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Assessment of Real-World Upper Limb Activity in Adults with Chronic Stroke

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Assessment of Real-World Upper Limb Activity in Adults with Chronic Stroke

by

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This dissertation is dedicated to my parents and my husband, Jason. I love you all dearly.

ABSTRACT OF THE DISSERTATION

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Professor Catherine E. Lang, Chair

Hemiparesis is a common motor impairment following stroke that leads to disability. The goal of stroke-related physical rehabilitation is to reduce the severity of motor-related disability in hopes that improved motor capacity (i.e. what one *can* do) will generalize to improved motor performance (i.e. what one actually *does*) in everyday activities. Recent studies have demonstrated that motor capacity and motor performance are distinct domains of motor function, but few have objectively measured motor performance. Furthermore, even though many studies have demonstrated that motor capacity is only moderately associated with motor performance, few studies have examined *other factors* that might influence motor performance. The purpose of this dissertation was to characterize motor performance, and potential modifying factors of motor performance, in nondisabled adults and adults with chronic stroke, and to develop and validate a novel, accelerometry-derived assessment methodology to quantify motor performance.

Using wrist-worn accelerometry, we characterized duration of upper limb (UL) activity that occurred in everyday environments (i.e. real-world activity) as an index of motor performance. We also characterized several potential modifying factors of UL activity [i.e. self-reported time spent in sedentary activity, cognitive impairment, depressive symptomatology, number of comorbidities, living arrangement, age, motor capacity, pre-stroke hand dominance, and

Activities of Daily Living (ADLs) status]. Increased self-reported time spent in sedentary activity was associated with decreased UL activity in nondisabled adults. Decreased motor capacity and dependence in ADLs were associated with decreased UL activity in adults with chronic stroke. These results identify potential factors that could be targeted during rehabilitation in patient populations. Additionally, duration of UL activity obtained from nondisabled adults could be used as a referent value for setting outcome goals for patients with UL impairment.

We also developed and validated a novel, accelerometry-based methodology to quantify real-world bilateral UL activity. This methodology was first validated in a laboratory setting in nondisabled adults. We derived two accelerometry-based metrics to quantify intensity of bilateral UL activity and contribution of each UL to activity. The accelerometry-derived metrics distinguished between high- and low-intensity UL activity, and between UL activities that were completed using both ULs versus one UL. The accelerometry-derived metrics were also strongly correlated with secondary measures (i.e. convergent validity was established).

Having established the validity of the accelerometry-based methodology, we characterized real-world bilateral UL activity during a "typical" day in nondisabled adults and adults with chronic stroke. We demonstrated that duration and intensity of UL activity were lower in adults with stroke than in nondisabled adults, and that UL activity was more lateralized (i.e. unaffected UL activity exceeded affected UL activity) in adults with stroke. We also demonstrated that motor capacity and motor performance were not associated in a subset of adults with stroke.

Taken together, our results suggest that motor capacity and motor performance are distinct domains of motor function that should be assessed separately. Furthermore, factors other than motor capacity should be identified and targeted during rehabilitation to improve motor performance above that which can be obtained by improvement in motor capacity alone.

Chapter 1: Assessment of Real-World Upper Limb Activity

1.1 Introduction

Stroke is a cardiovascular disease that affects 7 million Americans, and occurs at a rate of ~800,000/year.[1] Upper limb (UL) hemiparesis is common after stroke, and results in impaired motor function that often persists greater than 6 months post-stroke.[2] Impaired motor function leads to disability in performing daily activities (e.g. self-care, cooking, shopping), where an individual must depend on a caregiver for assistance.[3,4] Disability, in turn, leads to decreased quality of life and life satisfaction in individuals with stroke[4-7] and increased caregiver burden (e.g. emotional distress, negative feelings, loss of social and leisure activities).[8,9] Furthermore, stroke-related disability imposes a significant economic burden on individuals and society. In 1990, the average lifetime cost per person of first strokes in the United States was $103,576.[10] Lost earnings in the United States due to stroke-related morbidity totaled $10.4 billion,[10] and is expected to exceed $760 billion by the year 2050.[11]

Physical rehabilitation is often sought to reduce the severity of stroke-related UL disability and the accompanying functional, psychosocial, and economic consequences. An important goal of physical rehabilitation is to reduce the impact of motor impairment and to restore overall function through effective interventions. This is often accomplished through intensive rehabilitation in clinical or research settings (e.g. constraint-induced movement therapy,[12] task-specific training,[13] and robot-assisted training[14]). Structured clinical and research settings, however, differ greatly from the unstructured ebb-and-flow of daily activity that makes up everyday life (i.e. real-world activity). It is important, therefore, to ensure that improvements in motor function observed *inside* the clinic or research laboratory generalize to everyday activity that occurs *outside* of the clinic.

1.2 Motor Capacity versus Motor Performance

In considering the impaired UL specifically, one must distinguish between two domains of motor function: capacity and performance.[15] Motor capacity is characterized by motor function that occurs under structured conditions (e.g. inside the clinic or laboratory) whereas motor performance is characterized by motor function that occurs under unstructured conditions (e.g. home, work, the community). A common goal of rehabilitation is to improve motor capacity through rehabilitation interventions, with the assumption that improved motor capacity will lead to improved motor performance during real-world activity.

