data analysis

The accelerometry data were visually inspected and analyzed for completeness and quality prior to processing. Twenty of the 21 participants had data for analysis, with 1 excluded because of accelerometer recording errors. Descriptive and summary statistics were completed for each variable. Correlation analysis was used to investigate the associations between the clinical assessments (FMA, WMFT, ARAT, MAL, SIS) and the mean of each home accelerometry variable using the Spearman correlation with a significance level of .05. Regression analysis was performed to determine if age, hand dominance, depression, or stroke duration confounded these relationships. Two linear regression models were fit, one including the accelerometry variable

Table 1 Demographics and stroke characteristics

Characteristics	Total (N=20)
Age (y), mean ± SD	60.8±8.6
Range (y)	47-73
Sex, n (%)	
Male	12 (60)
Female	8 (40)
Ethnicity, n (%)	
White	4 (20)
Black	15 (75)
Asian	1 (5)
Time since stroke (mo), mean ± SD	72.0±56.7
Range (mo)	17-129
Stroke type, n (%)	
Ischemic	12 (60)
Hemorrhagic	8 (40)
Affected arm, n (%)	
Right	8 (40)
Left	12 (60)
Handedness, n (%)	
Right	14 (70)
Left	6 (30)
Dominance of affected arm, n (%)	
Dominant	8 (40)
Nondominant	12 (60)
CESD score, mean ± SD	7.2±8.3
Range	0-31

and the other including that and the potential confounder. If the relative difference between the 2 regression coefficients was >10%, the extraneous variable was a confounder (SAS version 9.4).[c] A subanalysis of 12 higher functioning participants was completed using descriptive statistics.

Results

Clinical evaluations of arm function

Overall, participants presented with moderate impairment, with a mean FMA score of 36.1,[23,24] WMFT functional score of 2.9,[25] WMFT time of 32.0 seconds, and ARAT paretic total of 31.1. Participants reported low perceived use and quality of movement of their paretic arm with average scores of 1.2 and 1.3 of 5 for the MAL AOU and QOM. Likewise, the average SIS hand total was 38.5 of 100, indicating significant effect on their ability to accomplish basic functions, such as carrying heavy objects, turning doorknobs, opening jars, tying shoe laces, and picking up dimes (table 2). Minor errors were made on the Montreal Cognitive Assessment visual-constructional box and clock-drawing test, but overall they were well organized and symmetric.

Home UE activity

Table 3 displays the results of the home-based accelerometer recordings. The mean paretic magnitude was 37.7 activity counts, and on average the paretic arm contributed 38% of the total intensity of bilateral use over 3 days. The negative mean magnitude ratio indicates greater intensity of nonparetic arm movement.

The paretic arm was used 16 hours over 3 days, but was used only 1.8 hours independently (0.6 h/d). Comparatively, the nonparetic arm was used independently approximately 8 times more. Simultaneous activity was low, making up 50% (4.8/9.6h) of total daily activity. The use ratio <1 indicates the nonparetic arm was favored in everyday use.

Table 3 Home-based accelerometry data

Accelerometer Variables	Mean ± SD Median (Range) Total (N=20)
Paretic magnitude*	37.7±11.0 32.5 (24.7-63.3)
Bilateral magnitude*	100.4±16.9 97.1 (82.4-138.6)
Magnitude ratio*,†	−1.1±0.3 −1.1 (−1.6 to −0.6)
Simultaneous hours of use	14.3±7.4 13.6 (3.08-33.06)
Total paretic hours of use	16.0±7.4 15.8 (3.6-34.4)
Use ratio	0.6±0.1 0.6 (0.2-0.8)
Independent paretic hours use per day	0.6±0.3 0.5 (0.2-1.3)
Independent nonparetic hours use per day	4.3±0.8 4.4 (2.8-6.0)
Simultaneous hours use per day	4.8±2.5 4.5 (1.0-11.0)
Total paretic hours use per day	5.3±2.5 5.3 (1.2-11.5)
Total nonparetic hours use per day	9.1±2.3 8.4 (5.6-14.8)
Total hours of arm activity per day	9.6±2.4 9.1 (5.8-15.2)

NOTE. All variables reflect the average over 3 days unless otherwise specified.
* Measured in activity counts (0.001664*g*/count).
† Negative values indicate greater nonparetic arm activity.

