Objective Measurement of Functional Upper-Extremity Movement Using Accelerometer Recordings Transformed With a Threshold Filter

Gitendra Uswatte, MA; Wolfgang H.R. Miltner, PhD; Benjamin Foo; Maneesh Varma; Scott Moran, BA; Edward Taub, PhD

Background and Purpose—The consensus is that the most important outcome for rehabilitation is functional activity in the life situation. Constraint-Induced Movement Therapy, a new treatment that transfers in-clinic gains to the life situation, demands objective measurement of real-world movement. However, direct, objective, and accurate measures of arm use in the real world are not available. Previous attempts to use accelerometry to measure extremity movement have failed because of unacceptable variability. This problem has been addressed here by use of a threshold filter.

Methods—Nine stroke patients and 1 healthy individual wearing accelerometers were videotaped while they carried out their usual activities at home or in the clinic; the duration of their arm, torso, and ambulatory movements was judged by 2 observation teams. In addition, 11 college students performed 5 standardized activities of daily living for varying durations in the laboratory. The accelerometer data were transformed; the raw value recorded for a given epoch was set to a constant if it exceeded a low threshold.

Results—The threshold-filtered recordings measured the duration of movement accurately and with very little variability. Correlations between the threshold-filtered recordings and the observer ratings of the duration of arm, torso, and ambulatory movements were 0.93, 0.93 and 0.99, respectively; the corresponding correlations for the raw values were −0.17, 0.34, and 0.85.

Conclusions—These results present initial evidence for the validity of threshold-filtered accelerometer recordings for objectively measuring the amount of real-world upper-extremity movement as an index of treatment outcome for rehabilitation patients. (Stroke. 2000;31:662-667.)

Key Words: arm n monitoring, ambulatory n rehabilitation n treatment outcome

The current consensus in the rehabilitation field is that functional activity in the life situation is the most important outcome to pursue and measure.1,2 Existing physical rehabilitation outcome instruments, however, do not provide a direct measure of extremity function in the real world when subjects are out of the view of rehabilitation professionals.3 Investigators have recently used accelerometry as a measure of the duration of gross physical activities, such as walking, sitting, and lying down, in the laboratory and the home.4–7 A direct, objective, and accurate measure designed to assess real-world upper-extremity function specifically has not been developed.

Keil et al8 evaluated the validity of Vitaport accelerometers (Koelner Vitaport System, Vitaport GmbH) for measuring arm movement involved in activities of daily living (ADL). They found modest correlations between raw accelerometer and electromyographic recordings taken from the arm during ADL performance in the laboratory (mean multiple $r = 0.34$) and in the everyday life setting (mean multiple $r = 0.53$). They concluded that these 2 measures assess different aspects of arm movement. Parameters of arm movement that the Vitaport accelerometers were able to measure accurately were not identified, nor was reliability evaluated.

Our laboratory had addressed these issues in 2 experiments3,9–12 by examining the relationship between acceleration recordings and the speed, excursion, direction, and duration of simple arm movements and movements made in standardized ADL. The results suggested that the accelerometers used (model 7164, CSA, Inc) (1) provided highly reliable measures of arm acceleration (median $r = 0.95$; range, 0.83 to 0.99), (2) were sensitive to movement parallel to the x and y axes of the units, and (3) were sensitive to changes in the duration and speed of arm movement when the recordings were averaged across subjects.3,9–11 However, the results also indicated that the speed and duration of arm movements were measured with a large degree of error when the recordings for

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individual subjects were examined. The SD of individual data points around the line of best fit was on average 35% of the overall mean (See Data Transformation and Analysis in Subjects and Methods). One factor that appeared to contribute to the large error was that acceleration often changed in a variable and erratic fashion during arm movement. For example, small variations in the quality of movement sometimes produced large changes in the output of the accelerometers. Therefore, acceleration was not reliably associated with the target parameter of interest to this laboratory, duration or amount of movement.