There is sufficient data, however, to challenge this assumption, as indicated by the following studies. In two separate laboratory-based studies, participants with stroke used their unaffected UL to complete a motor task during spontaneous task conditions despite being able to complete the task using their affected UL during forced-use conditions.[16,17] In a hospital setting, participants did not increase daily activity of their affected UL after 3 weeks of inpatient rehabilitation, despite improved UL motor capacity as measured by standardized clinical assessments.[18] In an out-patient setting, increased motor capacity as measured by a Functional Capacity Evaluation was only weakly associated with economic predictors of return to work.[19] From these studies, one may infer that structured clinical- and laboratory-based assessments of UL motor capacity may not accurately predict motor performance. For this reason, both motor capacity and motor performance should be measured in order to assess recovery of motor function after stroke.

1.3 Assessment of Motor Capacity

Motor capacity can be measured inside the laboratory or clinic using several approaches. Inside the laboratory, kinematic parameters of UL movement (e.g. velocity, acceleration, accuracy, efficiency) can be objectively measured using electromagnetic- or video-based motion capture systems. These systems depend on accurate placement of markers on body surfaces that are then tracked in three-dimensional space as an individual performs a task. Results from kinematic analyses have been used to identify compensatory movements and to predict later capacity in adults with stroke. For example, kinematic analysis of UL movement identified how movements of the trunk and proximal arm were used to compensate for distal arm impairment during reaching and grasping tasks in adults with stroke.[20,21] Kinematic analysis also showed that shoulder active range of motion at 1 month post-stroke predicted motor capacity at 3 months.[22]

Inside the clinic, standardized assessments (e.g. Action Research Arm Test,[23] Fugl-Meyer Assessment[24]) are used to measure gross and fine motor skills during the performance of structured tasks. Use of standardized assessments is important for several reasons. First, the structured nature of standardized assessments allows motor capacity to be objectively scored, independent of the tester administering the assessment. Second, recovery of motor capacity can be measured by examining changes in assessment scores over time. Third, assessment scores for an individual with stroke can be compared to “normal values” obtained from nondisabled adults; thus, an individual’s motor capacity can be compared to normative data during the course of recovery. Standardized assessment scores can also be useful because of their ability to predict motor capacity at a later time. For example, a score ≥ 11 on the Fugl-Meyer Assessment measured 2 weeks post-stroke was predictive of recovery of dexterous motor control (as measured by the Action Research Arm Test) at 6 months.[25] Similarly, Fugl-Meyer Assessment scores measured at 1 month explained 86% of variance of the Fugl-Meyer Assessment score measured at 6 months.[26]

Two major limitations exist, however, with laboratory- and clinic-based assessment of UL motor capacity. The first limitation is that real-world motor performance is not assessed. Laboratory-based motion capture systems are too large and expensive to be practically used inside a patient's home or work environment, and placement of markers is likely to be burdensome to the wearer. Standardized clinical assessments are also limited because they measure motor function during a structured task or a limited set of tasks. Naturalistic human movement is extremely variable within and across individuals,[27,28] such that a structured clinical assessment cannot possibly capture the complexity of movement that occurs during real-world activity.

The second limitation is that both kinematic analysis and standardized clinical tests assess unilateral UL motor capacity. Typically, motor capacity of the affected and unaffected ULs is measured separately and then compared. This is of great concern because the majority of real-world UL activity consists of both ULs working together to complete a task (i.e. bilateral UL activity).[29] Some of this bilateral UL activity consists of symmetrical bilateral movements, where the kinematic, temporal, and spatial parameters of both ULs are similar. Most simultaneous UL activity, however, consists of complementary UL activity, where the ULs cooperate to complete a task (e.g. one hand stabilizes a piece of paper while the other hand holds a pen to write).[30] A small number of standardized clinical assessments measure bilateral UL motor capacity (e.g. Chedoke Arm and Hand Activity Inventory,[31] Motor Assessment Scale[32]), but the patient's score reflects the amount of assistance the patient requires to complete a task rather than parameters of UL movement. In order for laboratory- and clinic-based assessments to measure motor performance, they must be able to assess real-world motor activity as it occurs naturally. This is not possible, however, because it would not be practical to instrument an individual's home with expensive equipment nor would it be feasible for a therapist to observe a patient for 24 hours a day. At best, laboratory- and clinic-based assessments can only reflect one's capacity for motor function during the completion of structured tasks.

1.4 Assessment of Motor Performance

Motor performance of real-world UL activity is a challenging construct to measure. Because it cannot be easily captured using laboratory-based methods or standardized clinical assessments, many self-report questionnaires have been developed to assess motor function during the performance of real-world activity. Examples of self-reported real-world UL activity include the ABILHAND, the Stroke Impact Scale (Hand Function and ADL subscales), and the Motor Activity Log. The ABILHAND[33] is a self-report assessment that consists of 23 bilateral activities rated on a 3-point Likert scale according to task difficulty, and has low-to-moderate agreement (r=0.38-0.49) with various tests of motor capacity.[34] For the Stroke Impact Scale Hand and ADL subscales,[35] 5 and 10 UL activities, respectively, are rated on a 5-point Likert scale according to task difficulty. The Stroke Impact Scale has much better agreement with tests of motor capacity (i.e. the Fugl-Meyer Assessment, r=0.81).[36] The Motor Activity Log[37] consists of 28 items describing common activities of daily living that are rated on two 5-point Likert scales describing amount and quality of movement during UL tasks, and is correlated with the Stroke Impact Scale-Hand Function Subscale (r=0.72).