Table 2 Clinical scores

Clinical Measures	Mean ± SD Median (Range) Total (N=20)
FMA total (maximum 66)	36.1±9.4 39 (20.3-47.7)
FMA shoulder-elbow (maximum 42)	22.7±5.1 22.8 (13.7-30.7)
FMA wrist-hand (maximum 24)	13.4±5.8 15.3 (2.7-24)
WMFT average functional score (maximum 5)	2.9±0.8 3.0 (1.6-4.3)
WMFT average time (maximum 120s)	32.0±28.4 18.8 (3.1-88.5)
ARAT paretic total (maximum 57)	31.1±17.2 36.3 (6.3-56.7)
MAL average amount of use (maximum 5)	1.2±0.7 1.5 (0.1-2.4)
MAL average quality of movement (maximum 5)	1.3±0.6 1.4 (0.3-2.2)
SIS hand total (maximum 100)	38.5±23.3 42.5 (0-70)

Correlations

Table 4 shows Spearman correlation coefficients between accelerometry variables and clinical tests. The mean paretic magnitude had moderate to strong positive correlations with the FMA and WMFT average functional score. The mean magnitude ratio, representing the contribution of each arm during bilateral activities, correlated strongly with the FMA and WMFT average functional score (fig 2A and 2B) as well as with the WMFT average time and ARAT paretic total. The negative correlation with WMFT average time indicated that participants with greater relative intensity of paretic arm movement could perform tasks faster. Additionally, the use ratio negatively correlated with WMFT average time, indicating better motor performance with greater relative duration of paretic arm use at home.

No correlations were found between intensity variables and self-assessments. However, total paretic hours of use positively correlated with the MAL QOM ($\rho=0.49$, $P<.05$), and the use ratio correlated with the MAL AOU and QOM (fig 3A and 3B), indicating that duration of paretic arm use relative to the

Table 4 Spearman correlation coefficients: clinical evaluations

Variables	FMA Total	FMA Shoulder-Elbow	WMFT Average Functional Score	WMFT Average Time	ARAT Paretic Total
Mean paretic magnitude	0.51*	0.62†	0.47*	NS	NS
Mean magnitude ratio	0.60†	0.65†	0.59†	−0.49*	0.50*
Total paretic hours use	NS	NS	NS	NS	NS
Use ratio	NS	NS	NS	−0.47*	NS

Abbreviation: NS, not significant.
* $P<.05$.
† $P<.01$.

