

Quantitative Measures of Functional Upper Limb Movement in Persons after Stroke

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Abstract- Stroke disables many older adults each year. This disease impairs the motor functions of survivors, and rehabilitation intervention is a critical part of recovery. Quantitative assessment techniques could be a valuable guide to this intervention. In this study, we propose the use of linear and nonlinear features to assess subjects after a stroke with upper limb motor impairment. These features capture differences in accelerometer signals that mark patterns associated with functional movements performed by individuals with different severity of functional limitation and motor impairment. Our results indicate that the severity of functional deficit and motor impairment can be identified by quantifying the accelerometer signals for movements of the arm and hand while performing a functional reaching task.

I. INTRODUCTION

Stroke is a major cause of disability, with approximately 730,300 new cases in the United States annually, and about 160,000 Americans die each year from stroke [1][2][3]. Stroke often impairs motor function. Following a stroke, survivors may have impaired cognitive, language, perceptual, and sensorimotor limitations. Abnormal reflexes, weakness of volitional movements, and changes in muscle tone are the main motor characteristics of stroke survivors [4]. In a substantial number of stroke survivors, neurological impairment leads to partial or total dependence in activities of daily living. Recovery from stroke is a long process that extends well beyond the discharge of the patient from the hospital. An important part of the clinical management of post-stroke patients is the design of the rehabilitation intervention [5][6].

Standardized clinical motor assessments rely on observational measures of functional task performance; quantitative data could be obtained by simultaneously recording data from accelerometers. Analysis of wearable sensor data in this context could allow the identification of specific functional motor activities. Functional activities could be then decomposed into movement components whose characteristics (i.e. patterns of movement) would be associated with functional limitations and motor impairment. The use of accelerometers and more generally of wearable sensors is particularly attractive in this patient population because it would open the possibility of monitoring stroke patients in the

home and the community settings, namely in real-life conditions.

Data from wearable sensors has the potential to augment currently available assessment techniques that are limited to laboratory and clinical settings. Optimal ability measured in the clinic, and actual use of the stroke-affected upper limb in the home are frequently different [7]. Remote monitoring of wearable sensors can collect data in the field and thus may allow for objective assessments of the real life impact of rehabilitation on persons after stroke [8][9][10][10].

The use of wearable systems is particularly appealing as a tool to complement existing clinical outcome measures. As part of our work toward developing methods to monitor post-stroke patients in the home and the community settings based on wearable technology, we present preliminary results in support of the use of quantitative data for assessments recorded during the performance of functional motor tasks. We hypothesize that wearable sensors have the potential to capture characteristics of motor patterns associated with motor impairment and functional limitations in persons after stroke.

II. METHODS

A. Data collection

Eight subjects with upper limb hemiparesis from stroke were recruited for this study based on their current motor ability level, which included at least a rudimentary grasp and release ability. The subjects performed a subset of the tasks outlined by the Wolf Motor Function Test (WMFT) while accelerometer signals were recorded from the affected side of the body.

Prior to recording, each subject was clinically assessed for motor ability. Primary outcome measures included the upper limb section of the Fugl-Meyer test and the qualitative Functional Ability Scale (FAS) of the WMFT for each task. The Fugl-Meyer is a standardized test of post-stroke motor impairment and recovery. The FAS scale of the WMFT is an aggregate measure of the effort, smoothness, and overall quality of motor ability specific to several functional tasks performed with the upper limb.

