BRIEF REPORT

Ambulatory Monitoring of Arm Movement Using Accelerometry: An Objective Measure of Upper-Extremity Rehabilitation in Persons With Chronic Stroke

Gitendra Uswatte, PhD, Wai Leong Foo, BA, Harry Olmstead, BS, Kristine Lopez, BA, Ashleigh Holand, BA, Leslie Box Simms, BA

ABSTRACT. 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 Rehabil 2005;86:1498-501.

Objective: To evaluate the reliability and validity of accelerometry for measuring upper-extremity rehabilitation outcome.

Design: Validation study.

Setting: Data recorded in the community.

Participants: Consecutive Constraint-Induced Movement therapy (CIMT) patients (n=10) and volunteer community residents with stroke (n=10). All participants were more than 1 year poststroke and had mild to moderate motor impairment of the more affected arm.

Intervention: All study participants were asked to wear accelerometers outside the laboratory for 3 days immediately before and after treatment, or for an approximately equivalent no-treatment period (controls).

Main Outcome Measures: Participants wore an accelerometer on each arm, the chest, and the more affected leg and completed the Motor Activity Log (MAL), which is a semi-structured interview of real-world arm use.

Results: Test-retest reliability of transformed accelerometer recordings was greater than .86. There was also a large increase in the ratio of transformed more- to less-impaired arm recordings in CIMT therapy patients ($d'=0.9$, $P<.05$), while there was no change for controls. The correlation between this parameter and the MAL was .74 ($P<.001$).

Conclusions: Accelerometry provides an objective, real-world index of upper-extremity rehabilitation outcome and has good psychometric properties.

Key Words: Arm; Monitoring, ambulatory; Rehabilitation; Stroke; Treatment outcome.

From the Department of Psychology, University of Alabama, Birmingham, AL.

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Reprint requests to Gitendra Uswatte, PhD, Psychology, University of Alabama, 1530 3rd Ave S, CH415, Birmingham, AL 35294, e-mail: *guswatte@uab.edu.*

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SEVERAL RESEARCH STUDIES suggest that a large difference can exist between motor impairment, as assessed by laboratory performance tests, and upper-extremity activity outside the laboratory (reviewed in Uswatte and Taub[1]). Despite these findings, there are few instruments with which to measure upper-extremity activity directly.[1,2] We report here on an objective method for measuring the effects of upper-extremity rehabilitation on stroke-impaired arm use in daily life. We examined the reliability and validity of a system of 4 accelerometers, which are devices that record movement for measuring the outcome of constraint-induced movement therapy (CIMT), a rehabilitation method that improves impaired arm use in people with chronic stroke (summarized in Taub et al[3,4]). Uswatte et al[2] previously demonstrated that the accelerometry system described herein provides an accurate measure of the duration of arm, torso, and ambulatory movements in people with stroke.

METHODS

Participants

The institutional review board of the university approved the study procedures, and all participants gave informed consent. The treatment group included 10 consecutively admitted patients in a CIMT trial conducted at an urban medical center in the southeastern United States. A no-treatment group (n=10) was recruited from lists of people who had contacted the CIMT trial. All participants had had stroke more than 1 year earlier. Principal exclusion criteria for both groups were (1) Folstein Mini-Mental State Examination scores of less than 24, (2) inability to understand and follow verbal directions, (3) presence of uncontrolled medical conditions, and (4) presence of conditions other than stroke that might impair arm function. Demographic, stroke-related, and more-impaired arm motor characteristics of the participants are summarized in table 1.

Apparatus and Measures

The accelerometers used in this study were model 71256 Activity Monitors,[a] which are wireless plastic units about the size and weight of a large wristwatch. They contain a single piezoelectric crystal that is mounted so that the units are sensitive to movement in 2 directions. Acceleration is sampled at 10Hz and summed over a user-specified epoch. This sum is called a raw count; it represents a rough index of the amount of movement by the object to which the accelerometer is attached. For example, lifting a can from a table to a shelf produces roughly 20 raw counts/s from a wrist-mounted accelerometer. The recording epoch in this study was 2 seconds; recording capacity was approximately 72 hours (2-s epoch × 2 values × 128K bit memory). The system for mounting the accelerometers is shown in figure 1. Uswatte[2] describes the mounting system, selection of a 2-second recording epoch, and the accelerometers in detail.