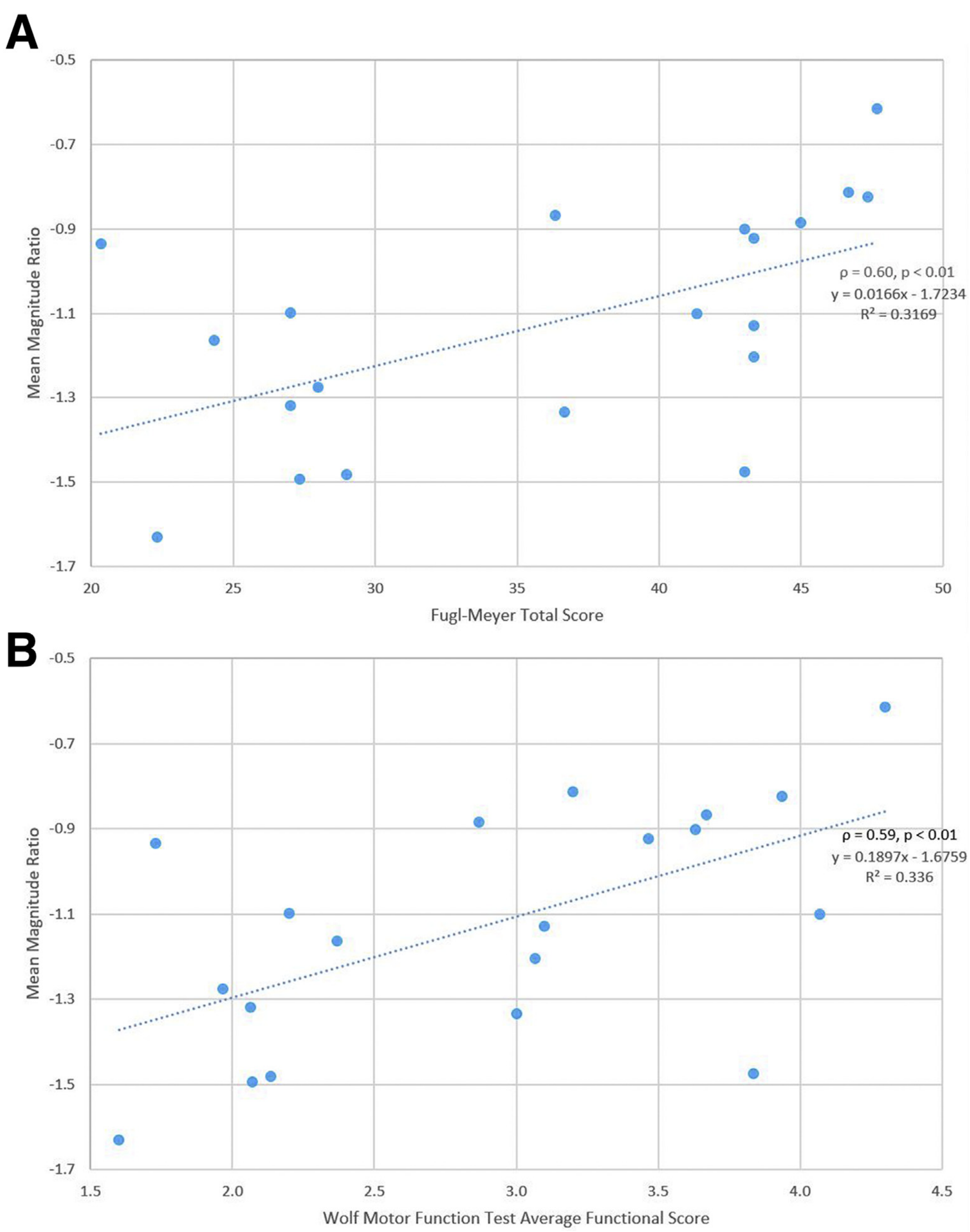

Fig 2 Relationship of clinical function and intensity of home paretic arm use. (A) Greater relative intensity of paretic arm use is seen with higher FMA ($\rho=0.60$, $P<.01$) and with WMFT ($\rho=0.59$, $P<.01$) scores (B).