Accelerometer signals were recorded using the Vitaport ambulatory digital recorder (Temec B.V., the Netherlands). Seven channels were used to capture movement characteristics

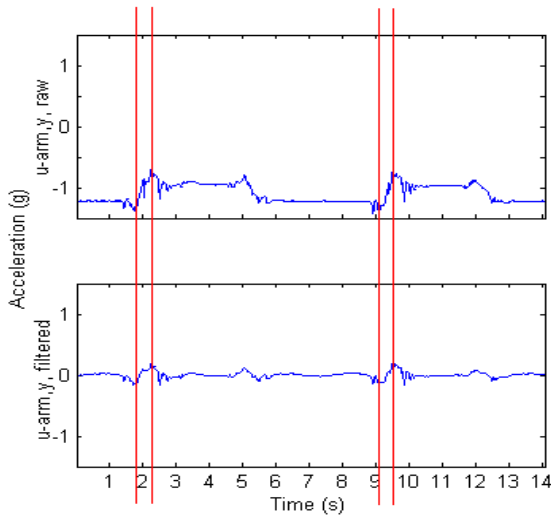


Fig. 1. Accelerometer signals showing the start and end of reaching segments over two repetitions of the proximal front reaching task for a randomly chosen individual. Raw data are shown in the top panel and filtered data are shown in the bottom panel. Data were recorded from the upper arm (U-arm). The signal detected along the longitudinal axis (y) is displayed. Arbitrary units were utilized.

in post-stroke patients. A dual-axis accelerometer was positioned on the hand. Its two axes were transverse to skin surface and longitudinal. A similar accelerometer was located on the forearm with one axis oriented in the anterior-posterior direction and the other axis longitudinal to the body segment. Finally, a sensor was positioned on the upper arm with its axes positioned as per the sensor on the forearm. An eighth channel of the Vitaport was used for a manual push-button marker operated by the experimenter for later segmentation of the data.

We chose to collect quantitative data from two WMFT tasks: reaching to the front and to the side. Seated subjects reached their hands from lap to table, performing five or six repetitions of each task while accelerometer data was collected.

B. Signal processing and analysis

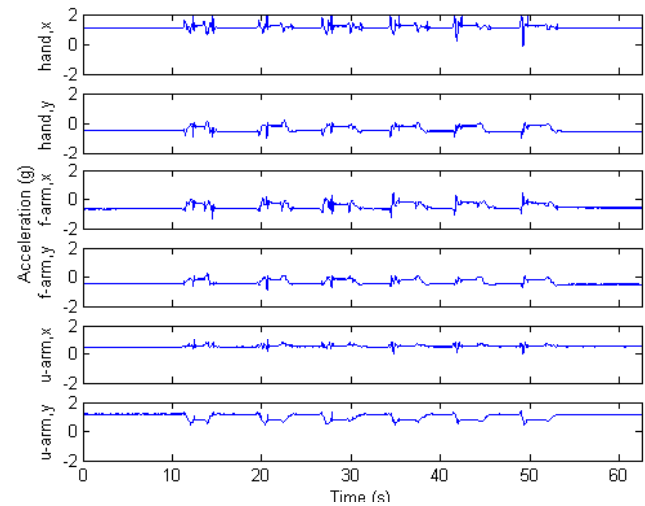
A highpass filter ($f_c = 0.4$ Hz) was first employed to remove the effect of gross orientation changes from the accelerometer signals. Then a lowpass filter ($f_c = 15$ Hz) was applied to remove high frequency noise components affecting the data. After filtering the accelerometer data, we segmented the recordings in order to isolate the reaching portion for each task. Figure 1 shows an example of the segmentation performed on the raw signal (top panel) and on the filtered signal (bottom panel).

Quantitative features were then extracted from the segments. We computed two linear parameters, the root mean square (RMS) value of the accelerometer data and the RMS value of its derivative. The derivative of the accelerometer data is typically referred to as jerk and is used to capture the smoothness of movement. We also computed one non-linear

parameter, the approximate entropy (ApEn) of the accelerometer data. The ApEn value reflects the complexity of movement [12].

Multiple linear regression models were designed to test the hypothesis that linear and nonlinear parameters can account for differences in Fugl-Meyer and FAS scores among patients. In total, 6 models were run for each task based on the accelerometer signals from the hand, forearm, and upper arm. Three models were used to test the ability of linear and non-linear measures to predict differences across patients in Fugl-Meyer scores. Three models were utilized to relate linear and non-linear measures and FAS scores. Six independent variables were used for each model including the linear and non-linear features for each of the two axes of the dual-axis accelerometer positioned on each body segment.

a.



b.