Two major concerns exist regarding the validity of self-report measures to assess motor performance. First, validity of self-report assessments is established, in part, by demonstrating convergent validity (i.e. a strong correlation) with other measures of UL function. When those other measures of UL function are standardized clinical assessments of motor capacity, self-report assessments tell us little about their validity for measuring real-world motor performance. Second, the validity of self-report assessments can be affected by report bias due to social approval (e.g. desire to please one's therapist or doctor, or embarrassment over not completing more activity at home[38]) or cognitive impairment following stroke (e.g. impaired comprehension, memory recall, attention[39-41]). Self-report bias has been explored in the field of physical activity, where low-to-moderate correlations exist between the majority of self-report assessments and direct measures of physical activity (e.g. pedometry, accelerometry, heart rate monitoring), and is likely to influence self-reported ratings of UL function after stroke.[42] Given the limitations of self-report assessments, an objective method for measuring real-world motor performance is needed.

1.5 Accelerometry

Wrist-worn accelerometry has emerged as a useful method for quantifying real-world motor performance. Piezoresistive, piezoelectric, and differential capacitive accelerometers are the most common types of accelerometers.[43] Regardless of the type used, each is an inertial sensor that detects linear acceleration in one orthogonal direction using a sensing element (i.e. a seismic mass attached to a mechanical suspension system or a seismic mass encapsulated between two electrodes). When the seismic mass moves due to human movement, voltage proportional to the applied acceleration is generated and converted to an electrical signal which is then filtered, wave-form rectified, and converted to a unit called an "activity count" (1 count = 0.001664g, see Appendix A for additional information).[44] When multiple sensors are housed within a single device, acceleration in all 3 orthogonal directions can be measured. Activity counts across axes can then be summed over user-defined "epochs" (e.g. 1 second, 1 minute) to quantify the total amount of activity that occurred over a given period of time (e.g. 24 hours). Although accelerometers can now be worn on the wrists to measure UL motor performance, they were initially developed to be worn on the hip to measure real-world physical activity.

1.5.1 Hip-Worn Accelerometry

In the early 2000s, hip-worn accelerometry emerged as a gold-standard for estimating energy expenditure during physical activity that occurs in real-world environments.[43] This is possible because accelerometers measure acceleration, and acceleration is proportional to force.[44] If force is accepted as a surrogate for energy expenditure, then it is possible to estimate energy expenditure using acceleration. Prior to the use of hip-worn accelerometers, direct measures of energy expenditure included doubly-labeled water[45] and the maximal volume of oxygen consumption[46] (i.e. VO_2 Max) to quantify physical activity. These methods are expensive and require instrumented equipment to measure how levels of oxygen and carbon dioxide change during physical activity performed inside a laboratory setting. Because energy expenditure as measured by accelerometry explains a large amount of the variance in energy expenditure measured by doubly-labeled water[47] (R^2>0.74) and maximal oxygen consumption[48,49] (R^2=0.62-0.89), accelerometry is accepted as an objective tool for measuring physical activity. Additionally, due to its small size and portability, hip-worn accelerometry allows for unobstructed measurement of real-world physical activity.[50]

1.5.2 Wrist-Worn Accelerometry

Due to the flexibility that hip-worn accelerometers provide for measuring real-world physical activity, wrist-worn accelerometry was evaluated early-on for its effectiveness in measuring energy expenditure. Studies showed that energy expenditure as measured by wrist-worn accelerometry was less accurate than energy expenditure as measured by hip-worn accelerometry,[51,52] likely because acceleration of the ULs exceeds acceleration at the hip during laboratory tests of energy expenditure (e.g. treadmill running). Despite this limitation, wrist-worn accelerometry has become a useful tool for quantifying real-world UL motor performance. Wrist-worn accelerometry cannot distinguish UL movements that are intentional (e.g. getting dressed) from unintentional (e.g. arm-swing while walking); nevertheless, it serves as a useful index of real-world motor function.[53] Due to the inability to distinguish between intentional and unintentional motor performance, real-world UL movement that is measured by accelerometry is referred to as real-world UL activity.

1.6 Quantifying Real-World Upper Limb Activity

1.6.1 Validation

Real-World UL activity as measured by accelerometry has been validated in adults with and without stroke through a variety of approaches. Studies have demonstrated that 1) duration of movement as measured by wrist-worn accelerometry is strongly correlated with observer-recorded duration of movement during the performance of standardized laboratory activities (r=0.93);[54] 2) UL movement as measured by wrist-worn accelerometry is strongly correlated with electrogoniometry-measured movement(r=0.94);[55] 3) wrist-worn accelerometry can discriminate adults with stroke from those without stroke,[55,56] and between the affected and unaffected ULs of adults with stroke;[56-58] 4) wrist-worn accelerometry is sensitive to change over time;[59-61] and 5) metrics of real-world UL activity are moderately-to-strongly correlated with standardized clinical assessments (r=0.40-0.62) and self-reported assessments of motor performance (r=0.52-0.61; see Lang et al. (2013) for review[62]).