We hypothesized that a data transformation technique that removed these extraneous sources of variation might yield an accurate measure of the duration of arm movement in the home. This was of particular relevance for this laboratory because it has developed a treatment for persons with stroke, termed Constraint-Induced Movement Therapy (CI Therapy), which has its main impact on the amount or duration of arm use in the real world. The treatment involves training use of the impaired arm for ADL in the clinic for at least 6 hours per day for 10 or 15 consecutive weekdays and constraining use of the less impaired arm for the treatment period in both the clinic and the home. These techniques, which essentially mass practice of use of the impaired arm over a period of consecutive weeks, have been demonstrated in controlled studies to improve upper-extremity function in persons with stroke.15 To date, a semistructured interview, the Motor Activity Log (MAL), has been used to document that CI Therapy patients use their arm at home after treatment much more often and for a larger repertoire of activities than before treatment. On the MAL, patients rate how well and how much they have used their impaired arm for 14 upper-extremity ADL. As with other self-report measures, it is subject to experimenter bias, demand characteristics, and errors in recall. A convergent, objective measure of the amount of arm use is clearly desirable.

This report evaluates whether transforming accelerometer recordings with a threshold filter provides an objective measure of the duration of arm movement when patients are outside the laboratory and cannot be directly observed by experimenters or clinicians. The threshold filter changes the acceleration value recorded for a given epoch to a constant if the raw value exceeds a low threshold; raw values at or below the threshold are set to zero. By removing the variation in the recordings above the threshold value, this transformation prevents erratic fluctuations in arm acceleration from influencing the measurement of the amount of movement. The validity of the threshold filter approach for measuring the duration of arm movement is evaluated here in (1) a laboratory experiment in which participants wore accelerometers and performed ADL-like tasks for varying times and (2) an observational study in which accelerometer recordings were compared with the duration of arm, torso, and ambulatory movements coded from videotapes recorded while participants carried out their usual activities in the clinic or home.

Subjects and Methods

The participants in the laboratory experiment were 11 right-dominant college students (mean age, 21 years; SD=2.5; 6 men, 5 women) who reported no musculoskeletal or neurological problems associated with their right arm. They were recruited from the Psychology Department subject pool at an urban university. The participants in the observational study were 1 healthy college student (age, 21 years; male) and 9 persons with stroke (mean age, 54.4 years; SD=19.5; 8 men, 2 women) recruited from the Occupational Therapy Clinic or a clinical research project at an urban rehabilitation hospital. The mean time since stroke was 3.7 years (SD=2.2); 3 patients had a right hemiparesis, while 6 had a left hemiparesis. Four of the patients and the college student were videotaped in their homes, while the 5 remaining patients were videotaped in the rehabilitation hospital; 3 of the patients engaged largely in lower-extremity activities (eg, walking), while the remaining subjects engaged mostly in upper-extremity activities (eg, therapeutic exercises, drinking a beverage, using the remote control to change television channels). The patients engaged in upper-extremity activities were capable of performing tasks with little or no assistance from a therapist or caregiver; patients engaged in lower-extremity activities were able to ambulate independently (assistance from an aide or orthotic device was permitted). The institutional review board of the university approved the study procedures, and all participants gave informed consent.

