Title

The Variable Relationship between Arm and Hand Use: A Rationale for Using Finger Magnetometry to Complement Wrist Accelerometry When Measuring Daily Use of the Upper Extremity

Authors

Rowe, Justin B
Friedman, Nizan
Chan, Vicky
et al.

Publication Date

2014

DOI

10.1109/embc.2014.6944522

The Variable Relationship between Arm and Hand Use: A Rationale for Using Finger Magnetometry to Complement Wrist Accelerometry when Measuring Daily Use of the Upper Extremity

Justin B. Rowe, Nizan Friedman, Vicky Chan, Steven C. Cramer, Mark Bachman, David J. Reinkensmeyer

***Abstract*—Wrist-worn accelerometers are becoming more prevalent as a means to assess use of the impaired upper extremity in daily life after stroke. However, wrist accelerometry does not measure joint movements of the hand, which are integral to functional use of the upper extremity. In this study, we used a custom-built, non-obtrusive device called the manumeter to measure both arm use (via wrist accelerometry) and hand use (via finger magnetometry) of a group of unimpaired subjects while they performed twelve motor tasks at three intensities. We also gave the devices to four stroke subjects and asked them to wear them for six hours a day for one month. From the in-lab testing we found that arm use was a strong predictor of hand use for individual tasks, but that the slope of the relationship varied by up to a factor of ~12 depending on the task being performed. Consistent with this, in the daily use data collected from stroke subjects we found a broad spread in the relationship between arm and hand use. These results suggest that analyzing the spread of the relationship between daily hand and arm use will give more insight into upper extremity recovery than wrist accelerometry or finger magnetometry alone, because the spread reflects the nature of the daily tasks performed as well as the amount of upper extremity use.**

I. Introduction

In order to develop effective therapies for individuals with stroke-related hemiparesis it is important to be able to quantitatively describe how they use their upper extremity in real life. Most studies that attempt to quantify upper extremity movement ability rely on measures of motor capacity obtained through in-lab assessments such as the Fugl-Meyer test, the Wolf-Motor test, or the ARAT[1]–[3]. While informative [4], these tests do not necessarily reflect the way that subjects use their impaired limbs in their day to day lives [5]–[7]. Rather these tests assess the subjects' ability to perform a subset of predefined tasks when they are forced to do those tasks with their impaired limb.

To address these concerns, researchers have begun to supplement their tests of motor capacity with tests that focus on subjects' actual use of their impaired limbs in daily life [8]. Wrist accelerometry is becoming a widely used tool to monitor subject's unrestricted limb use outside the lab [9]–[12]. In wrist accelerometry, non-obtrusive data-loggers worn on the wrists of one or both arms are used to measure and record the accelerations of the arms over extended periods of time [12]. In some implementations, the amount of use is determined from the magnitude of the accelerations observed, and in others movement is treated as a Boolean value and the devices are used to determine what percent of the time the accelerations were above a predetermined threshold [12].

One potential limitation of wrist accelerometry is that it does not measure the joint movements of the wrist and fingers, which are regularly used in functional activity. If the accelerometers are worn on the hand rather than the wrist, it is still not possible to isolate the joint movements of the wrist and fingers, as the accelerations and orientation changes are due to both proximal and distal joint movement. Sensing systems spanning multiple finger joints can measure finger movement [13], but are obtrusive, making it difficult to use them to measure long term daily use outside the lab.

To address these concerns we recently developed a new type of non-obtrusive, wrist-worn device for monitoring upper extremity use over long periods of time in an uncontrolled environment [14]. Like traditional wrist accelerometry devices, this device, called the manumeter, logs data from an accelerometer worn on the wrist. However, the manumeter uses magnetic sensors worn at the wrist in combination with a magnetic ring worn on the finger to monitor joint movements of the wrist and fingers.