1.6.2 Metrics

Historically, real-world upper limb activity has been quantified using one of two accelerometry-derived metrics: duration of UL activity or intensity of UL activity. When measuring *duration* of UL activity, each second of accelerometry data is dichotomized into “activity” or “no activity” based on whether an activity count was recorded for a given sample.[54] Seconds of “activity” can then be summed to determine total duration of UL activity. This approach has been used to demonstrate that duration of daily affected and unaffected UL movement can be as low as 3.0 and 4.5 hours, respectively, immediately following stroke[63], and 2.4 and 5.3 hours one year later (compared to 5.1 and 5.4 hours in nondisabled adults).[64] Other studies have reported similar values for duration of UL activity in adults with stroke.[56,64,65]

When measuring *intensity* of UL activity, activity counts for each sample of acceleration data are summed for a given period of time (e.g. 1 minute) and then averaged over a 24 hour period, or simply summed over 24 hours.[55] Studies have demonstrated that activity counts are lower in adults with stroke than in nondisabled adults,[66] and that activity counts in adults with stroke are lower in the affected UL than in the unaffected UL.[18,58]

While informative, the approaches described above are similar to standardized clinical assessments of motor capacity in that they measure *unilateral* UL activity and then compare activity between limbs. This is a major limitation because the majority of real-world UL activity consists of bilateral actions,[29,30] and reporting duration or intensity of unilateral UL activity does not provide information on how the ULs are used together. In an effort to account for bilateral UL activity, calculating the *ratio* of UL activity between limbs (i.e. affected-to-unaffected or non-dominant-to-dominant UL activity) has been suggested.[61] Using this approach, a ratio of 1 indicates that UL activity is equivalent between limbs, and ratios less than 1 indicate decreased UL activity of the affected limb related to the unaffected limb.

Like duration and intensity of unilateral UL activity, the ratio of UL activity is responsive to changes in motor capacity over time,[61,67] and can discriminate between adults with and without stroke.[58,63] Although this approach provides some information about the relative contribution from each UL during real-world UL activity, it does so incompletely. For example, if the affected UL is active for 3 hours and the unaffected UL is active for 6 hours during a 24 hour period, the use ratio would be 0.5 (3 hours / 6 hours = 0.5). This value could be obtained if both ULs were active simultaneously during the 24 hour period, or if the ULs were unilaterally active during the 24 hour period. Thus, calculating the ratio of UL activity does not accurately reflect actual bilateral UL activity.

Despite the obvious limitation of the above-mentioned accelerometry-derived metrics for assessing bilateral UL activity, calculating duration, intensity, or the ratio of affected-to-unaffected UL activity provides useful information about real-world UL motor activity that can be compared against motor capacity as measured by standardized clinical assessments. Scores on tests of motor capacity are, in most cases, only moderately associated with real-world UL activity (r=-0.45-0.62),[62] which indicate that motor capacity only partially explains real-world motor performance.

Factors *in addition* to motor capacity, therefore, likely influence how the affected UL is used during real-world motor performance. Identification of these additional factors is important because they could be targeted for intervention in order to improve real-world motor performance when improvement in motor capacity plateaus. One study demonstrated that real-world UL activity was lower in adults with stroke who were dependent in self-care activities than in adults who were independent,[63] but no other studies have examined factors that might influence real-world UL activity. Factors such as sedentary activity,[68] cognitive impairment,[69] depressive symptomatology,[70] the additive effect of comorbidities,[71] age,[72] and living arrangement[73] (i.e. living alone versus with others) are associated with overall physical activity in nondisabled adults. These same factors are often present in the rehabilitation population, and should be examine for their influence on real-world UL activity. Chapters 2 and 3 of this dissertation examine potential modifying factors of UL activity in adults with chronic stroke and in nondisabled adults.

1.6.3 Activity Classification

In an attempt to account for bilateral UL activity, computer-derived algorithms have been used to categorize UL activity based on accelerometry data collected from many body segments (e.g. wrists, upper arm, torso, and lower limbs). One approach attempted to categorize UL activity into “active” (e.g. stirring with a spoon) and “passive” (stabilizing the bowl) categories and subcategories.[74] Depending on the subcategory, this approach achieved low-to-high agreement between accelerometry-derived and observer-derived categorizations (percent agreement: 24%-100%). Unfortunately, this approach did not differentiate between unilateral and bilateral UL activity. A different approach sought to identify 20 *specific* tasks (e.g. washing, eating, brushing teeth) from UL accelerometry data.[75] Similar to the above approach, unilateral UL activity was not distinguished from bilateral UL activity. Furthermore, the algorithm could only identify 20 tasks; this is a limitation because real-world activity consists of many more than 20 tasks.

The limitations of computer-based activity classification algorithms described above can likely be attributed to the variation that exists in human movement. Previous research has demonstrated that in healthy adults, movement patterns vary *across* repetitions of the same task *within* individuals as well as *between* individuals.[27,28] Kinematic and kinetic patterns of UL movement are even *more* variable in adults with stroke than in adults without stroke,[76-78] therefore it is unlikely that an activity classification algorithm can be developed to identify every possible UL task in adults with stroke.

1.6.4 Bilateral UL Activity

A methodology to objectively measure bilateral UL activity is needed. Building on previous research approaches, chapters 4 and 5 of this dissertation propose a novel accelerometry-based methodology that quantifies two parameters of real-world UL activity: the intensity of bilateral UL activity and the contribution from both ULs to activity. Instead of quantifying the duration or intensity of one UL relative to the contralateral UL for a given time period (e.g. 24 hours), this methodology quantifies activity intensity and the contribution from both ULs for *each second* of UL activity to answer the question, “How are the upper limbs used during real-world activity?”

1.7 Significance for Rehabilitation

The data obtained from the proposed studies will provide valuable information for rehabilitation researchers and clinicians. First, if factors can be identified that are associated with real-world UL activity, they can be targeted for intervention to further improve real-world UL activity beyond that which is obtained by improvement in motor capacity alone. Second, the potential ability to quantify real-world bilateral UL activity is important because it can allow researchers and clinicians to 1) determine if patients are practicing their exercise programs at home, 2) determine if gains made in therapy translate into improvements at home, and 3) objectively quantify real-world UL activity that otherwise goes unmeasured. This knowledge has significant implications for how to improve motor performance in adults with chronic stroke who experience hemiparesis.