Table 1: Demographic, Stroke-Related, and More-Impaired Motor Characteristics of the Treatment and No-Treatment Groups

Characteristic	Treatment Group (n=10)	No-Treatment Group (n=10)
Demographic		
Mean age ± SD (y)	61.4±20.0	63.7±13.5
Women (n)	5	3
Stroke-related (n)		
Paresis of right side	7	5
Paresis of dominant side	7	6
More-impaired arm motor		
Mild to moderate impairment[†] (n)	10	9
Moderate to severe impairment[‡] (n)	0	1
Mean MAL arm use score ± SD (points)	1.1±0.7	2.8±1.6*

Abbreviation: SD, standard deviation.
*$P<.05$.
[†]Mild to moderate motor impairment was characterized by ability to actively extend the wrist at least 20° and each of the finger joints at least 10°.
[‡]Moderate to severe motor impairment was characterized by deficits more severe than those described above. The minimum motor criterion for this category was ability to actively extend the wrist at least 10°, abduct the thumb 10°, and extend the metacarpophalangeal and interphalangeal joints of 2 or more fingers at least 10°.

The Motor Activity Log (MAL) is a participant-centered measure of real-world arm function; the version in this study elicits information about 14 activities of daily living (ADLs) (eg, picking up a glass, using a key to open a door, buttoning clothes).[1,3] Patients are asked to rate on the quality of movement (QOM) scale and the amount of use (AOU) scale how well and how much they use their more impaired arm for each ADL over a specified period (eg, the past week). The QOM total score is reported because analyses suggest that the QOM scale is more internally consistent and reliable than the AOU scale, and that the QOM scale captures components of the amount as well as the quality, of arm use outside the laboratory[5] (eg, Pearson correlations between QOM and AOU scores during each of the testing occasions were >.96; all $P<.001$). The QOM scale is anchored at 5 points (0, no use; 1, very poor use; 2, poor use; 3, fair use; 4, almost normal use; 5, normal use) and participants may select scores halfway between the anchors (eg, 3.5). The QOM total score is the mean of the item scores. Several reports suggest that the MAL has high internal consistency, stability, test-retest reliability, and convergent and concurrent validity.[1,6,7]

Procedure

Participants were asked to wear accelerometers during all waking hours, except when washing, for 3 days before and after (periods 1, 2) 2 weeks of CIMT (treatment group), or an approximately equivalent no-treatment period (no-treatment group). During these recording periods, they kept a diary of when they slept, were not wearing the accelerometers, and were riding in a car. Periods when patients were sleeping or not wearing accelerometers were discarded from the accelerometer records because they were not relevant to the assessment of treatment outcome. Times when patients were riding in cars were also discarded because pilot work indicated that accelerometers recorded counts when a car was moving even if the subject was still. Other common forms of passive transport, such as being pushed in a wheelchair or riding in an elevator, were generally not found to produce artifacts. All subjects completed MALs. Participants resided at home during the recording periods, except for 7 out-of-town CIMT patients who stayed in hotels.

Data Reduction and Analysis

Accelerometer recordings were downloaded onto a personal computer, irrelevant or artifactual portions were discarded (see Procedure), and remaining portions were transformed. Transforming the accelerometer recordings involved dichotomizing the raw value recorded for each epoch around a low threshold; thresholds for the units worn on the arm, chest, and leg were 2, 2, and 10, respectively. Summary variables for the recordings from each placement were calculated by dividing the number of epochs with raw values above threshold by the total number of epochs. Thus, the summary variables expressed duration of movement as a percentage of the recording period. Uswatte et