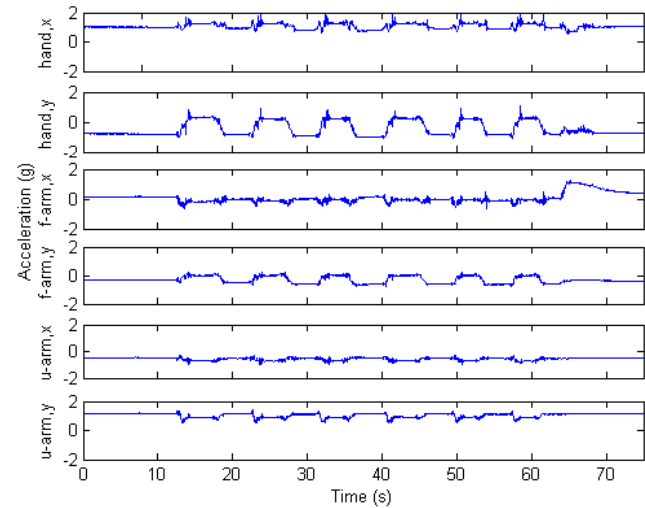


Fig. 2. Accelerometer signals from task 1, proximal side reaching task, 6 repetitions. Representative moderately impaired (a.) and severely impaired (b.) subjects are shown.

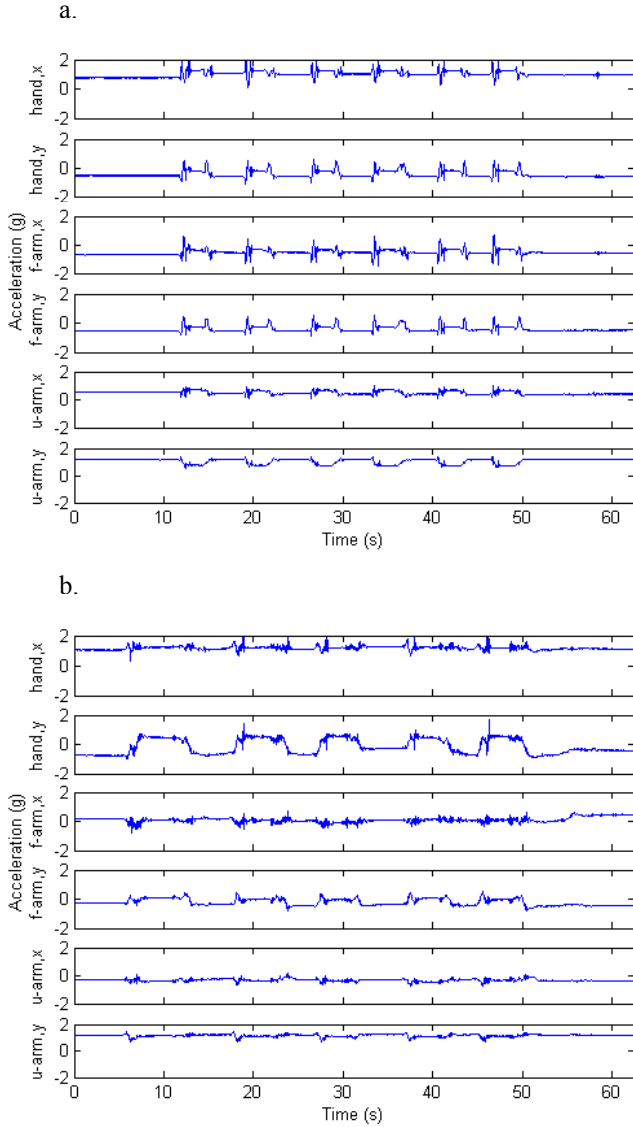


Fig. 3. Accelerometer signals from task 2, proximal front reaching task, 5-6 repetitions. Representative moderately impaired (a.) and severely impaired (b.) subjects are shown.

