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ORIGINAL ARTICLE

Network of Movement and Proximity Sensors for Monitoring Upper-Extremity Motor Activity After Stroke: Proof of Principle

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Abstract

Objective: To test the convergent validity of an objective method, Sensor-Enabled Radio-frequency Identification System for Monitoring Arm Activity (SERSMAA), that distinguishes between functional and nonfunctional activity.

Design: Cross-sectional study.

Setting: Laboratory.

Participants: Participants (N=25) were ≥0.2 years poststroke (median, 9) with a wide range of severity of upper-extremity hemiparesis.

Interventions: Not applicable.

Main Outcome Measures: After stroke, laboratory tests of the motor capacity of the more-affected arm poorly predict spontaneous use of that arm in daily life. However, available subjective methods for measuring everyday arm use are vulnerable to self-report biases, whereas available objective methods only provide information on the amount of activity without regard to its relation with function. The SERSMAA consists of a proximity-sensor receiver on the more-affected arm and multiple units placed on objects. Functional activity is signaled when the more-affected arm is close to an object that is moved. Participants were videotaped during a laboratory simulation of an everyday activity, that is, setting a table with cups, bowls, and plates instrumented with transmitters. Observers independently coded the videos in 2-second blocks with a validated system for classifying more-affected arm activity.

Results: There was a strong correlation ($r=.87$, $P<.001$) between time that the more-affected arm was used for handling objects according to the SERSMAA and functional activity according to the observers.

Conclusions: The convergent validity of SERSMAA for measuring more-affected arm functional activity after stroke was supported in a simulation of everyday activity.

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Data and models of disability suggest that what patients can do with a neurologically impaired limb (ie, their motor capacity), and what they actually do with that limb in their regular environment (ie, their motor performance), need to be measured separately.[1] Research on monkeys after surgical abolition of sensation from a forelimb demonstrates that such animals do not use their deafferented limb spontaneously, even after regaining sufficient motor capacity to do so several weeks after surgery because of a process named learned nonuse.[2] As predicted by the

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deafferented monkey research, studies of adults ≥3 months poststroke show that capacity to complete tasks with the more-affected arm on motor tests in the treatment setting often departs from the amount of spontaneous use of that arm in daily life.[3-7] The *International Classification of Functioning, Disability and Health* also supports the separate study of motor capacity and performance.[8]

In response to this need, both subjective and objective methods for measuring more-affected arm use in daily life have been developed.[1,9] Subjective measures, such as the Motor Activity Log (MAL),[3,10] are vulnerable to common self-report biases despite strong clinimetric data. The objective methods, of which the most widely used is accelerometry,[11-15] are free from these types of bias but cannot discriminate whether movement by the more-affected arm is functional or nonfunctional and cannot identify what tasks have been performed. Recently developed systems of physical sensors, such as Inertial Measurement Units, have the potential to discriminate between functional and nonfunctional movements. However, at present, they have only been shown to index quality of arm movement after stroke on standardized motor tests in the laboratory.[16,17]

This proof-of-principle study in adults with upper-extremity hemiparesis because of stroke examines the convergent validity of a distributed network of physical sensors for measuring the amount of more-affected arm movement related to functional activity and for identifying what tasks have been performed with the more-affected arm. The sensor network is named the Sensor-Enabled Radio-frequency Identification System for Monitoring Arm Activity (SERSMAA). It departs from existing approaches by placing sensors on objects in addition to the patient. Twenty-five stroke survivors had their activity monitored with a SERSMAA prototype and were videotaped during a laboratory simulation of an everyday activity, that is, setting a table with cups, bowls, and plates. The correspondence was then examined between the amount of time objects were handled with the more-affected arm, as determined by the SERSMAA, and the duration of task-related activity with the more-affected arm, as determined by an independent pair of observers using a validated behavioral coding system. Additionally, the identity of the objects handled with the more-affected arm according to the SERSMAA and the behavioral coding was compared.