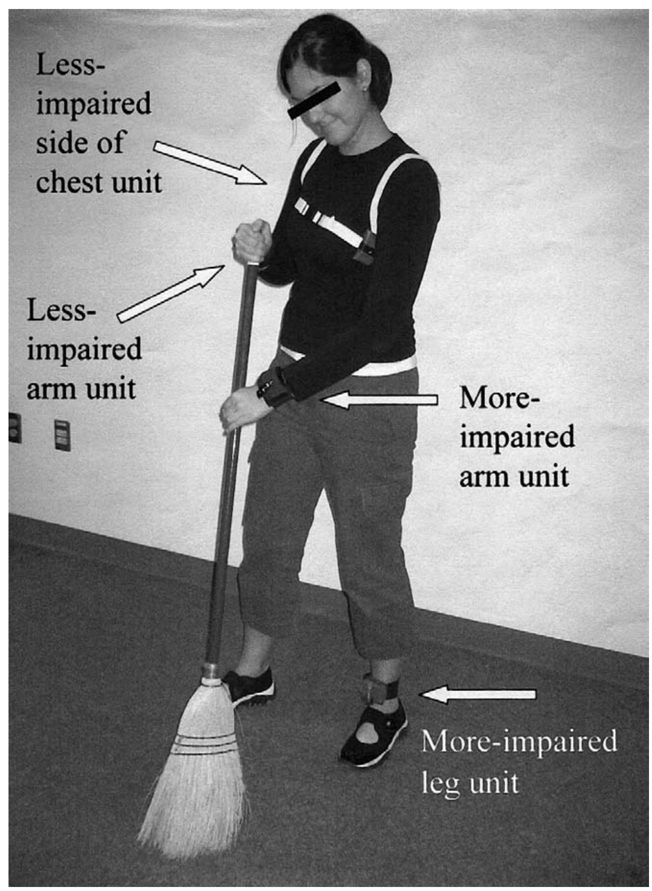

Fig 1. Accelerometer configuration. Four accelerometers were placed in snug pouches sewn onto terrycloth and elastic bands, and 1 unit was strapped onto each wrist, the chest (less impaired side), and ankle (more impaired side). Accelerometers were worn on both arms because a single unit worn on the more-impaired wrist might act as a cue to use that extremity and thereby confound the measurement of the effects of rehabilitation on arm function. In addition, recordings gathered from the less-impaired arm might serve as a comparison for data gathered from the more-impaired arm. The chest and ankle placements were chosen because examining the effects of rehabilitation on more-impaired arm movement that is independent of torso and ambulatory movements was thought to be valuable.

al[2] have discussed the rationale for this approach and the selection of the thresholds.

Construct validity of the ratio of more- to less-impaired arm threshold-filtered recordings (ratio summary variable) for measuring rehabilitation outcome was evaluated by testing whether there was a significant increase in this parameter from period 1 to 2 in the treatment group and no change in the no-treatment group. Sensitivity to the effect of rehabilitation was indexed using d', which is a within-subjects measure of effect size. The ratio summary variable was selected as a measure of treatment outcome because we expected it to be affected less by changes in overall physical activity than would a summary variable formed from more-impaired arm recordings alone. Thus, it would better capture changes in upper-extremity activity specific to the more impaired arm. For example, a large increase in ambulatory activity would result in a correspondingly large increase in the more-impaired arm summary variables, but a much smaller change in the ratio summary variables because an increase in overall physical activity would be likely to affect more-impaired and less-impaired arm recordings roughly equally.

We assessed convergent validity of the ratio summary variable for measuring treatment outcome by the strength of the correlation between this accelerometry summary variable and the MAL. Period 1 data from both treatment and no-treatment participants were included. Additionally, changes in the ratio summary variable from period 1 to 2 were compared with changes in the MAL by calculating partial correlations between these parameters at period 2. Period 1 ratio summary variable values were used as covariates.

Nonparametric statistics were used to evaluate both construct (Wilcoxon matched-pairs signed-rank tests) and convergent (Spearman rank correlations) validity. Data from 1 participant in each group were excluded because they were outliers (>2 standard deviations) with respect to change in the summary variables from period 1 to 2. Data from the accelerometer worn on the chest were excluded because chest data were missing from 6 participants because a fourth accelerometer was not available or because of errors in programming the accelerometers. Test-retest reliability of the summary variables was evaluated by the size of the correlations between period 1 and 2 accelerometer recordings from the no-treatment group.

RESULTS

Compliance

Estimating that participants slept 7h/d on the basis of diary data, the accelerometer records suggested that subjects wore the units for approximately 89%±10.3% and 83%±14.3% of waking hours during the first and second data collection stages (periods 1, 2), respectively. There were no significant differences in compliance between the treatment and no-treatment groups during those periods.