Apparatus

The accelerometers used were Computer Science and Applications, Inc. model 7164 activity monitors, which are 5.1x2.6x1.5-cm plastic units weighing 42.9 g that use uniaxial, piezoelectric crystal technology. The units are about the size and weight of a large wristwatch and are most to least sensitive to movement parallel to their x (5.1-cm side), y (1.5-cm side), and z (2.6-cm side) axes, respectively. The activity monitors sample acceleration at 10 Hz and sum these samples over a user-specified epoch. The summed acceleration values are stored in RAM, downloaded onto a personal computer, and reported as a whole number or count every epoch. The count indexes the amount of acceleration experienced by the unit during an epoch (1 activity count=0.01664 g for an acceleration of 2.13g directed parallel to the accelerometer x axis, produced by a movement with a frequency of 0.75 Hz, and recorded with a 0.1-second epoch).16 Two accelerometers sewn into a modified sweat band were secured on each arm, and 1 was placed on the right or impaired leg of the participants; an additional unit was strapped to the chest in a pouch sewn onto a back support belt. The first (distal) arm unit was worn just above the wrist, with the 5.1-cm side (x axis) of the unit parallel to the length of the arm; the second unit was proximal to the first, with the x axis perpendicular to the length of the arm. The 2 accelerometers were worn with the axis of maximum sensitivity pointing in different directions to test which orientation provided the best measure of upper-extremity movement. The leg unit was worn just above the malleoli with the x axis parallel to the length of the leg; the chest unit was secured just below and to the side of the sternum, with the x axis perpendicular to the length of the body. In healthy participants, the leg unit was worn on the lower extremity ipsilateral to the dominant arm, while the chest unit was secured to the side of the torso contralateral to the dominant arm. In participants with stroke, the leg unit was worn on the more-affected lower extremity, while the chest unit was secured to the less-affected side of the body. Accelerometers were worn on both arms because, when the units are used to monitor movement before CI Therapy, a single unit worn on the more-affected arm might act as a cue to use that of arm and thereby confound the measurement of the treatment effect. In addition, the accelerometer recordings gathered from the less-affected arm could serve as a comparison for the data gathered from the more-affected arm. The chest and leg placements were chosen because previous work has suggested that recordings from accelerometers worn on the chest and legs can be used to classify different types of gross physical activity (eg, sitting versus walking); this information may also be useful when treatment outcome is evaluated.

Procedure

In the laboratory experiment, the participants performed each of 5 standardized ADL for 30, 60, and 90 seconds with their right arm.
The activities, performed in fixed order, were as follows: vacuuming a rug, shelving a book, sponging a counter, sorting candy, and eating beans with a spoon. The excursion of the movements to be made was specified by visual guides, while the pace of movement was regulated by a metronome set to 0.67 Hz. The order of the duration of activities was counterbalanced across subjects; half of the subjects performed each task for 30, 60, and 90 seconds; the other half reversed this sequence.

In the observational study, the participants wore the standard array of 4 accelerometers and were videotaped for 15 minutes while they performed their regular therapeutic or home activities. Two “consensus” pairs of observers (physical therapy graduate students) evaluated in 2-second intervals over 3 separate screenings of each 15-minute videotape segment whether the participants moved their more-affected or dominant arm and torso and whether they walked. Any 2-second epoch in which participants displaced their more-impaired forearm >2.5 cm or pronated/supinated their arm >30° was coded as an arm movement interval; other epochs were coded as no movement. Two-second epochs in which participants displaced or rotated their torso (hips to shoulders) any amount were coded as torso movement intervals. Any 2-second epoch in which participants stepped forward or backward was coded as a walking interval; the first heel- (walking forward) or ball-strike (walking backward) marked the beginning of a walking sequence, while the last ball- or heel-strike marked the end. Within their pairs, the observers arrived at their decisions by consensus; the 2 pairs, however, conducted their work independently. After the observer pairs had completed rating all of the videotapes, they met and came to concurrence on any 2-second intervals in which there was disagreement. Movement was rated in 2-second intervals on the basis of pilot work in which we varied the length of the intervals and selected the interval that most frequently accomplished complete functional upper-extremity acts. The raters worked in pairs because we found that a team of 2 can monitor each other’s observations, motivate each other to perform at an optimal level, and most efficiently manage the multiple VCR and PC functions necessary to conduct the ratings. The intervals in which there was disagreement between the accelerometer recordings and final ratings of the judges were coded for (1) functional versus nonfunctional movement, (2) large versus small movement (<7.6 cm in excursion or 45° of pronation/supination), and (3) whether movement was recorded only by the accelerometers or only by the observers. Functional activity was defined as a movement or action that helps to accomplish a task (eg, grasping a can, wiping a table top) or has some function although it does not accomplish a task (eg, touch face, move arm from one position to another). Nonfunctional activity was defined as a movement or action that did not have any function (eg, tic, tremor) or was largely secondary to movement of other parts of the body (eg, arm swing when walking, passive movement). The agreement, in pilot work, between the pairs of observers on this scale was 93%.