The purpose of this study was to examine whether such a granular device is useful for quantifying upper extremity use. Given that the hand is the end effector of the arm, it might be reasonable to assume that the arm and hand are used proportionally. Thus, the goals of the present study were to 1) determine the relationship between arm and hand use and 2) determine to what extent adding an estimate of hand use adds information beyond that obtained using wrist accelerometry

II. Methods

A. In-lab testing with unimpaired subjects

Measures of arm use and hand use were collected from seven unimpaired male subjects (23.3 + /- 3.4 years of age) as they performed the following twelve activities, which were chosen on an ad hoc basis to represent typical daily activities involving the upper extremity:

1. Simulated eating of 10 goldfish crackers one at a time.
2. Fully flex and extend fingers 10 times.
3. Remove and replace five bills and ten coins from a wallet one at a time.
4. Flip and deal 30 playing cards to new pile.
5. Open and close a door eight times.

Funded by NIH-R01HD062744-01 from the National Center for Medical Rehabilitation Research, part of the Eunice Kennedy Shriver National Institute of Child Health and Human Development

J B Rowe is with the Department of Biomedical Engineering, University of California, Irvine, CA 92697 USA, (e-mail: jbrowe@uci.edu)

N Friedman was with the Department of Biomedical Engineering, UC Irvine

V Chan is a physical therapist with the UC Irvine

S C Cramer is with the Department of Neurology at UC Irvine

M Bachman is with the Department of Electrical Engineering at UC Irvine

D J Reinkensmeyer is with the Department of Mechanical and Aerospace Engineering at UC Irvine

978-1-4244-7929-0/14/$26.00 ©2014 IEEE

6. Pour 6 oz. of water from one cup to another spaced 12 inches away 8 times.
7. Move wrist through full radial/ulnar deviation 10 times.
8. Tie and untie the shoelaces of a provided shoe 3 times.
9. Type the phrase “The quick brown fox jumped over the lazy dogs” 6 times.
10. Lay the hand flat and remaining still for two minutes.
11. Fully flex and extend the wrist 10 times.
12. Writing the phrase “The quick brown fox jumped over the lazy dogs” 3 times.

Subjects performed the entire set of tasks three times at three different intensity levels. The number of repetitions indicated above for each task defined the number of movements for the low intensity level. At the medium intensity level, the number of repetitions was doubled and at the high intensity level the number of repetitions was tripled. To reduce order and learning effects, the presentation order of the three intensity levels was randomized across subjects. During all tasks, the subjects wore a custom built device for monitoring arm and hand use called the manumeter (Fig. 1). The manumeter includes a tri-axial accelerometer (Analog Devices adxl335) used to obtain estimates of gross arm use. It also has a pair of tri-axial magnetometers (Honeywell hmc5883l) which are used in combination with a magnetic ring to obtain estimates of wrist and hand use, as described in [14]. All raw data for this experiment were collected at a rate of 30Hz and were stored locally on the manumeter before being copied to a computer at the end of each trial.

B. Data collection and analysis

Estimates of arm use were obtained using the accelerometer. Data from the accelerometer were sampled by a microcontroller on the manumeter and stored locally on an sd-card. Once collected, the data from the accelerometer were processed using a widely-used method similar to that described by [15]. Typical factory values for the device’s sensitivities and offsets were used to convert the raw voltage measurements into units of Earth’s acceleration due to gravity (g). After converting the data, we used a low pass Butterworth filter with a cutoff frequency of 5 Hz to remove high frequency noise unrelated to arm movement. We then calculated the magnitude of each accelerometer measurement and subtracted off the expected 1g of acceleration due to the earth’s gravity. By computing the magnitude of the acceleration measurements we isolated the movement related changes in the signal from the orientation related changes. Finally we segmented the accelerometer data into two second long epochs and summed it. For epochs in which the summed magnitude did not exceed a threshold of 2g the score for that epoch was set to zero. Otherwise, the score for the epoch was set to the integrated magnitude. We defined the total arm use score for a trial as the sum of the scores for each epoch.