Reliability and Validity

Test-retest reliability of the more-impaired arm, less-impaired arm, and leg accelerometry summary variables was more than adequate (median r=0.9; range, .82–.94). Validity of the ratio of more-impaired to less-impaired arm threshold-filtered recordings (ratio summary variable) for measuring upper-extremity rehabilitation outcome was supported. In the treatment group, there was a significant increase from pre- to posttreatment (periods 1 to 2) in the ratio summary variable (mean change, .08±.09; $P<.05$). The change ($d'=0.9$) was large by the standards of the meta-analysis literature (ie, >.57).[8] In the no-treatment group, the change was not significant (mean change, .02±.08; $d'=0.3$, not significant). For all participants, the correlation between the ratio summary variable and the patient report of arm use (MAL) for period 1 was .74 ($P<.001$). When this correlation was recalculated with observations only in the interquartile range (IQR) of period 1 ratio summary variable values (median, .59; range, .34–1.02; IQR, .52–.77), it was still meaningful (r=.51, P=.14; n=10). This suggests that the correlation coefficient observed with all participants was not a function of extreme scores. With respect to change from period 1 to 2, the correlation between the ratio summary variable and MAL was .71 ($P<.001$). By the standards of the meta-analysis literature, these correlations were strong (ie, >0.5).[8]

Number of Accelerometers and Complexity of Processing Needed

Data from the more-impaired leg allowed us to evaluate whether changes in more-impaired arm movement were independent of changes in ambulatory activity. Epochs during which participants displayed ambulatory movements (leg unit threshold-filtered count=2; see Data Reduction and Analysis) were removed from the accelerometer recordings. In both the treatment and no-treatment groups, the changes in the ratio summary variable for the remaining "nonambulatory" segments from period 1 to 2 (treatment group mean change, .12±.12; $d'=1$; no-treatment group mean change, .03±.11; $d'=0.3$) were similar to those for the entire records. These results suggest that the change in the ratio summary variable reported was independent of changes in ambulation and imply that measures formed from ratios of more- to less-impaired arm recordings control adequately for changes in overall physical activity from pre- to postrehabilitation.

To evaluate whether treatment outcome could be measured with records that required less complex processing than described above (see Procedure), an additional version of the accelerometer data was produced in which only periods when subjects were not wearing the accelerometers were discarded. The reliability and validity of these records were very similar to those of the records with more complex processing.

DISCUSSION

This study provides preliminary evidence of the construct and convergent validity of the ratio of more- to less-impaired arm threshold-filtered accelerometer recordings (ratio summary variable) for measuring upper-extremity rehabilitation outcome in chronic stroke patients with mild to moderate arm motor impairment. Other important considerations regarding a new measure are safety, compliance, and ease of use. No participants reported injuries as a result of wearing the accelerometers; compliance with wearing them was approximately 86%. Relatively simple processing of accelerometer recordings (ie, discarding periods when subjects are not wearing accelerometers) produces data that have as high fidelity as complex processing.

A limitation of this study was that the no-treatment group reported more use of their more-impaired arm than the treatment group during period 1. This difference raised the possibility that a ceiling effect accounted for the lack of change in the ratio summary variable in the no-treatment group. This possibility was diminished by (1) the substantial overlap in the range of MAL and ratio summary variable values in the treatment and no-treatment groups (ie, two thirds of the period 1 ratio summary variable values in the no-treatment group were smaller than in the treatment group); (2) the absence of significant correlations between period 1 ratio summary variable values and change in these values from period 1 to 2 among no-treatment participants; and (3) the lack of a smaller increase in the ratio summary variable for no-treatment subjects with scores above the median on the period 1 MAL than subjects with scores below the median.

Two threats to the generalizability of the findings are the small sample size and the hotel residency of several treatment participants. To address this issue, we gathered accelerometer data before and after CIMT from 8 additional chronic stroke survivors who met the same screening criteria as for this study but who resided exclusively at home. As with the treatment group in this study, there was a large pre- to post-CIMT change in the ratio summary variable (mean change, $.06 \pm .03$; $d' = 2$; $P < .05$) and a strong correlation between the ratio summary variable and MAL ($r = .74$, $P < .05$). The replication of these study findings in a second, albeit small, sample of home residents reduces the above concerns about the generalizability of the results.

An alternative system of uniaxial accelerometers for measuring upper-extremity movement has been developed by Schasfoort et al.[9] It permits a breakdown of arm movement by type of overall physical activity (eg, duration of arm movement during walking, sitting, or lying down). Such information is desirable but comes at the cost of a reduced recording period (24h) and more cumbersome (7 sensors connected by wires to a central recording unit), complex, and expensive equipment.

CONCLUSIONS

Our study suggests that just 2 accelerometers are adequate for assessing whether rehabilitation has an effect on arm function outside the laboratory; if complementary self-report measures such as the MAL are used simultaneously, they can provide rich information about the specific types of upper-extremity activities in which changes have occurred.

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Supplier

a. Manufacturing Technologies Inc, 709 Anchors St, Fort Walton Beach, FL 32548.