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Sensor-Enabled RFID System for Monitoring Arm Activity in Daily Life

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Abstract—**After stroke, capacity to carry out tasks in the treatment setting with the more-affected arm is a poor index of actual use of that extremity in daily life. However, objective methods currently available for monitoring real-world upper-extremity use only provide information on amount of activity. These methods, which rely on movement sensors worn by patients, do not provide information about type of activity (e.g., functional vs. nonfunctional movement). The benchmark testing reported here evaluated an approach that involves placing sensors on patients *and* objects. An accelerometer and the transmitter component of a prototype radio frequency proximity sensor were attached to household objects. The receiver component was placed on the experimenter's right arm. This device triggered an on-board radio frequency identification tag to signal proximity when that arm was within 23 cm of the objects. The system detected > 99% of 6 cm or greater movements of objects. When handling of objects by the right or left arm was determined randomly, 100% of right arm trials were detected. No signals were recorded when objects were at rest or moved by the left arm. Testing of this approach, which monitors manipulation of objects (i.e., functional movement), is now warranted in stroke patients.**

Keywords—**radio frequency identification, RFID, sensors, acceleration, proximity, arm, activity, ambulatory monitoring, rehabilitation, stroke**

I. INTRODUCTION

MORE than 650,000 survive strokes annually in the United States [1]. Persistent impairment of the arm on the more-affected side of the body afflicts between 55% and 75% of survivors [2] and is associated with diminished health-related quality of life [3]. Advances in methods to assess and treat more-affected arm impairment after stroke, therefore, have the potential to improve the lives of many.

Well-known models of disability and data indicate that laboratory measures of function poorly index how stroke survivors actually use their more-affected arm in daily life [4]. Therefore, substantial effort has been spent on developing real-world measures of arm function. Most of these tests, however, rely on self-report [4]. Researchers have objectively measured amount of arm activity in the community by placing accelerometers on stroke survivors [5]. These techniques, however, cannot discriminate whether a given arm movement is functional or non-functional and cannot identify what tasks were performed. More complex activity monitors, such as Inertial Measurement Units, hold promise for making such discriminations but to date have been shown only to index quality of arm movement after stroke on a standardized motor test in the laboratory [6], [7].

This paper describes design and benchmark testing of a system of radio frequency identification (RFID) tags paired with proximity and movement sensors for measuring arm activity. In this approach, movement sensors (i.e., accelerometers) are placed on objects, along with one component of a RF proximity sensor. The other component of the proximity sensor is connected to an active RFID tag and placed on the arm of interest. Manipulation of instrumented objects with that arm produces synchronous signals from the movement and proximity sensors, permitting tracking of which objects are handled, when handling takes place, and whether handling is by the person and arm of interest. The proposed approach, thus, can collect much richer objective data than possible now.

II. BACKGROUND

A. Monitoring of Arm Activity with Accelerometers.

To overcome the limitations of self-reports, several researchers have employed accelerometers to objectively measure amount of arm activity in stroke survivors in the community [5]. For example, Uswatte et al. [8] asked stroke survivors with mild-to-moderate impairment of their more-affected arm to wear an accelerometer above each wrist during all waking hours for 2 days before and after upper-extremity physical rehabilitation or a corresponding no-treatment period. They found that the ratio of more-affected to less-affected arm accelerometer recordings was strongly correlated with amount of more-affected arm use in daily life ($r = .74$, $p < .001$). However, since any arm movement produces an acceleration reading, such approaches cannot discriminate whether a given movement is functional or non-functional nor identify what tasks are performed.

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B. Radio Frequency Identification Systems.

RFID systems consist of small tags that transmit a unique ID using RF and a RF reader that monitors the status of these tags [9]. Software on a PC connected to the reader processes the RFID signals. “Passive” RFID tags transmit their ID when they encounter the reader’s radio waves, whereas “active” RFID tags, which are battery powered, transmit their ID independently from as far as 85 m [10]. Typical applications involve tracking whether tagged objects are within the range of the reader or not. Examples are monitoring when hospital equipment or a patient leaves a room and monitoring how much merchandise remains in a warehouse [11]. RFID systems have not been used to remotely monitor upper-extremity activity in stroke survivors or other populations, for that matter.