1.8 Specific Aims

The overall purpose of this dissertation is to characterize real-world UL activity in adults with chronic stroke and nondisabled adults and to identify potential modifying factors of UL activity in adults with chronic stroke and nondisabled adults. Additionally, a novel accelerometry-based methodology is proposed and tested for its ability to quantify real-world bilateral UL activity in adults with chronic stroke and nondisabled adults.

Specific Aim 1 (Chapter 2):

Characterize duration of dominant UL activity during a typical day and potential modifying factors of UL activity in nondisabled adults.

Hypothesis 1a: Decreased duration of dominant UL activity will be associated with increased time spent in sedentary activity, severity of cognitive impairment, depressive symptomatology, number of comorbidities, and age.

Hypothesis 1b: Duration of dominant UL activity will be lower in adults who live with others compared to adults who live alone.

Specific Aim 2 (Chapter 3):

Characterize duration of affected UL activity during a typical day and potential modifying factors of UL activity in adults with chronic stroke.

Hypothesis 2a: Decreased duration of affected UL activity will be associated with increased time spent in sedentary activity, severity of cognitive impairment, depressive symptomatology, number of comorbidities, age, and with decreased motor capacity.

Hypothesis 2b: Duration of affected UL activity will be lower in adults who live with others compared to adults who live alone and in adults whose nondominant side was affected by stroke.

Specific Aim 3 (Chapter 4):

Examine the validity of an accelerometry-based methodology to assess bilateral UL activity in nondisabled adults during the performance of 8 everyday tasks.

Hypothesis 3a: The Bilateral Magnitude, an accelerometry-derived measure of bilateral UL intensity, will distinguish between high- and low- intensity tasks.

Hypothesis 3b: The Magnitude Ratio, an accelerometry-derived measure of the contribution of each UL to activity, will distinguish between unilateral and bilateral tasks.

Specific Aim 4 (Chapter 5):

Characterize bilateral UL activity during a typical day in nondisabled adults and adults with chronic stroke.

Hypothesis 4a: The Bilateral Magnitude and Magnitude Ratio will be greater in nondisabled adults than in adults with chronic stroke.

Hypothesis 4b: In adults with stroke, increased median Magnitude Ratios will be associated with increased motor capacity.

1.9 References

1. Roger VL, Go AS, Lloyd-Jones DM, et al. Heart Disease and Stroke Statistics--2012 Update: A Report From the American Heart Association. *Circulation.* 2012;125(1):e2-e220.

2. Sommerfeld DK, Eek EU, Svensson AK, Holmqvist LW, von Arbin MH. Spasticity after stroke: its occurrence and association with motor impairments and activity limitations. *Stroke.* 2004;35(1):134-139.

3. Wade DT, Hewer RL. Functional abilities after stroke: measurement, natural history and prognosis. *J Neurol Neurosurg Psychiatry.* 1987;50(2):177-182.

4. Hartman-Maeir A, Soroker N, Ring H, Avni N, Katz N. Activities, participation and satisfaction one-year post stroke. *Disabil Rehabil.* 2007;29(7):559-566.

5. Carod-Artal J, Egido JA, Gonzalez JL, Varela de Seijas E. Quality of life among stroke survivors evaluated 1 year after stroke: experience of a stroke unit. *Stroke.* 2000;31(12):2995-3000.

6. Patel MD, Tilling K, Lawrence E, Rudd AG, Wolfe CD, McKevitt C. Relationships between long-term stroke disability, handicap and health-related quality of life. *Age Ageing.* 2006;35(3):273-279.

7. Astrom M, Asplund K, Astrom T. Psychosocial function and life satisfaction after stroke. *Stroke.* 1992;23(4):527-531.

8. Thommessen B, Aarsland D, Braekhus A, Oksengaard AR, Engedal K, Laake K. The psychosocial burden on spouses of the elderly with stroke, dementia and Parkinson's disease. *Int J Geriatr Psychiatry.* 2002;17(1):78-84.

9. Anderson CS, Linto J, Stewart-Wynne EG. A population-based assessment of the impact and burden of caregiving for long-term stroke survivors. *Stroke.* 1995;26(5):843-849.

10. Taylor TN, Davis PH, Torner JC, Holmes J, Meyer JW, Jacobson MF. Lifetime cost of stroke in the United States. *Stroke.* 1996;27(9):1459-1466.

11. Brown DL, Boden-Albala B, Langa KM, et al. Projected costs of ischemic stroke in the United States. *Neurology.* 2006;67(8):1390-1395.

12. Wolf SL, Winstein CJ, Miller JP, et al. Effect of constraint-induced movement therapy on upper extremity function 3 to 9 months after stroke: the EXCITE randomized clinical trial. *JAMA.* 2006;296(17):2095-2104.

13. Birkenmeier RL, Prager EM, Lang CE. Translating animal doses of task-specific training to people with chronic stroke in 1-hour therapy sessions: a proof-of-concept study. *Neurorehabil Neural Repair.* 2010;24(7):620-635.

14. Fasoli SE, Krebs HI, Stein J, Frontera WR, Hogan N. Effects of robotic therapy on motor impairment and recovery in chronic stroke. *Arch Phys Med Rehabil.* 2003;84(4):477-482.