III. RESULTS

From both Figures 2 and 3, it is clear that the moderately impaired subject demonstrates smoother movements than the severely impaired subject. Overall, the data suggest that different patterns are associated with movements performed by individuals with different levels of motor impairment, thus making it likely that the values of energy (i.e. RMS accelerometer data) and complexity are associated with clinical measures of motor performance.

Tables 1-4 show the results of the analyses performed via linear regression models to establish whether a significant relationship exists between Fugl-Meyer scores and features derived from accelerometer data (Tables 1 and 3) as well as

between FAS scores and features derived from accelerometer data (Tables 2 and 4). Significant correlations are demonstrated by the analysis, indicating that accelerometer data contain features that can be interpreted as characteristic patterns associated with motor impairment and functional limitations.

	RMS ACC (x)	RMS ACC (y)	RMS jerk (x)	RMS jerk (y)	ApEn (x)	ApEn (y)
Hand	<0.01	NS	0.09	NS	<0.01	NS
Forearm	NS	NS	<0.01	NS	NS	NS
Upperarm	NS	0.04	NS	<0.01	NS	NS

Table 1. Results of the multiple linear regression models for task 1. The dependent variable for these three models is the Fugl-Meyer score. Significance is shown for all the independent variables used for the linear regression model: RMS value of the accelerometer data, RMS value of the jerk data, and ApEn of the accelerometer data. Results are shown for the axis oriented in the anterior-posterior direction (x) as well as the longitudinal axis, i.e. the one oriented along the body segment(y). p-values corresponding to significance ($p < 0.05$) and trends ($p < 0.10$) are shown. Otherwise p-values were considered not significant (NS).

	RMS ACC (x)	RMS ACC (y)	RMS jerk (x)	RMS jerk (y)	ApEn (x)	ApEn (y)
Hand	0.06	NS	NS	NS	NS	NS
Forearm	0.05	<0.01	NS	NS	NS	<0.01
Upperarm	NS	NS	NS	NS	NS	NS

Table 2. Results of the multiple linear regression models for task 1. The dependent variable for these three models is the FAS score. Otherwise, the models are the same as those whose results are shown in Table 1.

	RMS ACC (x)	RMS ACC (y)	RMS jerk (x)	RMS jerk (y)	ApEn (x)	ApEn (y)
Hand	0.09	NS	NS	NS	<0.01	0.01
Forearm	NS	0.06	0.05	NS	NS	NS
Upperarm	NS	0.07	NS	NS	NS	NS

Table 3. Results of the multiple linear regression models for task 2. The dependent variable is the Fugl-Meyer score. Data are shown as in Table 1 but for task 2.

	RMS ACC (x)	RMS ACC (y)	RMS jerk (x)	RMS jerk (y)	ApEn (x)	ApEn (y)
Hand	0.01	NS	NS	NS	NS	NS
Forearm	NS	NS	NS	NS	NS	NS
Upperarm	NS	<0.01	<0.01	NS	NS	NS

Table 4. Results of the multiple linear regression models for task 2. The dependent variable is the FAS score. Data are shown as in Table 2 but for task 2.

IV. DISCUSSION

The results summarized in Tables 1-4 support our hypothesis that wearable sensors have the potential to capture characteristics of motor patterns associated with motor impairment and functional limitations. Differences are shown among accelerometer data features and among body segments.

The RMS value of the accelerometer data appears to be more sensitive than the RMS value of the jerk trajectories and the ApEn values to differences in Fugl-Meyer and FAS scores across individuals. Also, features from accelerometer data gathered from distal segments appear to provide better correlation with clinical scores than features from data gathered from proximal segments. In fact, a significant relationship between clinical scores and dependent variables was found more often for features derived from data gathered from the hand compared to the forearm, and from the forearm compared to the upper arm. Although these results are preliminary and analyze only two functional upper limb tasks, they indicate that linear and nonlinear features from accelerometer data capture differences among patients that appear to correlate with clinical measures of functional limitation and motor impairment.

ACKNOWLEDGEMENTS

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