Estimates of hand use were obtained using data collected from the two magnetometers located on either end of the manumeter. These magnetometers measured changes in the local magnetic field caused by movement of a magnetic ring worn on the index finger. To isolate the signal changes due to movement of the ring from those caused by movement of the manumeter relative to the earth’s magnetic field, we subtracted the field measurements collected by the rear

Figure 2. The manumeter is an activity monitoring device worn on the wrist that is equipped with an accelerometer for quantifying arm movement and a pair of magnetometers that quantify movement of the wrist and fingers by sensing the magnetic field changes due to a magnetic ring worn on the finger.

magnetometer from those collected by the front magnetometer. This allowed us to reject any fields affecting both sensors equally without losing the signals produced by smaller and more local magnetic fields.

We processed the data collected from the magnetometers to obtain estimates of the distance traveled by the finger in flexion/extension and by wrist in both flexion/extension and radial/ulnar deviation (see [14] for details). Briefly, we fed the differential signal taken between the two magnetometers into a radial basis function network trained to map magnetometer measurements to joint angle estimates. We then took the sum of the absolute value of the change in joint angle to get the distance traveled by each joint. Finally, we defined the total distance traveled across all measured degrees of freedom as the indicator of hand use.

C. Monitoring daily use of stroke subjects

In addition to the in-lab testing performed with the seven unimpaired subjects, manumeters were given to four stroke subjects to use at home on a daily basis for approximately one month. Their ages were 57, 55, 57, and 59, and their Box and Blocks (BB) scores were 43, 25, 8, and 3. The BB assessment tests how many blocks they could transport in a 1 minute period; a normal score is about 70. In addition to the manumeter, the subjects were given an Android tablet computer capable of copying data off of a manumeter, processing that data, and providing the subjects with feedback of their hand use (Fig. 2). Subjects were instructed to wear the device for six hours a day and to switch back and forth between wearing the device on their impaired and less impaired hand at the beginning of every day.

Before sending them home with the subjects, the devices were calibrated to measure the subjects hand movements using the methods described in [14]. Separate calibrations were made for each hand and for each of the two possible orientations of the magnetic ring (positive pole facing the tip

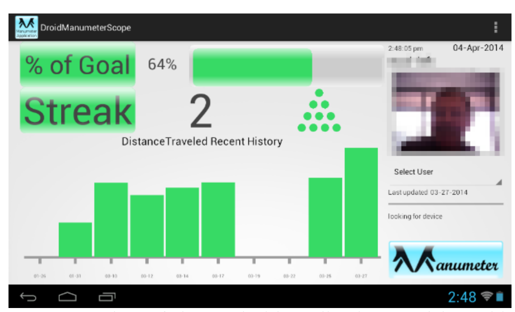

Figure 1. Screenshot of the Android application used by subjects to download and display data from the manumeter at the end of each day.

of the index finger vs positive pole facing the base of the index finger) – resulting in a total of four calibrations. The collected data were processed in 15 minute batches, and the calibration used for each batch was selected by computing the distance between the mean of the differential magnetometer data for the given batch to that of the data used to create each calibration and then picking the closest calibration.

For the in-lab data, we used a mixed-measures-ANOVA to test the relationship between arm use and hand use and to determine whether the task being performed and/or the subject performing the task affected this relationship. Hand use was treated as the response of the ANOVA model. Arm use, the task being performed, and the subject performing the task were all treated as factors. Random effects were applied to the arm use and subject factors, and repeated measures were applied to the subject factor.

To analyze the data collected from stroke subjects outside the lab, we first segmented each data set into five minute bins. For each bin we used the accelerometry data to estimate arm use and the magnetometer data to estimate hand use. To determine the relationship between arm and hand use we ran regression tests for each subject using arm use as the predictor and hand use as the response. We used Pierce's criteria [16] to identify and remove outliers caused by wearing the manumeter incorrectly (e.g. wearing the watch backwards or without the ring). Two datasets were flagged and removed for subject 2 and one subject 4.