15. Young NL, Williams JI, Yoshida KK, Bombardier C, Wright JG. The context of measuring disability: does it matter whether capability or performance is measured? *J Clin Epidemiol.* 1996;49(10):1097-1101.

16. Sterr A, Freivogel S, Schmalohr D. Neurobehavioral aspects of recovery: assessment of the learned nonuse phenomenon in hemiparetic adolescents. *Arch Phys Med Rehabil.* 2002;83(12):1726-1731.

17. Han CE, Kim S, Chen S, et al. Quantifying arm nonuse in individuals poststroke. *Neurorehabil Neural Repair.* 2013;27(5):439-447.

18. Rand D, Eng JJ. Disparity Between Functional Recovery and Daily Use of the Upper and Lower Extremities During Subacute Stroke Rehabilitation. *Neurorehabil Neural Repair.* 2011;26(1):76-84.

19. Gross DP, Battie MC. Does functional capacity evaluation predict recovery in workers' compensation claimants with upper extremity disorders? *Occup Environ Med.* 2006;63(6):404-410.

20. Alt Murphy M, Willen C, Sunnerhagen KS. Kinematic variables quantifying upper-extremity performance after stroke during reaching and drinking from a glass. *Neurorehabil Neural Repair.* 2011;25(1):71-80.

21. Michaelsen SM, Jacobs S, Roby-Brami A, Levin MF. Compensation for distal impairments of grasping in adults with hemiparesis. *Exp Brain Res.* 2004;157(2):162-173.

22. Beebe JA, Lang CE. Active range of motion predicts upper extremity function 3 months after stroke. *Stroke.* 2009;40(5):1772-1779.

23. Lyle RC. A performance test for assessment of upper limb function in physical rehabilitation treatment and research. *Int J Rehabil Res.* 1981;4(4):483-492.

24. Sanford J, Moreland J, Swanson LR, Stratford PW, Gowland C. Reliability of the Fugl-Meyer assessment for testing motor performance in patients following stroke. *Phys Ther.* 1993;73(7):447-454.

25. Kwakkel G, Kollen BJ, van der Grond J, Prevo AJ. Probability of regaining dexterity in the flaccid upper limb: impact of severity of paresis and time since onset in acute stroke. *Stroke.* 2003;34(9):2181-2186.

26. Duncan PW, Goldstein LB, Matchar D, Divine GW, Feussner J. Measurement of motor recovery after stroke. Outcome assessment and sample size requirements. *Stroke.* 1992;23(8):1084-1089.

27. Slifkin AB, Newell KM. Is variability in human performance a reflection of system noise? *Curr Dir Psychol Sci.* 1998;7(6):170-177.

28. Stergiou N, Decker LM. Human movement variability, nonlinear dynamics, and pathology: is there a connection? *Hum Mov Sci.* 2011;30(5):869-888.

29. Kilbreath SL, Heard RC. Frequency of hand use in healthy older persons. *Aust J Physiother.* 2005;51:119-122.

30. McCombe Waller S, Whitall J. Bilateral arm training: why and who benefits? *NeuroRehabilitation.* 2008;23(1):29-41.

31. Barreca S, Gowland CK, Stratford P, et al. Development of the Chedoke Arm and Hand Activity Inventory: theoretical constructs, item generation, and selection. *Top Stroke Rehabil.* 2004;11(4):31-42.

32. Carr JH, Shepherd RB, Nordholm L, Lynne D. Investigation of a new motor assessment scale for stroke patients. *Phys Ther.* 1985;65(2):175-180.

33. Penta M, Tesio L, Arnould C, Zancan A, Thonnard JL. The ABILHAND questionnaire as a measure of manual ability in chronic stroke patients: Rasch-based validation and relationship to upper limb impairment. *Stroke.* 2001;32(7):1627-1634.

34. Simone A, Rota V, Tesio L, Perucca L. Generic ABILHAND questionnaire can measure manual ability across a variety of motor impairments. *Int J Rehabil Res.* 2011;34(2):131-140.

35. Duncan PW, Bode RK, Min Lai S, Perera S. Rasch analysis of a new stroke-specific outcome scale: the Stroke Impact Scale. *Arch Phys Med Rehabil.* 2003;84(7):950-963.

36. Duncan PW, Wallace D, Lai SM, Johnson D, Embretson S, Laster LJ. The stroke impact scale version 2.0. Evaluation of reliability, validity, and sensitivity to change. *Stroke.* 1999;30(10):2131-2140.

37. Uswatte G, Taub E, Morris D, Light K, Thompson PA. The Motor Activity Log-28: assessing daily use of the hemiparetic arm after stroke. *Neurology.* 2006;67(7):1189-1194.

38. Adams SA, Matthews CE, Ebbeling CB, et al. The effect of social desirability and social approval on self-reports of physical activity. *Am J Epidemiol.* 2005;161(4):389-398.

39. Bradburn NM, Rips LJ, Shevell SK. Answering autobiographical questions: the impact of memory and inference on surveys. *Science.* 1987;236(4798):157-161.

40. Tatemichi TK, Desmond DW, Stern Y, Paik M, Sano M, Bagiella E. Cognitive impairment after stroke: frequency, patterns, and relationship to functional abilities. *J Neurol Neurosurg Psychiatry.* 1994;57(2):202-207.

41. Jobe JB. Cognitive processes in self report. In: A.A. S, Turkann JS, Bachrach CA, Jobe JB, Kurtzman HS, Cain VS, eds. *The science of self-report: implications for research and practice*. Mahwah: Lawrence Erlbaum Associates; 2000:25-28.