Methods

Participants

Participants (N=25) were adults (median age, 62.6y; range, 43−94y; 8 women) after cortical or subcortical stroke (median chronicity, 9.0y; range, 0.2−60.9y) of any etiology with a wide range of severity of upper-extremity hemiparesis. Principal exclusion criteria were (1) inability to complete the 3-step command from the Folstein Mini-Mental State Examination, that is, inability to understand and follow verbal directions; (2) unstable medical condition; and (3) condition other than stroke that might affect arm function. Spinal cord strokes were also excluded from the study. Table 1 summarizes participant characteristics. The institutional review board of the university approved the study procedures, and all participants gave informed consent.

List of abbreviations:

FAABOS **Functional Arm Activity Behavioral Observation System**
MAL **Motor Activity Log**
RF **radio-frequency**
RFID **radio-frequency identification**
SERSMAA **Sensor-Enabled Radio-frequency Identification System for Monitoring Arm Activity**

Apparatus

The design and operation of the SERSMAA prototype tested is diagrammed in figure 1, subsequently described, and discussed in detail in Barman et al.[19] Barman[19] reports testing this prototype in young adults without upper-extremity impairment under highly controlled conditions in a laboratory setting. The SERSMAA reliably and validly measured the amount of time household objects were handled with the arm of interest in this able-bodied population. Sensitivity and specificity for detecting the identity of the objects handled were >99%.

Radio-frequency transmitters[a] (7.8×3.8×2cm; 50g) were paired with movement sensors and were attached to the objects to be handled using a hook and loop fastener. Each RF transmitter sent 30-Hz oscillator signals at a fixed low frequency of approximately 10.7kHz with a unique signature. The choice of a low frequency permitted sensing proximity of the receiver and transmitter over short distances of 1 to 23cm, that is, for detecting when the more-affected arm was adjacent to an instrumented object.[19] The movement sensors were GT1M activity monitors[b]

Table 1 Demographic and stroke-related characteristics of the participants (N=25)

Characteristic	Value
Demographic	
Age (y)	62.0±13.4
Female	8 (32)
Ethnicity	
White	12 (48)
Black	12 (48)
Asian	1 (4)
Right dominant preinjury	21 (84)
Stroke-related	
Time poststroke (y)	9.0±12.2
Paresis of dominant side	9 (36)
Severity of more-affected arm motor impairment*	
Grade 2 (mild/moderate)	16 (64)
Grade 3 (moderate)	3 (12)
Grade 4 (moderately severe)	2 (8)
Grade 5 (severe)	4 (16)
Primary mode of ambulation during daily life†	
Independent	9 (36)
Walker/cane	15 (60)
Wheelchair	1 (4)

NOTE. Values are mean ± SD or n (%).
* Participants were assigned a grade by a therapist based on active range of motion available at the upper-extremity joints. This classification system is described in Taub et al.[18]
† Primary mode of ambulation is defined as the one used more than two thirds of the time.