Data Transformation and Analysis

In the simulated ADL experiment, the 2 dependent measures were the sum of the raw counts obtained during each task period from the distal accelerometer worn on the dominant arm and the sum of the respective threshold-transformed values. The threshold filter dichotomized the data from the accelerometers, which were programmed to record with a 2-second epoch: if the raw count was ≥1, the value assigned to a 2-second epoch was 2; if no accelerometer counts occurred in an epoch, it was assigned a value of 0. The sum of the threshold-transformed counts thus represented the duration of arm movement in seconds over the task period; the sum of the raw counts indexed the amount of acceleration experienced by the arm. Planned linear and quadratic repeated measures contrasts were used to evaluate whether there was an appropriate relationship (positively sloped and linear) between the duration of the tasks and the threshold-transformed accelerometer recordings. The accuracy of the measurement of movement was evaluated by calculating the variability (SD) in accelerometer recordings around the line of best fit. The SDs were expressed as a percentage of the overall mean to enable easy comparison between the threshold-filtered and raw counts. The data were collapsed across activities. We have presented data here only from the distally placed accelerometer on the dominant arm and have used it as the standard placement because the proximal position tended to be less stable and more uncomfortable over long periods. The threshold-transformed recordings from the proximal and distal units were very similar (intraclass correlation type 3,1=0.97).13

In the observational study, the variables analyzed were the threshold-filtered accelerometer counts from the distal arm, chest, and leg units and the observer ratings of the duration of arm, torso, and walking movements. The threshold values for filtering counts from the more-affected arm and the chest and leg units were 2, 2, and 10, respectively. (The threshold value for the arm unit in the experiment was 1.) The values for this study were determined by varying the thresholds when filtering the accelerometer data collected from the 2 initial participants in the home (labeled healthy subject and patient A in Tables 1 and 2) and selecting those values that maximized the percent agreement between the accelerometer and observer records of the duration of arm, torso, and walking movements, respectively; these optimal values were applied to the other 8 participants. (Post hoc analyses revealed that the threshold values of 2 and 10 used to filter recordings from the arm and leg units, respectively, were on average the optimal thresholds for these 8 subjects. The optimal threshold for the chest unit was 1 rather than 2; however, the difference in accuracy obtained with these 2 thresholds was less than 1 percentage point.) As with the threshold values, the epoch length of 2 seconds was chosen by varying the epoch length when filtering the accelerometer data collected from the 2 initial participants in the home and selecting the epoch that maximized the percent agreement between the accelerometer and observer records of the duration of movement. An additional data transformation was applied to the threshold-filtered counts from the leg unit; the values for any sequence of epochs with the pattern “2, 0, 2” were replaced with “2, 2, 2.” This transformation was done because, in our observations, people rarely stopped for just 2 seconds and then returned to walking. A sequence such as “2, 0, 2,” especially in persons with stroke, is usually due to hesitation in mid-stride rather than to a meaningful interruption of ambulation. Accuracy was evaluated by the percent agreement on a 2-second basis for individual subjects between the threshold-filtered accelerometer recordings from the more-affected or dominant arm unit, chest unit, and leg unit and the observer ratings of the duration of movements of these parts of the body. The agreement between the pairs of observers for arm, torso, and walking movements was 95%, 94%, and 99%, respectively.

Results

In the laboratory experiment, there was an appropriate (positively sloped, linear) relationship between the threshold-filtered accelerometer recordings from the right arm unit and the variation in the duration of arm movements for the 5 ADL (P<0.001). In addition, the variability around the line of best fit was more than an order of magnitude lower for the threshold-filtered recordings (SD=3%) than for the raw counts (SD=39%; P<0.001). When variance due to differences in subject means was removed, the variability around the line representing perfect measurement was still much lower for the threshold-filtered recordings (SD=2%) than for the raw counts (SD=11%; P<0.01). The Figure shows the regular relationship between threshold-filtered recordings and the duration of movement and illustrates the large reduction in variability produced by the threshold transformation.