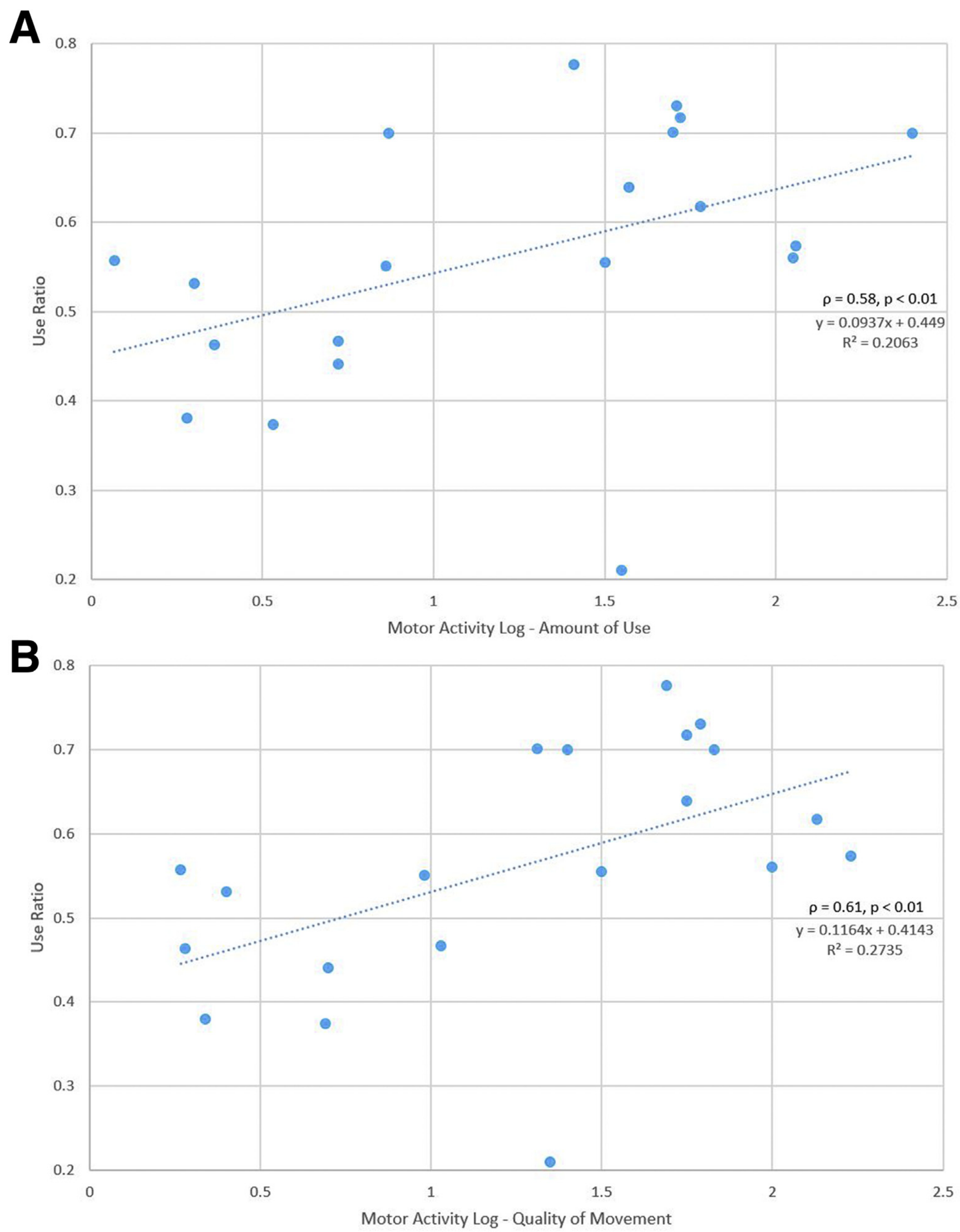

Fig 3 Relationship of self-assessments of function and relative duration of home paretic arm use. The Spearman correlation coefficient for the relationship of the use ratio with the MAL AOU (A) was 0.58 ($P<.01$) and for the MAL QOM was 0.61 ($P<.01$) (B).

nonparetic arm is an important factor in participant perceptions. No correlations were found with the SIS hand.

Regression analysis showed CESD score confounded all significant relationships except that of the use ratio and MAL. Age, hand dominance, and time since stroke were not confounders.

Subanalysis

A subanalysis was conducted to explore correlations between duration variables and the FMA, WMFT, and ARAT by examining independent paretic arm use, which is the focus of conventional clinical evaluations. Of the 12 higher functioning participants (FMA>33), 6 exhibited particularly low duration (independent paretic hours use<0.7) and intensity of paretic arm use. The use of their nonparetic arm, however, remained similar to their higher functioning counterparts (fig 4). To examine this quantitatively, independent paretic and nonparetic hours of use were calculated as a percent of the total hours of activity. The higher functioning, low-use group used their affected arm half as much as the higher functioning, high-use group and relied on their nonparetic arm 10 times more than their paretic arm compared with 5.4 times more among their counterparts (table 5). The low-use group was a median of 82.5 months post stroke, while the high-use group was 44 months post stroke.