III. METHODOLOGY

A. Apparatus.

1) Sensor-Enabled RFID System for Monitoring Arm Activity (SERSMAA): Fig. 1 shows the hardware setup, and how the movement and proximity sensors operate together when an object is manipulated with the arm of interest.

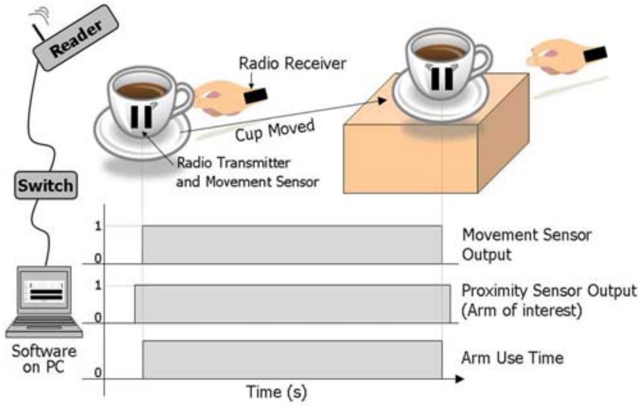

Fig. 1. Sketch of SERSMAA Prototype

A local area network (LAN) is setup between the PC and RF reader using an Ethernet 10/100 Mbps switch. The switch enables the RF reader and PC to communicate reliably over the LAN. A movement sensor (5 cm x 4 cm x 1.7 cm; 37 g) and proximity sensor transmitter (7.8 cm x 3.8 cm x 2 cm; 50 g) are placed on each object. The receiver component of the proximity sensor is connected to an on-board active RFID tag; this assembly (7.4 cm x 6.1 cm x 2.4 cm; 95 g) is attached to the arm of interest. Each movement sensor [12] and the RFID tag [10] possess a unique ID.

When the arm of interest approaches an instrumented object, the proximity sensor receiver detects the transmitter’s signals, triggering the RFID tag to broadcast an “ON” signal along with its ID. When the arm withdraws, the proximity sensor receiver no longer detects the transmitter’s signals, triggering the RFID tag to broadcast an “OFF” signal along with its ID. The RF reader relays the proximity status signals to the PC, which runs custom software that processes these signals and stores the output in a text file. If the object is manipulated, the movement sensor records the changes in its acceleration, and stores these values in on-board memory for offline downloading into a text file that includes the movement sensor ID. Custom software processes the proximity and movement sensor text files offline. Synchronous “positive” values from the proximity and movement sensors indicate that an instrumented object is being moved by the arm of interest. Moreover, analysis of the proximity status and acceleration values, along with their ID and time stamps, permits tabulation of which objects are moved, when they are moved, for how long, and by which arm.

2) Proximity Sensor: Fig. 2 and Fig. 3 shows block diagrams of the transmitter and receiver components, respectively, of the *prototype* RF proximity sensor. As noted, transmitters are attached to objects, while the receiver is attached to the arm of interest.

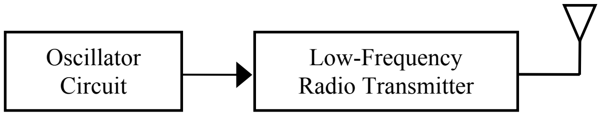

Fig. 2. Low-Frequency Radio Transmitter Circuit Block Diagram

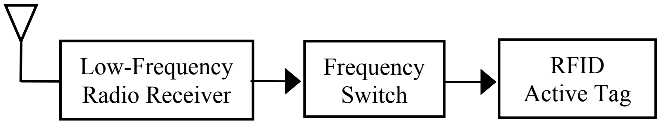

Fig. 3. Low-Frequency Radio Receiver Circuit Block Diagram

The RF transmitter sends 30 Hz oscillator signals at a fixed low frequency of ~10.7 KHz. A low-frequency is desirable for sensing proximity of the receiver and transmitter over distances of 1 to 23 cm, i.e., for detecting when the arm of interest is close to an instrumented object. The RF receiver is tuned to the same frequency as the transmitter. The receiver output connects to a frequency switch circuit that turns ON when it reads the 30 Hz signal and turns OFF in its absence. Because the frequency switch output cannot be readily connected to the ActiveWave RFID tag [10], a jerry-rigged solution is used in this prototype. The frequency switch output, instead of firing the tag directly, connects to an electromagnet, which produces a magnetic field when the frequency switch toggles ON. This magnetic field, in turn, activates an ActiveWave magnetic sensor active RFID tag, which sends a signal to the RF reader indicating a change in sensor status. The power sources for both components are 3 V coin cell batteries.

