Finger-Worn Sensors for Accurate Functional Assessment of the Upper Limbs in Real-World Settings

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Abstract— **Remote monitoring of stroke survivors' upper limb performance (stroke-affected vs. unaffected limbs) can provide clinicians with information regarding the true impact of rehabilitation in the real-world settings, which allows opportunities to administer individually tailored therapeutic interventions. In this work, we examine the use of finger-worn accelerometers, which are capable of capturing gross-arm as well as fine-hand movements, in order to quantitatively compare the performance of the upper limbs during goal-directed activities of daily living (ADLs). In this proof-of-concept study, data were collected over an eight-hour duration from ten neurologically intact individuals who wore the sensors and continued with their daily living. The sensor-based measure was compared to two clinically validated measures of handedness, i.e., Waterloo Handedness Questionnaire and Fazio Laterality Inventory, that quantify the level of preference of the limbs in performing ADLs. The results yielded statistically significant correlations to the Waterloo and Fazio scores with Pearson correlation coefficients of 0.90 and 0.87 respectively, which was substantially superior compared to the previously studied measure based on wrist-worn accelerometers. We believe this study presents an opportunity to accurately monitor the goal-directed use of the upper limbs in the real-world settings.**

I. INTRODUCTION

Stroke affects approximately 800,000 individuals in the U.S. alone [1]. It is a prominent cause of long-term disability in adults, where approximately 60% of stroke survivors suffer from upper limb paresis [2]. Upper limb paresis often impacts the performance of essential activities of daily living (ADL), such as bathing, dressing, eating, and brushing teeth. As a result, it can cause a significant deterioration in the overall quality of life [3].

The use of wrist-worn accelerometers has become an increasingly popular method for monitoring stroke survivors' upper limb performance in the home and community settings. It allows clinicians to provide optimal therapeutic interventions that can maximize patients' motor performance [4]. Parameters, such as the amount of unilateral activities of each limb, the amount of bimanual activities of both limbs, and the acceleration magnitude ratio between the two limbs, have been studied to assess the real-world upper limb performance. Previous studies have reported significant correlations between these sensor measurements to self-reported measurements of arm use in the real-world setting (e.g., Motor Activity Log and a subscale of Stroke Impact Scale) [5] and significant differences in the amount of limb use between stroke survivors and non-disabled healthy individuals [4]. The measurements from wrist-worn accelerometers, however, contain a high level of noise, as these sensors mainly capture gross-arm movements and fail to differentiate goal-directed use of the limbs vs. passive movements (e.g., arm swing during locomotion) [6]. This may result in the overestimation of movement intensity and the inability to capture small changes in the upper limb performance [7].

To address this fundamental limitation of wrist-worn accelerometers, our group has previously explored and validated the use of finger-worn accelerometers [8], [9]. These finger-worn sensors allowed us to capture both gross-arm and fine-hand movements that are more closely associated with the performance of essential ADLs and functional motor capacity. In this work, we deploy our finger-worn sensor in healthy individuals in their home and community settings, and validate its efficacy in capturing goal-directed use of the upper limbs. Specifically, we propose and validate our sensor-based measurement against two clinically validated, self-reported measures of handedness that quantify the level of preference of the two (right vs. left) limbs in performing various types of goal-directed ADLs. We hypothesize that, by focusing on quantifying the unimanual activities of the hand and arm, we can effectively eliminate noise in the sensor recordings that may be introduced by non-goal-directed and/or passive movements, thus allowing an accurate, comparative assessment of the performance of the two limbs. The secondary objective of this paper is to show that wrist-worn accelerometers provide limited information regarding the performance of the limbs for goal-directed ADLs compared to our finger-worn accelerometer. Based on the referent results found in this work, our ultimate vision is to apply the proposed technology to stroke survivors and monitor the use of their stroke-affected vs. non-affected upper limbs.

II. METHODS

A. Sensor System

This paper employed a miniaturized finger-worn sensor (Arcus, ArcSecond Inc., USA) that contained a nine-axis inertial measurement unit (IMU), a local memory for data storage (i.e., SD card), a 170 mAh battery, and an ultra-low-power 32-bit microcontroller, encapsulated in a waterproof enclosure (see Fig. 1). In this study, only the three-axis accelerometer was used for data collection while the gyroscope and magnetometer were disabled. Previous studies (including

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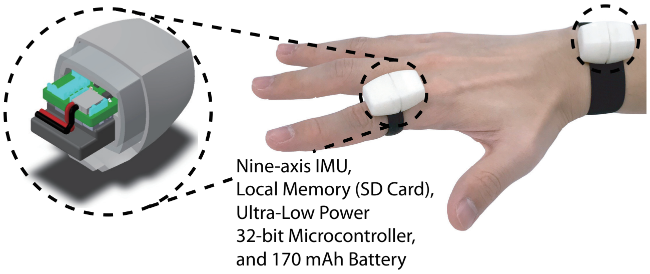