Writing numbers, an ADL that involves small movements of the hand, was also tested. The variability of the threshold-filtered recordings was relatively large for this small-excitation movement (SD=55%). However, when averaged across subjects, the recordings still provided a relatively
accurate index of the duration of movement; the ratio of the recordings for the 30-, 60-, and 90-second conditions was 1.0:2.1:2.9 (ideal ratio = 1:2:3).

In the observational study, the duration of arm, torso, and ambulatory movements involved in regular clinic and home activities was measured with high accuracy by the threshold-filtered accelerometer recordings, with the observer judgments of the duration of movement used as the standard of comparison. The average agreement between the recordings from affected or dominant arm accelerometer and the observer codings of the duration of arm movement was 98%, when 2-second intervals containing small movements for which there was accelerometer/rater disagreement were removed from the calculation (Table 1). When small movements (ie, <7.6 cm) were included, there was accelerometer/observer disagreement in 11.3% of intervals. Analysis of the type of upper-extremity movement occurring during these intervals revealed that 5.4% contained small and nonfunctional movements, 4.1% contained small and functional movements, 1.0% contained large and nonfunctional movements, and 0.9% contained large and functional movements (Table 2). Thus, 92% of the intervals in which there was disagreement contained movements that were small or not related to functional activity. Analysis of the source of discrepancies between the accelerometers and raters revealed that for 3.9% of intervals the raters identified movement, while the accelerometers did not record counts, and that for 7.4% the reverse applied. The threshold-filtered recordings thus overestimated the duration of movement relative to the observers' judgments by a small amount (mean overestimate = 7.7%). This result, however, is not surprising given that the observers were instructed to ignore movements of <2.5 cm in excursion or 30° in pronation/supination to increase the reliability and speed of the ratings. The discrepancy between the threshold-filtered recordings and the actual duration of arm movement is therefore likely to be even smaller. The agreement between the threshold-filtered accelerometer recordings from the leg unit and chest unit and the observer coding of the duration of ambulatory and torso movement was 93% and 86%, respectively (Table 1). The data from patient B were excluded from the percent agreement calculation for torso movement because of accelerometer malfunction. The data gathered to date suggest that the accelerometers measure movement equally well in the home (overall agreement = 90%) and clinic (overall agreement = 89%).

An additional analysis correlated the total duration of movement in the 15-minute videotape segment as coded by the observers both with the sum of the threshold-filtered accelerometer recordings and with the sum of the raw recordings across subjects. The correlations for arm, torso, and ambulatory movements were 0.93, 0.93, and 0.99, respectively; the corresponding correlations between the observer coding and raw recordings were −0.17, 0.34, and 0.85. These correlations indicate that threshold-filtered recordings reflect the duration of movement much more accurately than the raw counts.

**Discussion**

The results suggest that threshold-filtered accelerometer recordings accurately measure the duration of arm, torso, and walking movements involved in ADL performed in the laboratory and in spontaneous activities carried out in the clinic and home for both healthy individuals and persons with...
stroke. Analysis of the type of arm movement during intervals in which there was disagreement between the accelerometer and observer data revealed that >90% of the movements were small (eg, writing) or nonfunctional (eg, fidgeting). Given the emphasis in rehabilitation on functional activities and the inability of many neurological patients to make fine hand movements, this analysis suggests that the discrepancies between the accelerometer and observer records occur during activity that is not critical in the context of measuring rehabilitation outcome for the upper extremity.

The question arises of whether a more accurate measure of movement would have been obtained if we used triaxial accelerometers, which are equally sensitive in all directions, rather than the CSA Inc units, which are sensitive to movements in the x and y axes but relatively insensitive to movement in the z axis.3,14 Redmond and Hegge18 have shown that for most applications the record from an uniaxial accelerometer quickly begins to approximate that of a triaxial accelerometer; at 1 minute the correlation between the 2 different types of accelerometers is 0.85, while at 4 minutes the correlation is 0.99. The uniaxial accelerometers we employed, therefore, are likely to closely approximate the records from triaxial accelerometers for the recording periods used (15 minutes).