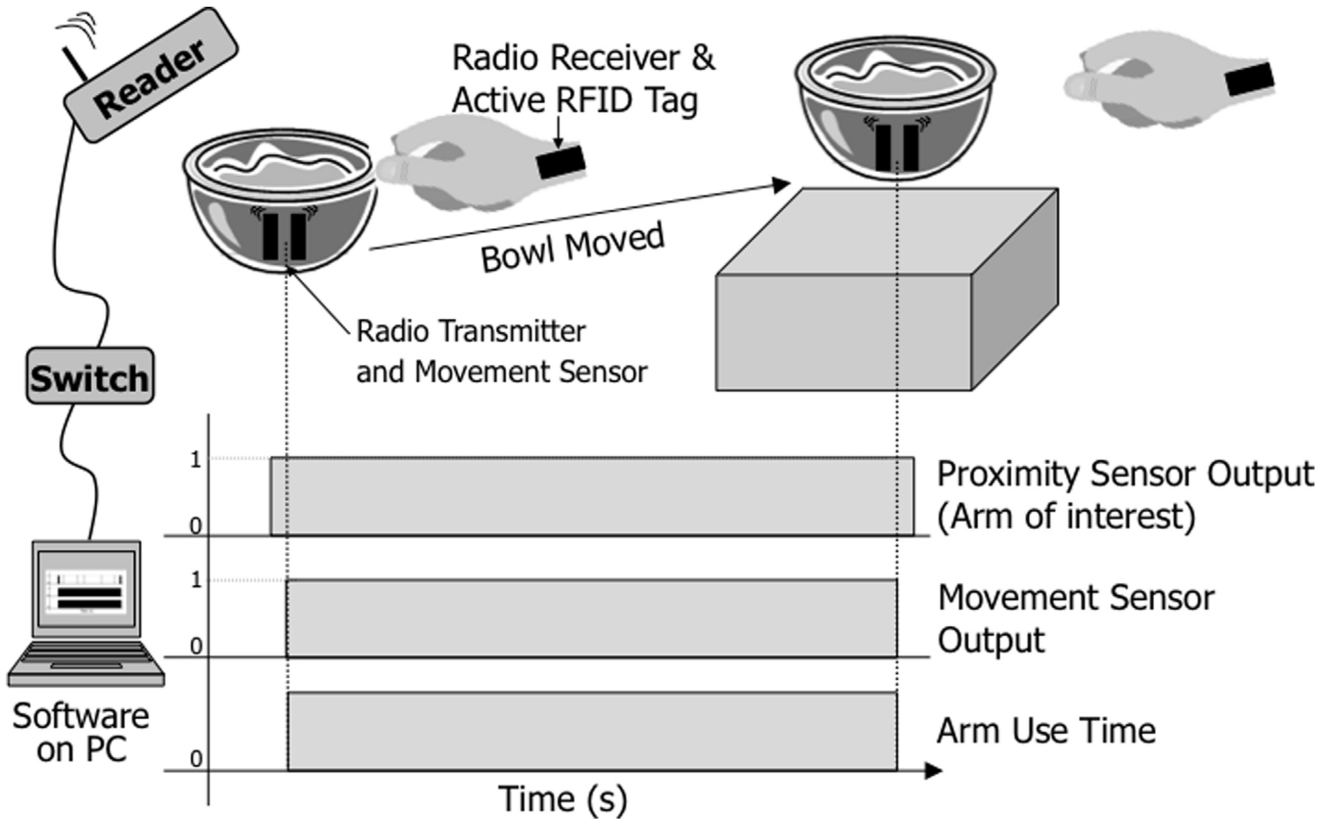

Fig 1 Diagram of the design and operation of the SERSMAA. The components of the SERSMAA prototype were an RF proximity-sensor receiver, which was placed on the more-affected arm, and multiple units that combined an RF proximity-sensor transmitter and a movement sensor, which were placed on objects, an RF reader, and a PC. A local area network was set up between the PC and an RF reader using an ethernet 10/100 megabits per second switch, which enabled the reader and PC to communicate reliably over the local area network. Abbreviation: PC, personal computer.

(5×4×1.7cm; 37g), which have a unique identification and a biaxial accelerometer. Acceleration was sampled at 60Hz and integrated separately for each axis over a 1-second epoch. The movement status for an epoch was marked as ON if the integral value for at least one of the two axes was >2; otherwise, OFF was marked. The threshold of 2 excluded very small movements that were unlikely to be functional.[11] Biaxial accelerometers are adequate for monitoring arm activity because manipulation of objects invariably results in movement components in all 3 axes.[11]

Participants wore the RF proximity-sensor receiver, which was connected to an on-board active radiofrequency identification (RFID) tag (7.4×6.1×2.4cm; 95g) on the wrist of their more-affected arm just above the styloid process. The RF receiver was tuned to the same frequency as the RF transmitter. The RF receiver on the more-affected arm turned on when it came within broadcast range of the transmitter on an instrumented object. The receiver turned off when the more-affected arm was withdrawn from the broadcast range. Proximity status, along with the unique identification of the transmitter on the object approached, was relayed via the RF reader to the computer, which ran custom VB.NET software[c] that processed the signals and stored output in a text file.

