# Measuring Functional Arm Movement after Stroke Using a Single Wrist-Worn Sensor and Machine Learning

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*Background and Purpose:* Trials of restorative therapies after stroke and clinical rehabilitation require relevant and objective efficacy end points; real-world upper extremity (UE) functional use is an attractive candidate. We present a novel, inexpensive, and feasible method for separating UE functional use from nonfunctional movement after stroke using a single wrist-worn accelerometer. *Methods:* Ten controls and 10 individuals with stroke performed a series of minimally structured activities while simultaneously being videotaped and wearing a sensor on each wrist that captured the linear acceleration and angular velocity of their UEs. Video data provided ground truth to annotate sensor data as functional or nonfunctional limb use. Using the annotated sensor data, we trained a machine learning tool, a Random Forest model. We then assessed the accuracy of that classification. *Results:* In intrasubject test trials, our method correctly classified sensor data with an average of 94.80% in controls and 88.38% in stroke subjects. In leave-one-out intersubject testing and training, correct classification averaged 91.53% for controls and 70.18% in stroke subjects. *Conclusions:* Our method shows promise for inexpensive and objective quantification of functional UE use in hemiparesis, and for assessing the impact of UE treatments. Training a classifier on raw sensor data is feasible, and determination of whether patients functionally use their UE can thus be done remotely. For the restorative treatment trial setting, an intrasubject test/train approach would be especially accurate. This method presents a potentially precise, cost-effective, and objective measurement of UE use outside the clinical or laboratory environment. **Key Words:** Upper extremity—outcome measures—accelerometry—machine learning—body-worn sensors—rehabilitation—stroke.


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## Introduction

A primary goal of upper extremity (UE) poststroke rehabilitation is restoration of use in the home and community. The inability to sensitively and specifically demonstrate treatment response is a major impediment to obtaining and improving rehabilitation treatments. This measurement problem also poses a challenge to trials of restorative interventions such as cellular therapies or brain stimulation because treatment responses are unlikely to be large enough to show change on standard trial measures such as the modified Rankin Scale. These investigators have thus focused their attention on motor-specific responses, especially of the UE.[1] Presently, no widely accepted method exists to assess the amount of real-world functional use of the affected UE in an objective, quantitative, low-cost, and reproducible way. Thus, clinicians and stroke trialists cannot directly measure the real-world impact of a treatment on UE use.

In practice, 2 UE evaluation approaches[2] are used: the administration of performance-based measures that rate the patient's ability to perform specific motor tasks associated with functional use[3] or self-report scales assessing the amount or quality of arm movement for a standard set of activities.[4,5] Neither method objectively measures performance in the home or community environment, and neither directly assesses the use of the UE to accomplish the primary goals of treatment, the use of the UE in activities of daily living (ADLs), and vocational and leisure activities.

Sensor technology is an emerging approach to quantitative community-based assessment, with work focused on the application of various sensor types, especially inertial measurement units (IMUs).[6-10] These typically involve placing IMUs on multiple body parts. However, these sensor suites are difficult to don, and their appearance may limit user acceptance and cause changes in behavior. Finding an unobtrusive and easy-to-use solution has proven difficult. In another approach, bilaterally worn IMUs compare the movement of the more affected and less affected UE after stroke on the assumption that changes in the ratio of movement duration between the UEs reflect changes in the amount of use of the more affected UE.[9,11-13] However, the sensitivity and specificity of this approach may be limited because functional movements are not separated from nonfunctional movements such as arm swing during walking.

Machine learning-based models can be used to recognize specific ADLs using sensor streams.[6,14] Most studies focus on lower-limb activities such as walking versus climbing stairs. Such approaches have been tested predominantly in lab settings or are limited to very specific movement patterns; their translation to the UE and to the community is unknown. Automatically classifying specific human activities poses several challenges. The length of a single activity, even when performed by a single subject, can vary widely, and movement patterns can differ among subjects.[15,16]

In prior work, we developed a sensor system and a classifier model that can be implemented outside a lab for persons with unilateral UE impairments.[2] The hardware was unobtrusive to minimize behavioral changes, and the software was computationally lightweight enough for use on a smartphone. We previously showed that IMUs, coupled with machine learning algorithms, can separate UE voluntary functional movements from the UE movements that occur while walking.[2] We now extend our work by presenting a method for using a single wrist-worn sensor to measure UE functional use during ADLs in healthy controls and persons with post stroke hemiparesis.

## Materials and Methods

The MedStar Health Research Institute Internal Review Board approved the study; participants provided informed consent.

### *Subjects*

Control subjects were screened for self-reported neurological or physical impairments that would prevent full study participation. A convenience sample of stroke participants met the following criteria: (1) age 21 or older; (2) Mini-Mental Status Examination score higher than 24[17]; (3) ischemic or hemorrhagic stroke that occurred more than 6 months prior; (4) no UE conditions that limited use prior to the stroke; and (5) community dwelling. No participant had severe hemineglect or complete upper-limb plegia.

### *Measures*

Participants' wrists were instrumented (see Fig 1) with an IMU (ADIS16400BMLZ; Analog Devices, Norwood, MA) that was polled by a microcontroller (Arduino Pro Mini, Somerville, MA) at a rate of 200 Hz, and the data were stored on a micro SD card using an embedded logger (Sparkfun OpenLog, Somerville, MA). Triaxial linear acceleration and triaxial angular velocity were used in the analysis. Both wrists were instrumented to avoid having subjects favor an extremity based on the presence or absence of a sensor, but analyses were performed only on the nondominant UE (controls) or affected UE (stroke participants).

The Action Research Arm Test (ARAT) was used to assess functional limitations and the severity of weakness of the UE. It uses a 4-point ordinal scale on 19 items, with subscales for gross motor, grasp, grip, and pinch. The ARAT has proven reliable, valid, and responsive to change across a variety of time points post stroke.[3,18] The Edinburgh Inventory was used to measure handedness.[19]