III. Results

For the in-lab testing with unimpaired participants, the amount of arm use and the task being performed made statistically significant contributions to the model's ability to predict hand use ($p = 0.002$ and 0.003, respectively). This result suggests that although there is a relationship between arm use and hand use, the nature of this relationship varies depending on the task being performed. As illustrated in Fig. 3, the slope of hand to arm use for fine manipulation tasks like typing and flipping a deck of cards was ~12 times higher than the slope for arm movement oriented tasks writing.

For the community-based testing with the stroke participants, there was a wide spread in the relationship between hand and arm use, consistent with the concept that the relationship depended on the tasks being performed in the measured 5 min epoch (Fig. 4, $R^2 < 0.2$ for all). For subjects 1-3 the average amount of arm use for the unimpaired limb was significantly higher than that of the impaired limb, however, the opposite was true of subject 4 ($p < 0.001$), paired Student's t-test). Subject 4 was also unique because he exhibited significantly less arm movement overall than any of the other three for the unimpaired arm ($p < 0.001$). For all subjects the total amount of hand use of the unimpaired limb was significantly higher than that of the impaired limb. The relationship between arm and hand use was significant for both hands for all subjects ($p < 0.001$).

IV. Discussion

We examined the relationship between arm use as measured using wrist accelerometry and hand use as measured using finger magnetometry, which are both sufficiently non-obtrusive to be used outside the lab on a daily basis. In both the clearly defined motor tasks performed in the lab by unimpaired subjects, and in the unconstrained upper extremity use sampled from the daily lives of stroke subjects outside of the lab, accelerometry and magnetometry proved to be complementary technologies.

For the in-lab testing, arm use significantly predicted hand use. However, the slope of hand versus arm use varied substantially (by more than a factor of 12) with the task being performed. Thus, there are some behaviors that wrist accelerometry measures well, but other behaviors that finger magnetometry is much more sensitive at measuring. This suggests that the two sensing approaches complement one another. Not only can the one fill in the other's blind spots, but when considered together they give better insight into the type of task being performed. For example, a higher slope indicates a greater use of distal joints of the upper limb, and thus provides insight into patterns of recovery after stroke.

The task-dependent relationship between arm and hand use observed in the lab can be used to interpret the unrestricted daily use pattern of the upper extremity by subjects with stroke. The coefficient of determinations (R^2) for the relationship between hand and arm use were low for all subjects and arms, indicating a high amount of

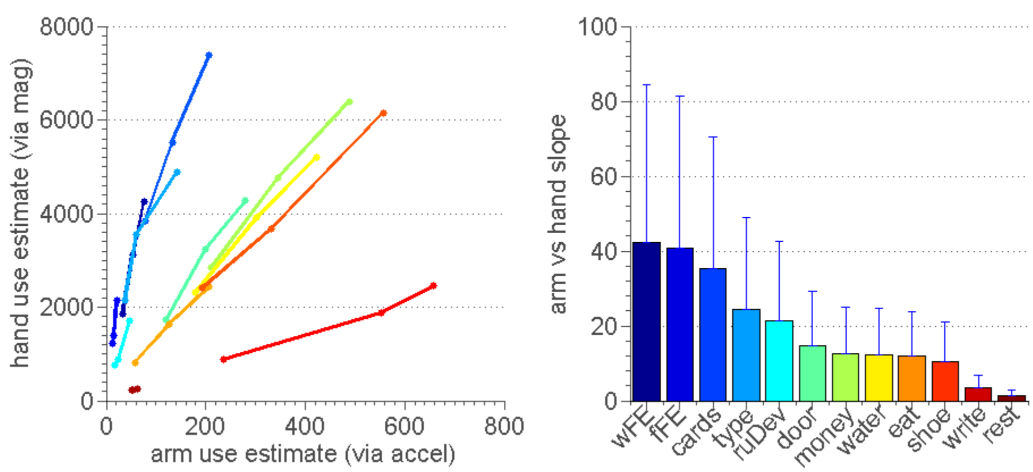

Figure 3. Results from lab-based testing. The left plot shows average estimates of hand use via magnetoetry vs arm use via accelerometery for each of the twelve tasks. The bottom plot shows the slopes of the lines fit to the hand vs arm use data for each task. The error bars on the bottom plot show the confidence intervals of the line fits, and the colors of the lines in the top plot match their corresponding bars in the bottom plot.

unexplained variance in the model. We would expect this wide spread given the dependence of this relationship on the task being performed, and the fact that the individuals with stroke performed many tasks throughout the day.