Fig. 1: Miniaturized finger-worn and wrist-worn accelerometers that were used in the data collection process. The sensors contained a nine-axis accelerometer, local memory for data storage (i.e., SD card), a 170 mAh battery, and an ultra-low-power microcontroller (Arcus, ArcSecond Inc., USA), but we utilized only the three-axis accelerometer for the data collection and analyses.

our own) support the feasibility of accurate assessment of upper limb movements based only on accelerometer data [4], [8]. Furthermore, accelerometers require significantly less battery power compared to gyroscopes (microwatts vs. milliwatts), which is necessary for continuous monitoring of upper limb movement for at least eight hours per day. The accelerometer data were sampled at 67Hz and stored in the SD card. The same sensing components were encased in a wrist-worn form factor – the most conventionally used wearable form factor to monitor upper limb performance – in order to enable a comparative analysis.

B. Data Collection

A total of 10 healthy individuals between the ages of 18-40 were recruited from the University of Massachusetts Amherst. All individuals were recruited by word of mouth and had no major health issues that affected their ability to perform motor tasks independently. All subjects read and signed a written consent form. All study procedures were approved by the Institutional Review Board of the institute.

When subjects arrived at the Advanced Human & Health Analytics (AHHA) Laboratory, they were asked to complete the Waterloo Handedness Questionnaire [10] and Fazio Laterality Inventory [11] to evaluate their handedness. Handedness is generally defined as the upper limb preference when performing various ADLs. We employed these two self-reported outcome measures for the handedness to replicate the clinical standards for assessing real-world upper limb function in stroke patients, namely the Motor Activity Log (MAL) [12]. Specifically, the Amount of Use (AOU) scale of the MAL asks stroke survivors to self-evaluate their use of the impaired vs. unimpaired limbs in the real-world setting during 14 essential ADLs (e.g., towel, brushing teeth, picking up a glass, etc.), which is similar to the aim of handedness questionnaires that measure the use of the dominant vs. non-dominant limbs.

The Waterloo Handedness Questionnaire asks individuals the degree to which they prefer to use the right vs. left upper limbs during 36 different ADLs. The response for each question includes five options: right always or left always (i.e., 95% or more of the time), right usually or left usually (i.e., 75% or more of the time), and equal often (i.e., use each hand about 50% of the time). Each item of the Waterloo questionnaire is scored as the following: right always (+2), right usually (+1), equal use of both hand (0), left always (-2), left usually (-1). The final handedness score was calculated by summing up all responses, which ranges from -72 (pure left-handed) to +72 (pure right-handed).

The Fazio Laterality Inventory asks individuals about the percentage (0% to 100%) of time that they use their right limb during 10 different ADLs. The responses from the 10 items were then averaged to represent the overall handedness score. The computed value ranges from 0 to 100 (i.e., 0 for pure left-handed, 100 for pure right-handed).

After completing the handedness tests, subjects were bilaterally equipped with our sensors on the index fingers and wrists. Subjects were instructed to wear the sensors for an eight-hour period and to go about their normal daily routine. Upon completion of the study, subjects returned to the AHHA Lab to return the sensors. The accelerometer data stored in the SD cards were downloaded for off-line analyses.

C. Objective Quantification of the Goal-Directed Upper Limb Use

In this section, we discuss the analytic methodology used to quantitatively compare the use of the two upper limbs during goal-directed ADLs based on the data collected from our finger-worn sensor. First, we applied a sixth order Butterworth low-pass filter with a cutoff frequency at 8 Hz to remove any non-human-generated noise in the accelerometer data. Then, we employed a sliding window with a length of one second without overlap to down-sample the data to 1 Hz, which has been previously studied and determined as a adequate sampling rate to compare the goal-directed use of the two limbs [4]. The gravity-free acceleration magnitude was computed at each t (i.e., each second): $|a_r[t]| = \sqrt{a_{r,x}^2[t] + a_{r,y}^2[t] + a_{r,z}^2[t]} - g$ and $|a_l[t]| = \sqrt{a_{l,x}^2[t] + a_{l,y}^2[t] + a_{l,z}^2[t]} - g$ for the right and left limbs, respectively. g represents the gravity. The gravity-free acceleration magnitude of the sensor on the right limb was divided by that of the left limb (i.e., $(|a_r[t]|/|a_l[t]|)$ to compute the relative use of the two limbs, similarly to the method used in [4]. A natural logarithm was applied to the calculated the magnitude ratio in order to make the measurement symmetric to the value ratio between $|a_r[t]|$ and $|a_l[t]|$ (preventing the underestimation of the denominator) [5]:

$$r[t] = \ln\left(\frac{|a_r[t]|}{|a_l[t]|}\right) = \ln\left(|a_r[t]|\right) - \ln\left(|a_l[t]|\right).$$