A number of distinguished investigators have tried to use accelerometer recordings for clinical purposes and in rehabilitation research. These attempts were not successful because the variability created by fluctuations in arm acceleration, especially those caused by sudden, jerky movements, made the accelerometer data unreliable as an index of the amount of extremity movement. The contribution of the threshold-filter approach is to convert accelerometry from a measure of a parameter that is not central to most assessment needs in rehabilitation, ie, acceleration, to a measure that is of considerable interest, duration or amount of movement.

In 1979, Andrews and Stewart19 noted that a substantial fraction of stroke outpatients performed every ADL they were asked to conduct in the clinic better than they did at home, as reported by a spouse or other informant. In this laboratory it has been found that this is true for most persons with stroke with significant residual motor deficit for at least some ADL.3,10,14 Many stroke patients are capable of performing all the tasks on a laboratory motor test when an experimenter asks them to do so and with only a moderate elevation in performance time (eg, 100% to 200%) relative to the less-impaired extremity. However, on returning home, they report virtually zero use of the more-affected extremity.3,14 This very common phenomenon strongly demonstrates the need for assessing the actual amount of use of a more-affected upper extremity in the real-world setting. As noted, laboratory motor tests cannot provide this information because there is a disassociation between performance in the laboratory and behavior at home. Interviews or paper-and-pencil tests given to either patients or informants suffer from the many flaws inherent in subjective reports. In contrast, threshold-filtered accelerometer data provide objective information on the duration of movement in the home, which is an important aspect of patients’ functional activity.

Accelerometry, however, does not at present yield a direct measure of the amount of functional use of an extremity, which is arguably the main concern of physical rehabilitation. The parameter that it does measure, amount of movement, may nevertheless be considered a meaningful parameter. An increase in arm movement is a useful therapeutic goal in itself since it is a means of preventing adverse changes in the tone and mechanical properties of muscle. More importantly, it is

<table>
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<th>Participant</th>
<th>Type of Movement, %</th>
<th>Movement, %</th>
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*Expressed as percentage of total number of 2-second intervals in the 15-minute segment of behavior sampled.
†Small movements were <7.6 cm in excursion or <45° of pronation or supination. Functional movements accomplished a task (eg, opening a jar) or some function (eg, adjusting glasses).
highly likely that an increase in arm movement is associated with increased use of that extremity. The data from this study, however, should not be construed as supporting the use of threshold-filtered accelerometer data as the sole index of patient motor status or treatment outcome in real-world environments. For a more comprehensive picture, it is valuable to obtain data on the amount of functional use and quality of movement. In this laboratory, information on amount of functional extremity use is provided by a structured interview, the MAL, and an observational test of spontaneous extremity use in the laboratory, the Actual Amount of Use Test. A panel of judges, blinded to the treatment status of patients, rate quality of movement from videotapes of the Actual Amount of Use Test and a laboratory motor test, the Wolf Motor Function Test. The different measures are viewed as complementary; together they generate a comprehensive picture of the patient’s extremity use. Moreover, if the different measures converge, all indicating a substantial therapeutic gain, the objective accelerometer data tend to lend credibility and validity to the other more subjective measures.

It is an empirical issue whether further research will enable accelerometry to measure the amount of functional upper-extremity movement or even the quality of movement. One approach is to have “consensus groups” of observers use a clearly specified scale of the functionality of movement to rate the videotaped behavior of stroke patients and then identify simple associations, using regression methods, between the observers’ ratings and the output, both raw and threshold-filtered, from a set of 4 accelerometers, as used here. A related approach is to use neural net technology to identify whether there are complex temporal and spatial patterns in the accelerometer output that can be used to discriminate between nonfunctional and functional movement. Both approaches are currently being pursued here, the neural net approach in collaboration with W.H.R. Miltnner, L. Leistritz, and H. Witte of the University of Jena.

This report presents initial evidence for the validity of accelerometry for objectively measuring real-world treatment outcome for rehabilitation patients with upper-extremity impairments when it is used in conjunction with other measures that contribute information about amount of functional use and quality of movement. Accelerometry thus presents an advance toward an important goal in rehabilitation science: the objective measurement of the actual impact of rehabilitation treatments on the functional activity of patients in their daily environment.

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