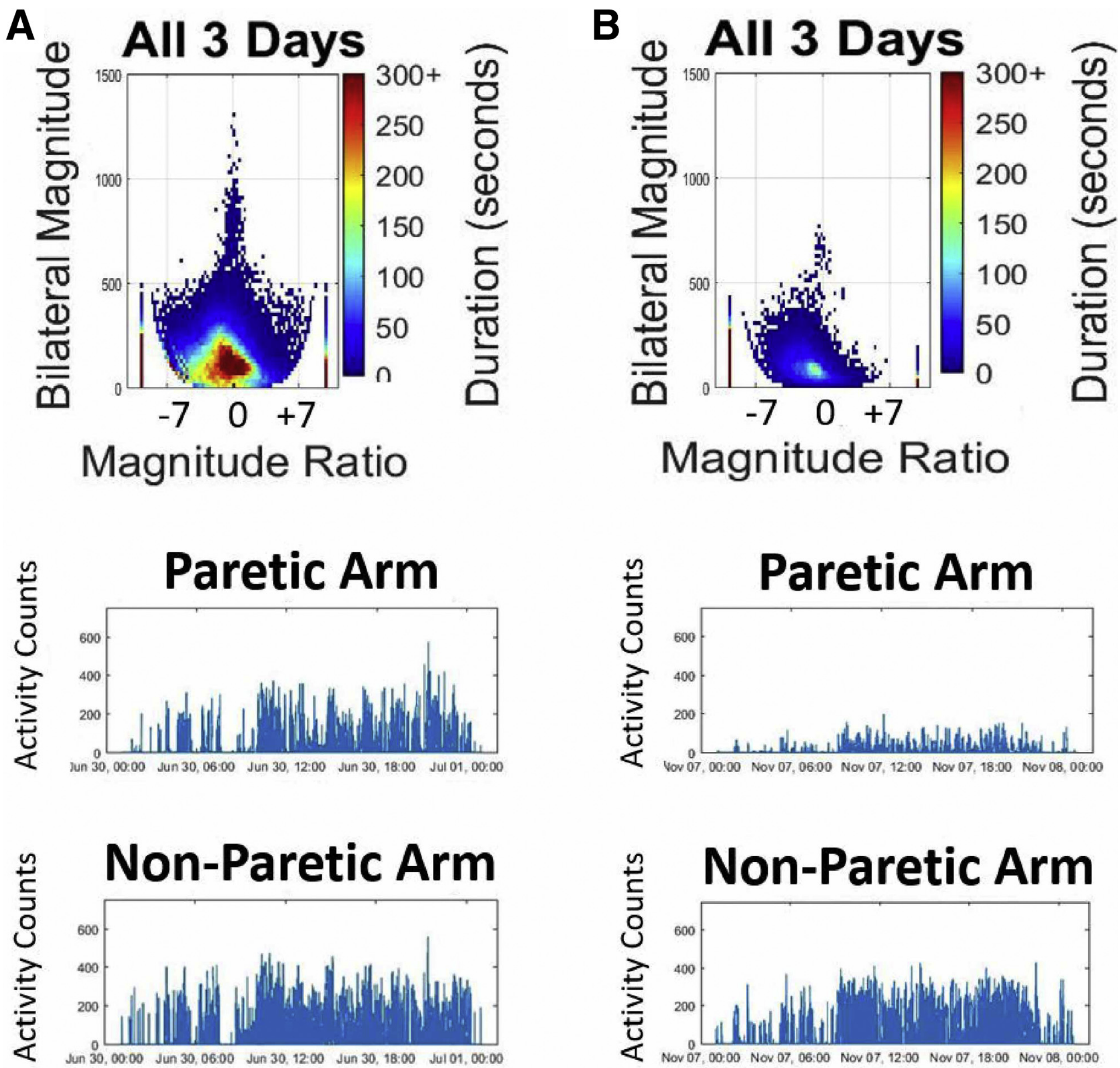

Fig 4 Exemplar density plots and activity counts for 2 dominant arm-affected participants with similar clinical scores. Participant A (A) has an FMA score of 45 and a WMFT average functional score of 3.5. Participant B (B) has an FMA score of 44 and a WMFT average functional score of 3.1. Despite the similarities in conventional clinical tests, participant B uses the paretic arm significantly less at home and with less intensity, as depicted by the color and skew of the density plots. However, the intensity of use of the nonparetic arm is comparable when looking at the second-by-second activity counts throughout the day.

When further analyzed by dominance of the affected arm, the majority of the higher functioning, low-use group had nondominant hemiparesis, while the high-use group was equally dominant and nondominant affected. Generally, those with nondominant hemiparesis had low use of the paretic arm across all FMA scores (fig 5).

Discussion

The goals of this study were to determine if daily arm use, quantified by accelerometry, correlated with clinical evaluations of paretic arm function in patients with chronic stroke and to better understand habitual arm use to guide rehabilitation. Our data revealed important accelerometer relationships and home activity patterns. The accelerometer intensity variables correlated significantly with several clinical assessments. Those with less impairment (FMA) demonstrated greater acceleration and movement intensity of the stroke-affected arm at home. Similarly, those able to use their paretic arm with greater intensity exhibited better performance (WMFT) and motor capability (ARAT). The use ratio positively correlated with the MAL, while variables describing intensity did not. This implies that participants

Table 5 Arm activity in higher-functioning participants

Variables	Higher FMA, Low Use (n=7)	Higher FMA, High Use (n=5)
Independent paretic arm use (%)	4.6	8.6
Independent nonparetic arm use (%)	46.8	46.3
Simultaneous bilateral arm use (%)	48.7	45.1
Nonparetic/paretic arm use (%)	10.2	5.4

perceived their disability based on how much they used their impaired arm compared with the nonimpaired one, rather than on the intensity of movement. Our findings are consistent with duration and intensity values for mildly to moderately impaired populations with stroke[8] and with previous studies showing significant correlations of vector magnitude with the FMA[26] and duration with the MAL QOM.[27]