We note that both modalities still have a key limitation because they rely on the assumption that more movement means more use. Although this is often the case, it is not universally true because the arm and hand are often used without moving them. This is illustrated by the results of the hand writing task shown in Fig. 3. Despite the fact that handwriting clearly requires hand function, the actual wrist and finger movements involved in handwriting are small. Thus, the estimates of hand use measured by the manumeter for the handwriting task were relatively low despite the fact that it was one of the most hand-use intensive tasks in the set.

V. Conclusion

In conclusion, we found that arm use as detected by a wrist accelerometer correlates with hand use as detected by finger magnetometry for individual tasks, but the slope of the relationship depends on the task being performed. This helps explain our further finding that individuals with stroke exhibit a wide spread in the relationship between hand and arm use in daily life. Quantifying and analyzing the shape of this spread will likely give more insight into recovery than wrist accelerometry or finger manumetry alone because it relates to the content of the daily tasks performed and the relative frequency of hand versus arm movement (via the spread) as well as the amount of upper extremity use (via the centroid).

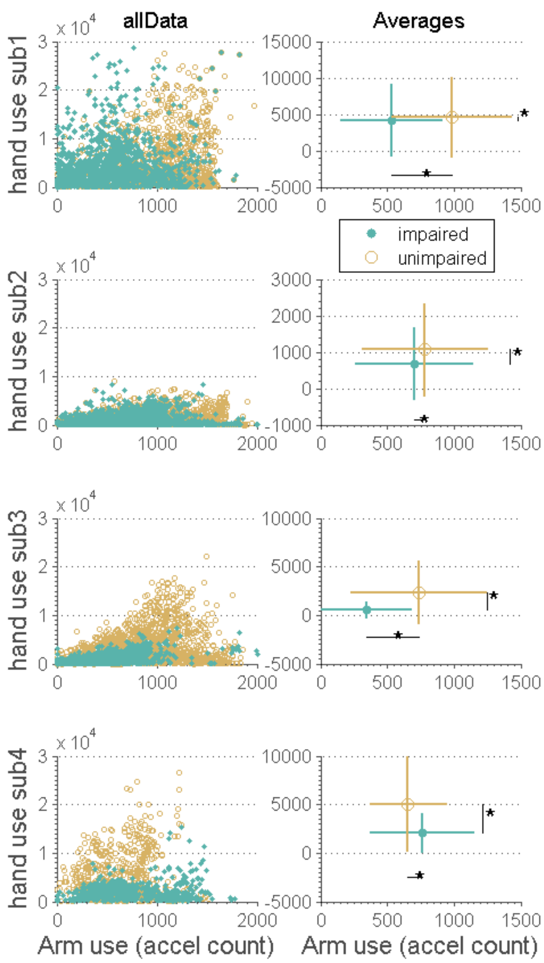

Figure 4. The left column shows arm use vs hand use estimates obtained using the magnetometers and accelerometer respectively for the impaired and unimpaired arms of four stroke subjects. The right column shows the means and variances of each of the point clouds in the left column. The box and blocks scores of these four subjects (in order) were 43, 25, 8, and 3.

References

A. R. Fugl-Meyer, L. Jääskö, I. Leyman, S. Olsson, and S. Steglind, "The post-stroke hemiplegic patient. 1. a method for evaluation of physical performance.," *Scand. J. Rehabil. Med.*, vol. 7, no. 1, pp. 13–31, Jan. 1975.