3) Movement Sensor: The object movement sensors are ActiGraph GT1M Activity Monitors. GT1M units employ a biaxial accelerometer, which detects 1 g acceleration with a sensitivity of ±10%. Acceleration is sampled at 60 Hz in each axis. These samples are integrated separately for each axis over a user-specified epoch, which in this case was 1 s, and are stored in 1 Mb flash memory [12]. To remove non-functional movement (e.g., simply brushing the arm of interest against an object), integral values ≤ 1 are set to 0; other values are set to 1 [13]. To generate a single ON/OFF movement signal, the movement status in each epoch is set to OFF only if the threshold-transformed integral values for *both* axes are 0. Otherwise, movement status is set to ON.

Biaxial accelerometers are adequate for monitoring arm activity because manipulation of objects invariably results in movement components in all 3 axes [14].

B. Procedure.

Benchmark testing was performed under highly controlled conditions in the laboratory to determine whether the sensitivity and specificity of the SERSMAA prototype was adequate, i.e., ≥98% and >99%, respectively.

1) Proximity Sensor Testing: The proximity sensor transmitter was attached to the side of a coffee mug using Velcro. The proximity sensor receiver was attached with an elastic band to the right forearm of the experimenter just above the wrist. The mug was placed on a target at the center of several circles of varying radii drawn on a table. Two hundred trials of each test were conducted, except for Test 1a, which had 100. The start and end of trials were marked with beeps emitted by custom software on a PC.

a) To determine the range of proximity detection, the experimenter moved his hand along the table top in 1 cm increments every 5 s starting from a target 24 cm away from the mug and ending 20 cm away. Movement was parallel to the *y* axis of the mug. Proximity sensor status was recorded at each 1 cm increment.

b) To evaluate how sensitivity varies with angle of approach, the experimenter placed his hand on a target > 23 cm from the mug. The experimenter then grasped the mug handle with his right hand, released it, and returned his hand to the target. This movement was conducted parallel to the *x*, *y,* and *z* axes of the mug in separate sets of 200 trials.

c) To evaluate how sensitivity varies with interval between releasing and grasping an object, the *y*-axis test was repeated with inter-trial intervals of 1, 3, 5, and 7 s.

d) To determine how sensitivity varies with type of household object and hand size, the *y*-axis test was repeated with a telephone, book, hair brush, and television remote and with experimenters with hand sizes ranging from 18.5 to 21.5 cm (tip of middle finger to styloid process of radius).

e) To evaluate specificity, the proximity sensor receiver was set > 23 cm away from any transmitters for 24 hours.

f) To test robustness to interference from other electronic devices that emit RF waves, the *y*-axis test was repeated at varying distances from a loud speaker and television set.

2) Movement Sensor Testing:

a) To test how sensitivity varies with distance an object is moved, the movement sensor was attached to the mug. The experimenter moved the mug from one target to another on the table surface parallel to the *x*-axis of the mug. Two hundred trials each were conducted with the targets 2, 4, 6, 8, 12 and 16 cm apart. The interval between trials was 3 s.

b) To test how sensitivity varies with direction of movement, the 12 cm test above was repeated with movements parallel to the *y* and *z* axes of the mug.

c) To test how sensitivity varies with interval between movements, the12 cm test for movement parallel to the mug's *x*-axis was repeated with a 2 s inter-trial interval.

d) To evaluate specificity, a movement sensor was turned on and left in one spot for 24 hours.