Our results identified specific accelerometer correlations for patients with moderate poststroke arm deficits across a multidimensional clinical battery of impairment, performance, and activity participation. Paretic magnitude and magnitude ratio can be potential surrogates of clinical impairment and performance capacity, providing a remote method to assess improvement in the home setting. The significant correlation between the use ratio and MAL highlights the importance of paretic relative to nonparetic arm participation in daily activities. It can serve as an important supplementary value to measure success of a rehabilitation program in a way that is meaningful to participants. These results support the use of accelerometry to assess multiple dimensions of arm function. As such, therapists may consider replacing some time-consuming clinical assessments with an objective, quantifiable alternative.

Most ADLs involve the complementary use of both arms. Each arm has a separate function but uses similar temporal, spatial, and force parameters.[13] Given this definition and activity findings for unimpaired community-dwelling adults,[28] one would expect more equal arm contributions in those with better function. For our population, time spent in simultaneous activity was 50% compared with 67% in nondisabled adults.[8] Additionally, the magnitude ratio was negative, reflecting asymmetric arm use where nonparetic activity exceeded paretic. This ratio had significant correlations with all clinical tests, suggesting a relationship between more equivalent arm intensity contributions and better motor performance. The asymmetric values found in our population are indicative of low functional use and limited cooperative bilateral movement in home tasks. Additionally, the use ratio was lower than ranges reported for healthy adults.[28] This too reflects decreased function because of asymmetry in duration of activity between arms. As a patient is recovering, the duration of paretic arm use should approach 95% of that of the unimpaired arm.[28] Improving simultaneous and symmetric arm use would be a positive indicator of successful therapy and recovery.

CESD score confounded many correlations, except for those with the MAL, by affecting the intensity of home

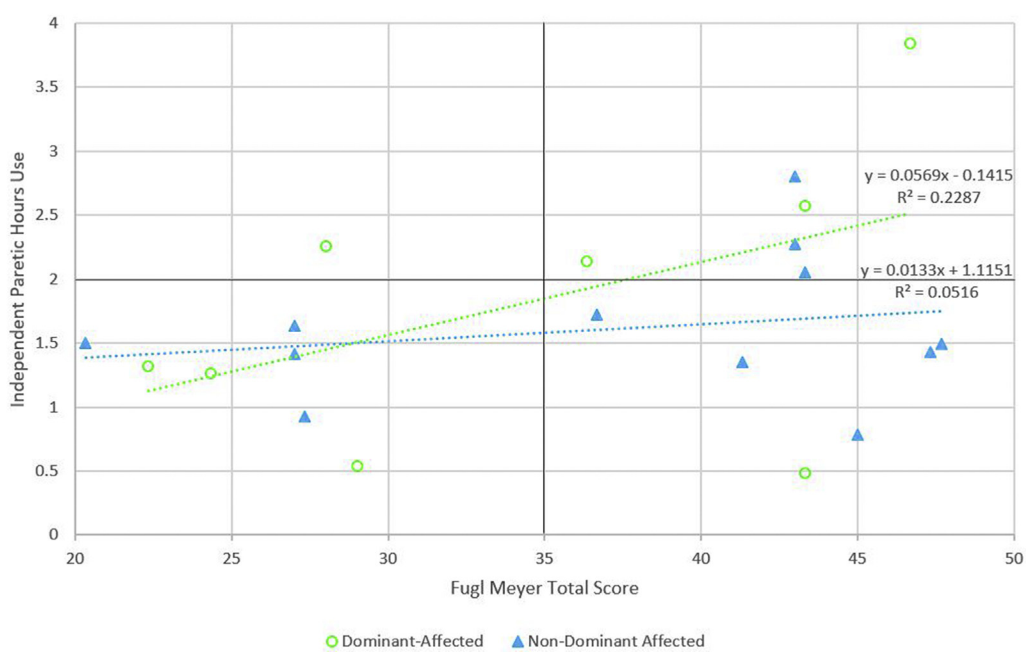

Fig 5 Effect of dominance and stroke severity on independent home use of the paretic arm. The upper right quadrant depicts participants who are high functioning (FMA>33) and have higher paretic arm use at home (independent paretic hours use>0.7). There are 3 dominant-affected and 3 nondominant-affected participants in this group. The lower right quadrant depicts participants who are high functioning and have lower paretic arm use at home. There is 1 dominant-affected and 5 nondominant-affected participants in this group.