When an instrumented object was moved, the sensor recorded the changes in acceleration. These values were stored in the on-board memory of the accelerometer and downloaded into a file that included the movement sensor identification. Synchronous activity from the movement and RF proximity sensors indicated that (1) a particular instrumented object was being moved and (2) it was being moved by the more-affected arm.

Measures

Behavioral coding

To quantify the duration of the functional activity of the more-affected arm, 2 independent pairs of observers coded videos of the observation sessions in 2-second blocks using the Functional Arm Activity Behavioral Observation System (FAABOS).[20] FAABOS codes were 0 (no activity or movement), 1 (nonfunctional activity), 2 (nontask-related functional activity), and 3 (task-related functional activity). Examples of activities were 0 (arm at rest on wheelchair arm), 1 (arm movement secondary to movement of other body parts, such as arm swing when walking), 2 (adjusting glasses), and 3 (picking up cup). A single code that reflected the highest category of activity observed was assigned to each 2-second block of video. This observation system was selected because previous studies with adult stroke survivors with upper-extremity hemiparesis showed that the duration of more-affected arm activity, as captured by 2 to 3 days of in-home wrist-worn accelerometer recordings, is strongly positively correlated with function of the more-affected arm in daily life, as measured by the MAL.[12,21]

The observers were undergraduate students who received approximately 9 hours of instruction and 15 hours of practice prior to coding study videos. As part of their training, observers rated 5-minute segments of video of stroke survivors (N=10) performing everyday activities (eg, drinking, opening a door) in home and hospital settings. For this training set, the intraclass correlation coefficient model 2,1, an index of interrater agreement, was .93.[22]

To ensure independent responses, each pair of observers used separate workbooks and scored videos at separate times. Each pair was explicitly instructed not to share findings with the other pair until all coding had been completed. Thereafter, both pairs reviewed 2-second blocks for which ratings disagreed and came to a consensus on correct coding for these blocks.

In addition to the FAABOS coding, observers also coded in 2-second blocks from video whether participants were engaged in the task (ie, setting the table) and which objects (ie, cups, bowls, and plates) were being handled with which hand. Task codes were 0 (upper-extremity activity unrelated to performing experimental task) and 1 (upper-extremity activity related to performing experimental task). Examples of activities that received a task code of 0 were adjust glasses or push up from chair with arm. This code was necessary because the FAABOS was designed to code spontaneous activity in natural settings and therefore did not discriminate more-affected arm use in experimental tasks from other movements. Hand codes were 0 (object manipulated or about to be manipulated with the less-affected hand only) and 1 (object manipulated or about to be manipulated with the more-affected hand or both hands). For these codes, the object handled was also noted. This coding was performed to permit evaluation of how accurately the SERSMAA monitors the identity of objects handled with the more-affected arm.

Procedures

In our laboratory, a wide-angle video camera was installed in the corner of a 4.1×3.5m room, which was modified to simulate a pantry. Video camera and computer clocks were synchronized. Operation of the sensors was checked by testing whether they triggered when proximity was ≤23cm. Proximity-sensor transmitter and movement sensor units were placed on 3 sets of cups, bowls, and plates. Assignment of units to objects was determined by a computer-generated random numbers table. All household objects were placed on a small tabletop (38×85cm). Cups and bowls were placed on a washcloth, whereas plates were stacked vertically in a dish rack. A large rectangular table (61×152cm) was directly adjacent to the smaller table. It was covered with a tablecloth, and 3 separate table settings were marked by placemats. The RF proximity-sensor receiver was placed on the participants' more-affected forearm. Participants were instructed to set the table with cups, bowls, and plates as they would at home. Just before giving participants the signal to start the task, the SERSMAA system and video camera were set to record.