3) Testing of System: To test the sensitivity and specificity of the entire system, proximity sensor transmitters and movement sensors were attached to two mugs (Mug 1, 2) resting 43 cm apart. The proximity sensor receiver was put on the experimenter's right arm. The experimenter placed his right and left hands on separate targets each > 23 cm from both mugs. When instructed, the experimenter grasped either Mug 1 or 2, moved it to a target 12 cm away with either his Right or Left hand, and returned the hand employed to its starting position. Two hundred trials were conducted, with 5 s between trials. This procedure was repeated with objects set 5 cm apart. The choice of which object to grasp and which arm to employ was determined by a random process on each trial.

C. Data Processing and Analysis.

As noted, the proximity and movement sensor data were stored as text files. A VB.NET software algorithm was developed to process the files offline. The algorithm combined the two files by using the time and ID stamps in these files as keys. Summary variables were then calculated for each test: number of times the experimenter's right arm approached each object (i.e., proximity status transitions from ON to OFF); number of times each object was moved (i.e., movement status transitions from ON to OFF); number of times each object was manipulated by the experimenter's right arm (synchronous transitions from ON to OFF status for the proximity and movement sensors). (Changes in sensor status were deemed synchronous if the transitions in status from each sensor type were within 2 s of each other.) Other summary variables that can be derived are how long each object is moved and manipulated. In addition, total time the arm of interest is used to manipulate objects can be derived by summing across objects.

IV. RESULTS

A. Proximity Sensor Testing.

Fig. 4 shows that the proximity sensor receiver on the experimenter's right arm detected proximity of an instrumented mug on 100% of trials when the mug was < 21 cm away. When the mug was 22 cm and 23 cm away, sensitivity fell to 95% and 90%, respectively. When the mug was > 23 cm away, i.e., outside of the intended range, the proximity sensor, appropriately, did not change status.

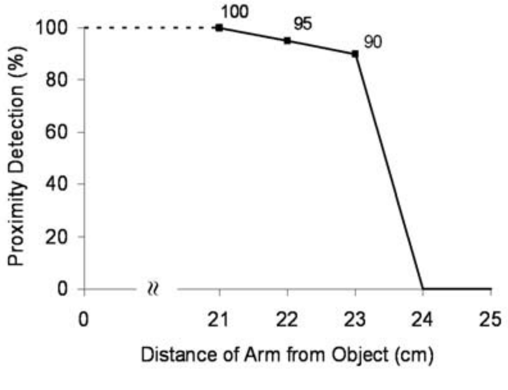

Fig. 4. Sensitivity of Proximity Sensor

Sensitivity did not vary substantially with angle of approach. Out of 200 approach, grasp, release, and withdraw trials, proximity was detected 202, 198, and 204 times, respectively, for angles parallel to the *x*, *y*, and *z* axes of the mug. Nor did proximity detection vary substantially with interval between trials (1 s = 194, 3 s = 202, 5 s = 198); type of object grasped (mug = 198, telephone = 203; book = 198; hair brush = 194, remote control = 196); or experimenter hand size (18.5 cm = 198, 19.6 cm = 202, 21.5 cm = 204).

Specificity was supported; no proximity detection signals were recorded when the proximity sensor receiver and transmitter were kept ≥ 23 cm apart for 24 hours. In addition, proximity was detected during only 0.4% of inter-trial intervals during the above tests. Operation of a television set and loud speaker interfered with proximity detection; when the proximity sensor receiver and transmitter were within 20 cm of each other but ≤ 20 cm from one of these electronic devices the sensor stopped detecting proximity.

B. Movement Sensor Testing.

Fig. 5 shows that when the experimenter moved an instrumented mug 6 cm or more, the movement sensor detected ≥ 99% of the movements. For 4 cm movements, detection was 90%. For 2 cm movements, detection was only 57%.