The value of $r[t]$ was used to detect the performance of unimanual ADLs (i.e., ADLs that involved the substantial use of one side of the hands and arms) captured by our finger-worn accelerometer. When the absolute value of $r[t]$ was greater than a certain threshold ($|r[t]| > \delta$), the ADL at t was determined as a unimanual activity. Currently, there's no reported value of δ in the literature that can be used to determine whether the performed activity at t is bimanual or unimanual. However, the results reported in [13] show

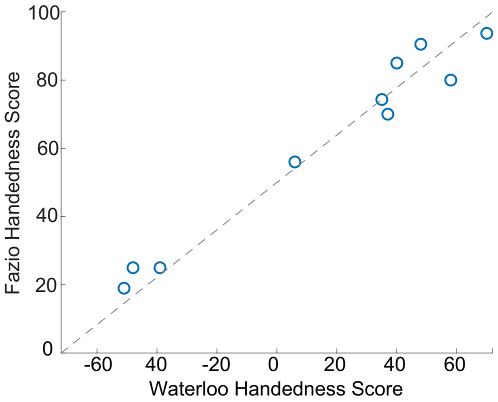

Fig. 2: A scatter plot for the two handedness scores, i.e., Waterloo and Fazio scores, obtained from the participated subjects. The two scores showed a nearly perfect correlation with a Pearson correlation coefficient of 0.98.

that the threshold may vary approximately from 0.3 to 1.5. Thus, we performed a brute-force search to find the optimal value of δ (i.e., the best correlation to the handedness scores) within this range. Given the optimal value of δ, which will be discussed in detail in Section III, the movement intensity of the two limbs during the performance of unimanual ADLs throughout the eight hours of data collection were compared :

$$M = \sum_{t \in \{|r[t]| > \delta\}} |a_r[t]| - \sum_{t \in \{|r[t]| > \delta\}} |a_l[t]|.$$

When the value of M is positive, it indicates that a subject makes use of the right limb (arm and hand) more frequently and intensely to perform unimanual ADLs. Similarly, the negative value of M indicates more frequent and intense use of the left limb. When the value of M is close to zero, it indicates that the subject uses the two limbs to perform different types of unimanual ADLs but with approximately equal frequency and intensity (e.g., using the right limb for brushing teeth while the left limb for using utensils). The proposed metric M obtained from our finger-worn sensor was compared to the median value of $r[t]$ obtained from the wrist-worn sensor (without any δ), which has been previously used to quantify the relative (or preferred) use of the two limbs [4].

III. RESULTS

Fig. 2 shows a scatter plot of the two handedness scores considered in this work (i.e., Waterloo and Fazio scores). The two scores showed a nearly perfect correlation with a Pearson correlation coefficient of 0.98, indicating that the handedness scores obtained from the participated subjects provided reliable measures of the preferred limb use during the performance of ADLs.

Fig. 3 compares the proposed objective measure (i.e., M) of the comparative use of the two limbs during goal-directed ADLs against the two self-administrated handedness scores obtained by the Waterloo and Fazio questionnaires. Each data point in the scatter plot represents the measurements of a single subject. The proposed measure showed a statistically significant correlation to both the Waterloo handedness score ($p < 4.6 \times 10^{-4}$ with a Pearson correlation coefficient of 0.90) and the Fazio handedness score ($p < 1.1 \times 10^{-3}$ with a Pearson correlation coefficient of 0.87). These results support that the proposed measure based on our finger-worn sensor could provide an accurate assessment of the comparative use of the two limbs during goal-directed ADLs. The optimal value of δ used to derive this result was 0.5, which provided the maximum Pearson correlation coefficient within the range of $0.3 \leq \delta \leq 1.5$ (incremented by 0.01). The Pearson correlation coefficients within this range showed small variation with 0.88 ± 0.02 and 0.85 ± 0.02 against the Waterloo and Fazio handedness test scores, respectively.

Fig. 4 compares the correlation coefficients of the proposed measure M obtained from the finger-worn sensor vs. the median $r[t]$ of the wrist-worn sensor (i.e., the measure used in [4]) against the two handedness scores. The finger-worn sensor yielded significantly superior correlations to the handedness scores compared to the wrist-worn sensor: wrist sensor-based measure showed Pearson correlation coefficients of 0.06 and 0.002 to Waterloo and Fazio scores, respectively. These results support that finger-worn sensors would capture the goal-directed (or preferred) use of the limbs more reliably compared to the wrist-worn sensor.