Data reduction

Data from proximity and movement sensors were stored on a computer as text files. A custom-made VB.NET software algorithm combined files offline by using time and identification stamps as keys. The algorithm calculated duration of the following events for each household object: participant's more-affected arm approached object (ie, proximity status transitions from off to on), object moved (ie, movement status transitions from off to on), and object manipulated by the participant's more-affected arm (synchronous transitions from on to off status for proximity and movement sensors). Changes in proximity and movement sensor status were deemed synchronous if the transitions in status from each sensor type were ≤2 seconds apart.[19] The SERSMAA summary variable calculated was the total amount of time objects were handled with the more-affected arm. The calculated FAABOS coding summary variable was the duration of functional task-related activity with the more-affected arm, that is, double the number of 2-second blocks with codes of 3. Other summary variables were duration of task engagement (double the number of 2-s blocks with task codes of 1) and number of objects manipulated with the more-affected hand or both hands (hand code 1) and the less-affected hand (hand code 0).

Data analysis

Interrater reliability for the behavioral coding was quantified using intraclass correlation coefficient model 2,1. For this index of interrater agreement, values ≥.80 are considered adequate.[22] Reliability was calculated between pairs of observers across participants for the summary variables derived from each coding scheme (see Data Reduction section).

Convergent validity of the SERSMAA output was evaluated by calculating the Spearman correlation between the SERSMAA and FAABOS summary variables across participants. This correlation was calculated separately for 2 slices of the data: the entire observation session and only epochs during which participants were engaged in the experimental task (task code 1). Correlation coefficients ≥.50 are considered strong.[23]

Sensitivity for detecting which objects were manipulated with the more-affected hand during observation sessions was calculated by counting the number of objects that the observers coded as such (hand code 1), counting the number of those objects correctly identified by the SERSMAA, and dividing the latter by the former. Specificity was calculated by counting the number of objects that were handled with the less-affected arm according to the observers (hand code 0), counting the number of those objects correctly identified by the SERSMAA, and dividing the latter by the former. For the purpose of these calculations, the SERSMAA had to signal handling of an object for >2 seconds continuously for an object to be counted as handled with the more-affected hand. This rule was determined by parametrically varying the value of this threshold and selecting the smallest value that yielded an appropriate trade-off between sensitivity and specificity. It was necessary to set such a threshold to reduce the number of false positives, that is, synchronous on signals from the SERSMAA proximity and movement sensors produced by close proximity of the more-affected hand to an instrumented object while it was being handled with the less-affected hand. There is no general agreement concerning optimal values for sensitivity and specificity.[24] In this case, the cost of undercounting object handling with the less-affected arm only (ie, having a low specificity rate) was considered small relative to the cost of undercounting object handling with the more-affected arm (ie, having a low sensitivity rate).

Results

Reliability of the behavioral coding

Interrater reliability was high. Intraclass correlation coefficient model 2,1 values for the FAABOS and task codes were .96 and

Table 2 Selected features of different slices of the observation session (N=25)

Characteristic	Slice of Session: Entire Session	Engaged in Experimental Task*	Not Engaged in Experimental Task†
Duration of slice (s)			
Mean ± SD	72.8±38.6	50.6±26.4	19.0±8.2
Median IQR	58 (48–88)	40 (32–58)	18 (14–22)
FAABOS summary variable, duration of more-affected arm task-related activity (s)			
Mean ± SD	32.4±32.6	30.9±31.4	1.5±3.9
Median IQR	26 (0–44)	26 (0–44)	0 (0–0)
SERSMAA summary variable, time objects were handled with more-affected arm(s)			
Mean ± SD	27.6±24.8	27.6±24.8	0.0±0.0
Median IQR	26 (12–30)	26 (12–30)	0 (0–0)

Abbreviation: IQR, interquartile range.
* Task code 1.
† Task code 0.

.99, respectively. For coding of which objects were handled by which hand, agreement was 98%±5%.