movement and performance on clinical tests. The CESD Scale is a common instrument used to assess depression in stroke,[19] on which 4 participants scored at risk for clinical depression. Depression should be routinely screened in rehabilitation programs because it can hinder daily function in the community and long-term clinical improvement.[29] Properly addressing depression can thereby aid in recovery and allow for more accurate assessment of poststroke UE function.

High function, low use

While as a whole, we saw greater paretic arm use with higher baseline function, our subanalysis, consistent with other studies,[8] identified participants with low home activity despite less impairment. Unilateral neglect is a common behavioral syndrome in patients following strokes in the nondominant hemisphere[30,31] and can thereby contribute to low use of the nondominant arm.[32] A total of 60% of our participants had a history of nondominant hemispheric strokes. The majority of the higher functioning, low-use group was nondominant affected, and similarly, those with low FMA scores and low-use were nondominant affected. Therefore, nondominance of the impaired arm may be a predictor of this home activity pattern.[8,32] A screening of visual-construct organization using box and clock drawings did not reveal visual-spatial neglect; however, neglect is a multifactorial behavior, and a formal assessment was not included.

Another possible explanation for low home use of the paretic arm is learned nonuse, a well-documented phenomenon where initial stroke deficits and failure with early attempts at use result in poor recovery despite motor improvement.[33,34] This subset of participants was farther out from their stroke, suggesting that it may be more difficult to overcome the longer it is established. Other possible explanations for low use of the affected arm could be sedentary behavior, older age, and help from caretakers; however, these factors, if present, would result in reduced nonparetic arm use as well, which was not seen. As 13 of the 20 participants were nondominant affected and 10 had low paretic arm use, neglect and learned nonuse may explain the lack of correlation between duration variables and clinical assessments. Early identification of this home activity pattern may assist in developing more comprehensive and targeted treatment plans.

This study quantified real-world UE activity and compared it with a battery of conventional clinical assessments measured in a structured environment. It extends the understanding of home arm use in persons with chronic moderate stroke-related disability across multiple days and multiple functional aspects (impairment, performance, perceived use). Our results showed that while some home accelerometry variables are predictive of clinical measures, the reverse is not always true. Therefore, individualized activity profiles are needed to fully understand paretic arm use. Home activity profiles can provide important information on movement intensity, duration, and bilateral use to individualize therapy and optimize impaired arm use within the setting most important to patients—their everyday life.

Study limitations

Aspects of this study that may limit generalizability include the small sample size, 72-hour recording window, lack of formalized neglect testing, and study population with primarily moderate chronic arm deficits. Other limitations include unaccounted differences in sleep time and nonpurposeful movement. This could lead to overestimation of paretic arm activity, but the effect is likely small because of the disability level. The accelerometer placement proximal to the wrist may have limited hand activity detection, which may have affected correlations involving the FMA wrist-hand subscore and SIS hand total. However, our population had limited isolated finger or hand movements. Correlations with the mean bilateral magnitude, simultaneous hours of use, and total hours use may be disrupted by disproportionately high use of the nonparetic arm. Additionally, clinical outcome measures have inherent limitations related to evaluator bias and experience and assessment of specific tasks in a structured environment.

Conclusions

Clinical evaluations are brief episodes that do not provide adequate information regarding arm activity in a real-world, unstructured setting. It is important to understand a person's habitual home performance over multiple days to direct care and meaningfully assess use and recovery. Accelerometers can provide valuable supplementary information for those with significant disability. This study identified paretic magnitude, magnitude ratio, and use ratio for further examination as surrogates for clinical evaluations to monitor change in UE activity in the home setting.

Future studies should examine more subjects and disability levels as well as change in response to therapy. If sensitive, accelerometers could be used to monitor function remotely throughout a UE rehabilitation intervention. Ultimately, this technology could define meaningful recovery and provide therapists with valuable intensity and duration information to individualize rehabilitative care.

Suppliers

a. GT3X+, ActiLife v.6.13.3; ActiGraph.
b. MATLAB R2009b; MathWorks.
c. SAS version 9.4; SAS Institute.

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