IV. CONCLUSION

In this paper, we introduced a novel use of finger-worn accelerometers to quantitatively compare the use of the upper limbs during goal-directed ADLs in the real-world setting. Specifically, we proposed a metric that compares the intensity of the two limbs (both hand and arm) during the performance of bimanual ADLs. The results presented herein show that the proposed finger-worn sensor has great potential to accurately monitor the goal-directed use of the upper limbs, which is particularly important in understanding stroke survivors' ability to perform ADLs and live independently.

There are some limitations worth noting. First, this pilot study involved a small number of young healthy individuals (three left-hand dominant and seven right-hand dominant according to the two handedness tests), indicating that the presented results may not be used to generalize the overall healthy population. Second, the proposed method may discard information regarding the simultaneous use of the two limbs during ADLs (i.e., $|r[t]| < \delta$), such as lifting a box with two limbs, which are also purposeful, goal-directed activities. It is particularly difficult to accurately capture the performance of these bimanual ADLs based on one or two wearable sensors with limited dimensions of information (e.g., three-axis acceleration in the sensor's local coordinate frame), since many passive movements, such as arm swing during gait, also involve two limbs. It may be possible to detect the purposefulness of the bimanual activities based on machine learning-based classification algorithms by aggregating data from multiple sensors. However, it requires heavy communication and computational throughput. Thus, we argue in this paper that simply focusing on capturing the movement intensity during unimanual activities would

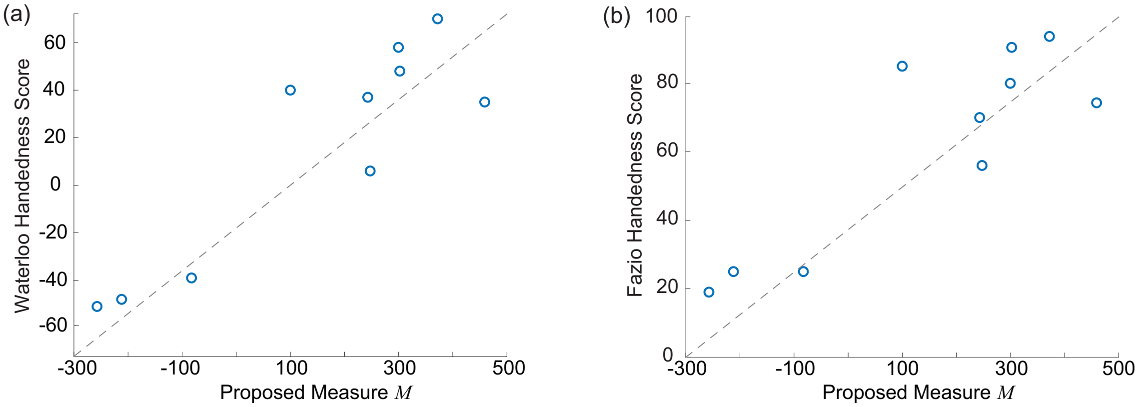

Fig. 3: (a) A scatter plot between the proposed measure M that quantifies the relative goal-directed use of the two limbs vs. the Waterloo handedness score (Pearson correlation coefficient of 0.90 with a $p < 4.6 \times 10^{-4}$). (b) A scatter plot between the proposed measure M vs. the Fazio handedness score (Pearson correlation coefficient of 0.87 with $p < 1.1 \times 10^{-3}$)

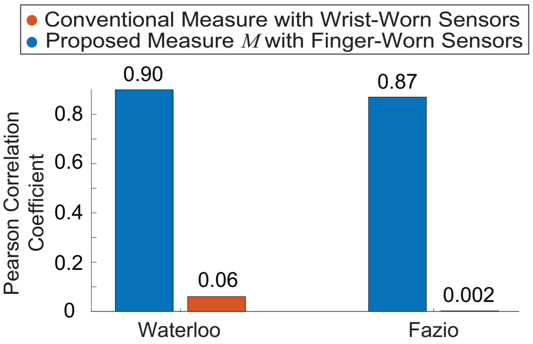

Fig. 4: The comparison of correlation coefficients to the two handedness scores between the proposed measure M obtained from the finger-worn sensor vs. the median $r[t]$ of the wrist-worn sensor (i.e., the metric used in [4]). These results support that finger-worn sensors would capture the goal-directed (or preferred) use of the limbs more reliably compared to the wrist-worn sensor.

provide more accurate information regarding the comparative use of the two limbs.

The ultimate vision of this study is to continuously monitor the goal-directed use of the stroke-affected vs unaffected limbs in individuals post-stroke. We believe that our finger-worn sensor enables an opportunity to accurately analyze the purposeful use of the two limbs during ADLs, such that individually tailored therapeutic interventions could be provided to patients to maximize their functional performance in the real-world settings.

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