Length and other characteristics of the observation sessions

Table 2 summarizes several features of the observation sessions. The mean number ± SD of experimental objects manipulated with the more-affected hand only or with both hands (hand code 1) was 4±4. The mean number ± SD manipulated with the less-affected hand only (hand code 0) was 5±4. During the observation sessions, 17 participants ambulated without any assistance, 7 used a walker or cane, and 1 used a wheelchair.

Convergent validity and sensitivity and specificity of the SERSMAA

Figure 2 plots the amount of time objects were handled with the more-affected arm according to the SERSMAA summary variable against the duration of task-related activity with the more-affected arm according to the FAABOS summary variable. The correlation between the SERSMAA and FAABOS summary variables was very strong regardless of whether the summary variables were calculated for the entire observation session ($r=.87$, $P<.001$) or only the slice during which participants were engaged in the experimental task ($r=.87$, $P<.001$). The value of this correlation was also similar for participants who walked without assistance ($r=.88$, $P<.001$) and those who used a walker, cane, or wheelchair ($r=.86$, $P<.025$).

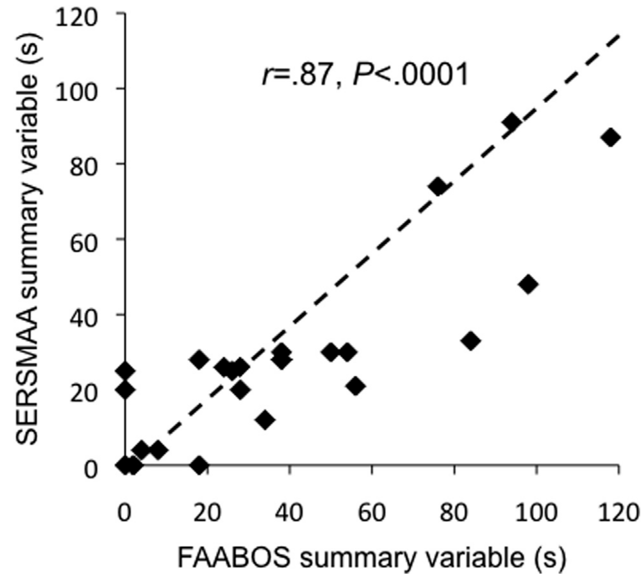

Fig 2 Scatterplot of the amount of time objects were handled with the more-affected arm according to the SERSMAA summary variable against the duration of task-related activity with the more-affected arm according to the FAABOS summary variable (N=25). The diagonal broken line represents perfect correspondence. Each data point represents a participant. The SERSMAA and FAABOS summary variable values are plotted for the entire observation session.

Furthermore, mean values of the SERSMAA and FAABOS summary variables were similar. For the experimental-task slice, the SERSMAA mean ± SD was 27.6±24.8 seconds, whereas the corresponding value for the FAABOS was 30.9±31.4 seconds (table 3). For the slice of the observation session during which participants were not engaged in the experimental task (task code 0), the mean value ± SD of the FAABOS summary variable was 1.5±3.9 seconds, indicating that participants used their more-affected arm for task-related activity very little or not all. The SERSMAA summary variable value was 0±0, indicating the same.

Mean sensitivity ± SD for detecting which objects were manipulated with the more-affected hand during observation sessions was 90%±18%. Mean specificity ± SD was 72%±32%.

Discussion

The close correspondence observed between the SERSMAA and FAABOS summary variable values, regardless of the mode of ambulation used by participants, supports convergent validity of the SERSMAA prototype for measuring duration of more-affected arm functional activity in adults after stroke in a simulated everyday setting. Sensitivity for detecting the identity of instrumented objects handled with the more-affected arm was greater than specificity. In the ultimate application, that is, remotely monitoring how stroke patients use their more-affected arm at home, identity of objects handled could be used to infer the type of activities performed with that arm.