42. Prince SA, Adamo KB, Hamel ME, Hardt J, Gorber SC, Tremblay M. A comparison of direct versus self-report measures for assessing physical activity in adults: a systematic review. *Int J Behav Nutr Phys Act.* 2008;5:56.

43. Yang CC, Hsu YL. A review of accelerometry-based wearable motion detectors for physical activity monitoring. *Sensors (Basel).* 2010;10(8):7772-7788.

44. Chen KY, Bassett DR, Jr. The technology of accelerometry-based activity monitors: current and future. *Med Sci Sports Exerc.* 2005;37(11 Suppl):S490-500.

45. Schoeller DA, Ravussin E, Schutz Y, Acheson KJ, Baertschi P, Jequier E. Energy expenditure by doubly labeled water: validation in humans and proposed calculation. *Am J Physiol.* 1986;250(5 Pt 2):R823-830.

46. Hawkins MN, Raven PB, Snell PG, Stray-Gundersen J, Levine BD. Maximal oxygen uptake as a parametric measure of cardiorespiratory capacity. *Med Sci Sports Exerc.* 2007;39(1):103-107.

47. Leenders NY, Sherman WM, Nagaraja HN. Energy expenditure estimated by accelerometry and doubly labeled water: do they agree? *Med Sci Sports Exerc.* 2006;38(12):2165-2172.

48. Miller NE, Strath SJ, Swartz AM, Cashin SE. Estimating absolute and relative physical activity intensity across age via accelerometry in adults. *J Aging Phys Act.* 2010;18(2):158-170.

49. Bouchard DR, Trudeau F. Estimation of energy expenditure in a work environment: comparison of accelerometry and oxygen consumption/heart rate regression. *Ergonomics.* 2008;51(5):663-670.

50. Plasqui G, Westerterp KR. Physical activity assessment with accelerometers: an evaluation against doubly labeled water. *Obesity (Silver Spring).* 2007;15(10):2371-2379.

51. Chen KY, Acra SA, Majchrzak K, et al. Predicting energy expenditure of physical activity using hip- and wrist-worn accelerometers. *Diabetes Technol Ther.* 2003;5(6):1023-1033.

52. Tanaka C, Tanaka S, Kawahara J, Midorikawa T. Triaxial accelerometry for assessment of physical activity in young children. *Obesity (Silver Spring).* 2007;15(5):1233-1241.

53. Uswatte G, Giuliani C, Winstein C, Zeringue A, Hobbs L, Wolf SL. Validity of accelerometry for monitoring real-world arm activity in patients with subacute stroke: evidence from the extremity constraint-induced therapy evaluation trial. *Arch Phys Med Rehabil.* 2006;87(10):1340-1345.

54. Uswatte G, Miltner WH, Foo B, Varma M, Moran S, Taub E. Objective measurement of functional upper-extremity movement using accelerometer recordings transformed with a threshold filter. *Stroke.* 2000;31(3):662-667.

55. de Niet M, Bussmann JB, Ribbers GM, Stam HJ. The stroke upper-limb activity monitor: its sensitivity to measure hemiplegic upper-limb activity during daily life. *Arch Phys Med Rehabil.* 2007;88(9):1121-1126.

56. Lang CE, Wagner JM, Edwards DF, Dromerick AW. Upper extremity use in people with hemiparesis in the first few weeks after stroke. *J Neurol Phys Ther.* 2007;31(2):56-63.

57. Seitz RJ, Hildebold T, Simeria K. Spontaneous arm movement activity assessed by accelerometry is a marker for early recovery after stroke. *J Neurol.* 2011;258(3):457-463.

58. van der Pas SC, Verbunt JA, Breukelaar DE, van Woerden R, Seelen HA. Assessment of arm activity using triaxial accelerometry in patients with a stroke. *Arch Phys Med Rehabil.* 2011;92(9):1437-1442.

59. Page SJ, Sisto SA, Levine P. Modified constraint-induced therapy in chronic stroke. *Am J Phys Med Rehabil.* 2002;81(11):870-875.

60. Reiterer V, Sauter C, Klosch G, Lalouschek W, Zeitlhofer J. Actigraphy--a useful tool for motor activity monitoring in stroke patients. *Eur Neurol.* 2008;60(6):285-291.

61. Uswatte G, Foo WL, Olmstead H, Lopez K, Holand A, Simms LB. Ambulatory monitoring of arm movement using accelerometry: an objective measure of upper-extremity rehabilitation in persons with chronic stroke. *Arch Phys Med Rehabil.* 2005;86(7):1498-1501.

62. Lang CE, Bland MD, Bailey RR, Schaefer SY, Birkenmeier RL. Assessment of upper extremity impairment, function, and activity after stroke: foundations for clinical decision making. *J Hand Ther.* 2013;26(2):104-114.

63. Thrane G, Emaus N, Askim T, Anke A. Arm use in patients with subacute stroke monitored by accelerometry: association with motor impairment and influence on self-dependence. *J Rehabil Med.* 2011;43(4):299-304.

64. Michielsen ME, Selles RW, Stam HJ, Ribbers GM, Bussmann JB. Quantifying nonuse in chronic stroke patients: a study into paretic, nonparetic, and bimanual upper-limb use in daily life. *Arch Phys Med Rehabil.* 2012;93(11):1975-1981.

65. Lang CE, Edwards DF, Birkenmeier RL, Dromerick AW. Estimating minimal clinically important differences of upper-extremity measures early after stroke. *Arch Phys Med Rehabil.* 2008;89(9):1693-1700.