[2] S. L. Wolf, P. A. Catlin, M. Ellis, A. L. Archer, B. Morgan, and A. Piacentino, "Assessing Wolf motor function test as outcome measure for research in patients after stroke.," *Stroke.*, vol. 32, no. 7, pp. 1635–9, Jul. 2001.

[3] R. C. Lyle, "A performance test for assessment of upper limb function in physical rehabilitation treatment and research.," *Int. J. Rehabil. Res.*, vol. 4, no. 4, pp. 483–92, Jan. 1981.

[4] N. Gebruers, C. Vanroy, S. Truijen, S. Engelborghs, and P. P. De Deyn, "Monitoring of physical activity after stroke: a systematic review of accelerometry-based measures.," *Arch. Phys. Med. Rehabil.*, vol. 91, no. 2, pp. 288–97, Feb. 2010.

[5] C. E. Han, S. Kim, S. Chen, Y.-H. Lai, J.-Y. Lee, R. Osu, C. J. Winstein, and N. Schweighofer, "Quantifying arm nonuse in individuals poststroke.," *Neurorehabil. Neural Repair*, vol. 27, no. 5, pp. 439–47, Jun. 2013.

[6] K. Andrews and J. Stewart, "Stroke recovery: he can but does he?," *Rheumatol. Rehabil.*, vol. 18, no. 1, pp. 43–8, Feb. 1979.

[7] E. Taub, J. E. Crago, and G. Uswatte, "Constraint-induced movement therapy: A new approach to treatment in physical rehabilitation.," *Rehabil. Psychol.*, vol. 43, no. 2, pp. 157–170, 1998.

[8] G. Uswatte, E. Taub, D. Morris, K. Light, and P. A. Thompson, "The Motor Activity Log-28: assessing daily use of the hemiparetic arm after stroke.," *Neurology*, vol. 67, no. 7, pp. 1189–94, Oct. 2006.

[9] R. J. Seitz, T. Hildebold, and K. Simeria, "Spontaneous arm movement activity assessed by accelerometry is a marker for early recovery after stroke.," *J. Neurol.*, vol. 258, no. 3, pp. 457–63, Mar. 2011.

[10] G. Thrane, N. Emaus, T. Askim, and A. Anke, "Arm use in patients with subacute stroke monitored by accelerometry: Association with motor impairment and influence on self-dependence - Abstract - Journal of Rehabilitation Medicine - Content," *J. Rehabil. Med.*, vol. 43, pp. 299–304, 2011.

[11] G. Uswatte, W. H. Miltner, B. Foo, M. Varma, S. Moran, and E. Taub, "Objective measurement of functional upper-extremity movement using accelerometer recordings transformed with a threshold filter.," *Stroke.*, vol. 31, no. 3, pp. 662–7, Mar. 2000.

[12] C. E. Lang and M. O. Saint Louis, "Assessment of upper extremity impairment, function, and activity following stroke: Foundations for clinical decision making," *J. Hand Surg. Br. Eur. Vol.*, pp. 1–21, 2013.

[13] H. G. Kortier, V. I. Sluiter, D. Roetenberg, and P. H. Veltink, "Assessment of hand kinematics using inertial and magnetic sensors.," *J. Neuroeng. Rehabil.*, vol. 11, no. 1, p. 70, Jan. 2014.

[14] J. B. Rowe, N. Friedman, M. Bachman, and D. J. Reinkensmeyer, "The Manumeter: a non-obtrusive wearable device for monitoring spontaneous use of the wrist and fingers.," *IEEE Int. Conf. Rehabil. Robot.*, vol. 2013, p. 6650397, Jun. 2013.

[15] S. C. van der Pas, J. A. Verbunt, D. E. Breukelaar, R. van Woerden, and H. A. Seelen, "Assessment of arm activity using triaxial accelerometry in patients with a stroke.," *Arch. Phys. Med. Rehabil.*, vol. 92, no. 9, pp. 1437–42, Sep. 2011.

[16] B. Peirce, "Criterion for the rejection of doubtful observations," *Astron. J.*, 1852.