As noted, the SERSMAA differs from current objective methods for assessing spontaneous use of the more-affected arm in daily life by placing sensors on household objects in addition to the patient. This approach permits handling of household objects, which is required for most upper-extremity functional activity in the home to be detected directly. Current upper-extremity activity

Table 3 Examples corresponding to each FAABOS category

Categories of Arm Activity in FAABOS Coding Scheme	Examples
Category 3: task-related; a movement or action that helps to accomplish a task	Reaching to grab object
	Grabbing a cup (failed attempts are included)
	Releasing object
	Wiping dishes, tabletop
	Transporting object from one place to another
	Transferring object from one hand to other
	Holding object while object is being used by person being rated or someone else
	Using hand/arm to push-up from chair
	Use hand to obtain support from rail
Category 2: nontask-related, functional; a movement or action that has some function but does not accomplish a task	Adjust glasses
	Scratch leg
	Touch face
	Hand/arm gesture
	Hand to mouth to cover yawn
	Holding object, but object is not being used or transported
	Incomplete movement (adjusting placement of arm in preparation for reaching for object)
	Moving arm from one position to another
	Support/hold body part
Category 1: nonfunctional; a movement or action that does not have any function or has minimal function	Tic, tremor
	Arm movement secondary to other body part movements (eg, arm swings when walking)
	Passive movement (ie, rated arm is moved by unrated arm; any amount of assistance classifies the movement as passive; drops mostly because of the effect of gravity)
Category 0: no activity or movement; no movement or action of the arm	Arm at rest on chair when watching television

NOTE. The FAABOS categories, coding rules, and training procedures are described at length in Uswatte and Hobbs Qadri,[20] which present data from studies set in the hospital and community supporting the reliability and validity of the FAABOS.

monitors, such as accelerometers, count any movement of the arms, regardless of whether it is related to functional activity or not. Thus, accuracy of these methods for measuring more-affected arm functional activity depends on upper-extremity movement and corresponding functional activity.

Study limitations

Limitations were that observation sessions were not representative of everyday activity in several ways: sessions were short, only contained 3 different household objects, and were set in the laboratory. In addition, the small sample size raised questions about generalizability of findings and precluded meaningful examination of questions about the effect of participant characteristics, such as sex and side of paresis, on results. Last, the behavioral coding did not permit examination of the relation of the SERSMAA output with the frequency of more-affected arm functional movement and did not distinguish between use of the more-affected arm alone and use of that arm in conjunction with the less-affected arm. The implication of the latter is that the behavioral coding might have overestimated the amount of use of the more-affected arm. Before the SERSMAA can be considered as an objective measure of functional status or treatment outcome, data are needed from larger samples on (1) how long the observation period needs to be and how many household objects need to be instrumented to produce a stable estimate of the duration of more-affected arm functional activity, (2) how frequently the type of false positives encountered here take place in the home, and (3) how strongly the SERSMAA output correlates with indices of more-affected arm use (eg, the MAL) over extended periods.

The SERSMAA system would benefit from a couple of modifications. One, an alternative design in which passive RFID tags[25-27] are placed on objects and a short-range RFID reader and movement sensor are placed on the more-affected arm, would reduce both footprint of the sensors on household objects and overall cost of the system because only 1 accelerometer would be needed on the arm instead of 1 per object. Two, real-time processing of system signals would enable immediate analysis of data and provision of feedback to stroke patients on the use of their more-affected arm in the home setting.

Conclusions

Proof of principle was demonstrated for the SERSMAA system, which is designed to remotely monitor duration and type of more-affected arm functional activity after stroke in the home. Before this instrument can be used to assess upper-extremity functional status or neurorehabilitation outcome, some modifications need to be made to the hardware and software, and real-world testing needs be performed.

Suppliers

a. ActiveWave Inc, Congress Corporate Plaza, 902 Clint Moore Rd, Ste 126, Boca Raton, FL 33487.
b. Actigraph, 49 E Chase St, Pensacola, FL 32502.
c. Microsoft Corporation, One Microsoft Way, Redmond, WA 98052.

Keywords

Arm; Outcome and process assessment (health care); Paresis; Rehabilitation; Stroke

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