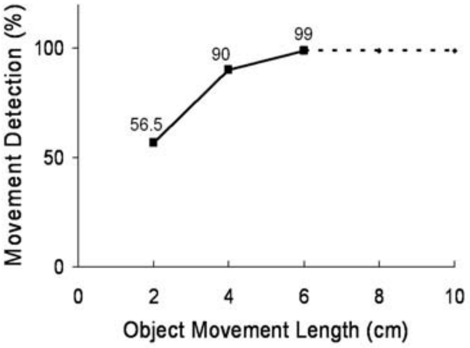

Fig. 5. Sensitivity of Movement Sensor

Sensitivity did not vary substantially with direction of movement. For 12 cm movements parallel to the *x*, *y*, and *z* axes of the mug, detection was 99%, 99%, and 98%, respectively. Detection was poor when the interval between movements was ≤ 2 s. For a 12 cm movement parallel to the *x* axis of the mug, detection was 99% when the inter-trial interval was 3 s but was only 48% when the inter-trial interval was 2 s.

Specificity was supported; no movement was recorded when a movement sensor was turned on but kept in one spot for 24 hours. In addition, for tests where the inter-trial interval was ≥ 3 s and movement was ≥ 4 cm, no movement was detected during the inter-trial intervals.

C. Testing of System.

Fig. 6 graphs performance of the SERSMAA system, i.e., joint operation of the proximity and movement sensors when the object to be moved and arm to be employed was randomly selected. Manipulation of the object of interest with the right arm was detected with 100% sensitivity and specificity both when the objects were 43 and 5 cm apart.

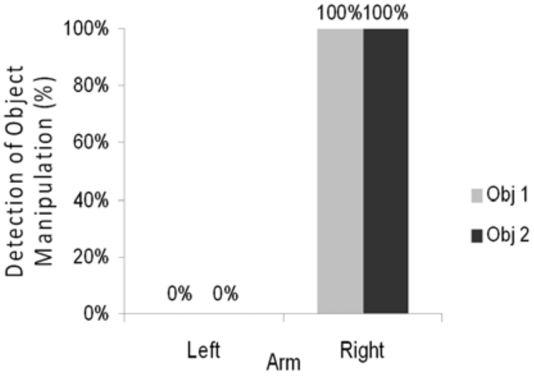

Fig. 6. Performance of SEARSMAA System

V. CONCLUSION

The sensitivity and specificity of the SERSMAA prototype under controlled conditions in the laboratory appeared to be adequate for its ultimate purpose, i.e., remotely monitoring everyday arm activity after stroke. When the proximity sensor receiver on the experimenter's right arm drew close (≤21 cm) to an instrumented object, proximity was detected on ≥97% of trials, regardless of angle of approach, inter-trial interval, type of object, and hand size. When the experimenter's right arm was far (≥23 cm) from an instrumented object, proximity, appropriately, was not signaled. The movement sensor detected ≥98% of instrumented object movements when they were ≥6 cm long and ≥3 s apart, regardless of movement direction. No movement signals were recorded when instrumented objects were at rest. When the object to be manipulated and the arm to be used were randomly selected, the conjoint proximity and movement sensor signals detected handling of the object of interest with the right arm with 100% sensitivity and specificity even when the objects were just 5 cm apart.

These results suggest that testing with stroke patients in more natural settings is warranted after some modifications. The size of the sensors needs to be reduced. One approach for doing so would be placing passive RFID tags, which are the size of stickers, on objects, while placing a RF reader with a short range and accelerometer on the arm of interest. A capacity for real-time processing of the system signals would be desirable. The frequency with which household objects in daily life are manipulated by the less-affected arm when the more-affected arm is within 23 cm of the object, needs to be assessed, as the current system cannot identify which arm has manipulated the object under such conditions. In addition, the frequency of interference from electronic devices such as television sets in everyday environments needs to be assessed.

If these issues can be addressed successfully, this technology will be able to provide a much richer objective picture of everyday arm activity after stroke than possible now. Such an advance would permit more accurate measurement of real-world gains after upper-extremity rehabilitation. For this application, the patient's more-affected arm and a representative sample of household objects would be instrumented and the RF reader and PC would be placed in the patient's home for several days before and after rehabilitation. Other rehabilitation applications are monitoring compliance with home exercise programs and therapeutic use of activity monitoring records. For example, the SERSMAA output could serve as input for software on the PC controlling a virtual therapist who reinforces patients immediately after they use their more-affected arm to manipulate instrumented objects in their homes. Applications outside of medicine are tracking how often consumers use a company's products (i.e., handle them) and monitoring who handles what on production lines.

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