66. Rand D, Eng JJ. Arm-hand use in healthy older adults. *Am J Occup Ther.* 2010;64(6):877-885.

67. Urbin MA, Bailey RR, Lang CE. Validity of Body-Worn Sensor Acceleration Metrics to Index Upper Extremity Function in Hemiparetic Stroke. *J Neurol Phys Ther.*(in press).

68. Martinez-Gonzalez MA, Martinez JA, Hu FB, Gibney MJ, Kearney J. Physical inactivity, sedentary lifestyle and obesity in the European Union. *Int J Obes Relat Metab Disord.* 1999;23(11):1192-1201.

69. Yaffe K, Barnes D, Nevitt M, Lui LY, Covinsky K. A prospective study of physical activity and cognitive decline in elderly women: women who walk. *Arch Intern Med.* 2001;161(14):1703-1708.

70. Penninx BW, Leveille S, Ferrucci L, van Eijk JT, Guralnik JM. Exploring the effect of depression on physical disability: longitudinal evidence from the established populations for epidemiologic studies of the elderly. *Am J Public Health.* 1999;89(9):1346-1352.

71. Rijken M, van Kerkhof M, Dekker J, Schellevis FG. Comorbidity of chronic diseases: effects of disease pairs on physical and mental functioning. *Qual Life Res.* 2005;14(1):45-55.

72. Caspersen CJ, Pereira MA, Curran KM. Changes in physical activity patterns in the United States, by sex and cross-sectional age. *Med Sci Sports Exerc.* 2000;32(9):1601-1609.

73. Joung IM, van de Mheen H, Stronks K, van Poppel FW, Mackenbach JP. Differences in self-reported morbidity by marital status and by living arrangement. *Int J Epidemiol.* 1994;23(1):91-97.

74. Schasfoort FC, Bussmann JB, Stam HJ. Ambulatory measurement of upper limb usage and mobility-related activities during normal daily life with an upper limb-activity monitor: a feasibility study. *Med Biol Eng Comput.* 2002;40(2):173-182.

75. Bao L, Intille SS. Activity recognition from user-annotated acceleration data. *LECT NOTES COMPUT SC.* 2004;3001/2004:1-17.

76. Archambault P, Pigeon P, Feldman AG, Levin MF. Recruitment and sequencing of different degrees of freedom during pointing movements involving the trunk in healthy and hemiparetic subjects. *Exp Brain Res.* 1999;126(1):55-67.

77. Kamper DG, McKenna-Cole AN, Kahn LE, Reinkensmeyer DJ. Alterations in reaching after stroke and their relation to movement direction and impairment severity. *Arch Phys Med Rehabil.* 2002;83(5):702-707.

78. Ye Y, Ma L, Yan T, Liu H, Wei X, Song R. Kinetic measurements of hand motor impairments after mild to moderate stroke using grip control tasks. *J Neuroeng Rehabil.* 2014;11:84.

Chapter 2: Upper Limb Activity in Adults: Referent Values Using Accelerometry

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2.1 Abstract

The goal of physical rehabilitation following upper limb (UL) impairment is functional restoration of the UL for use in daily activities. Because capacity for UL function may not translate into real-world activity, it is important that assessment of real-world UL activity be used in conjunction with clinical measures of capacity. Accelerometry can be used to quantify duration of UL activity outside of the clinic. The purpose of this study was to characterize hours of UL activity and potential modifying factors of UL activity (sedentary activity, cognitive impairment, depressive symptomatology, additive effects of comorbidities, cohabitation status, and age). Seventy-four community dwelling adults wore accelerometers on bilateral wrists for 25 hours and provided information on modifying factors. Mean hours of dominant UL activity was 9.1 ± 1.9 hours and the ratio of activity between the non-dominant and dominant ULs was 0.95 ± 0.06. Decreased hours of dominant UL activity was associated with increased time spent in sedentary activity. No other factors were associated with hours of dominant UL activity. These data can be used to help clinicians establish outcome goals for patients given pre-impairment level of sedentary activity, and to track progress during rehabilitation of the ULs.

2.2 Introduction

Upper limb (UL) impairment as a result of illness or injury results in significant financial and functional deficits, many of which have long-lasting consequences. Workers' compensation claims for upper limb injuries exceed $500 million.[1] Hemiparesis following stroke, a condition that affects the ULs, contributes to increased mortality and Medicare costs.[2] For individuals with severe rheumatoid arthritis (RA), another condition that affects the ULs, the cumulative cost per patient per decade approaches $200,000.[3] Actual costs of UL impairments are likely much higher when indirect costs, such as loss of work time, psychological stress, and increased likelihood of repeated injury, are considered.[4-6] Functional deficits of traumatic UL injury result in decreased independence in activities of daily living (ADLs) and decreased quality of life that can persist from 1-4 years post-injury.[5,7] Disability in activities of daily living due to hemiparesis following stroke persists beyond 6 months in 54% of people who participate in inpatient rehabilitation,[8] and functional capacity decreases over time in persons with RA.[9] Effective rehabilitation of the ULs following impairment can improve functional outcomes, assist people in returning to gainful employment, and reduce costs.

Paramount to effective UL rehabilitation is appropriate assessment of UL function within the clinic and outside in the real-world environment. A common assumption is that increased *capacity* for UL function, as measured by clinical assessments (e.g. Jebsen-Taylor Hand Function Test, Action Research Arm Test, etc.), translates into increased real-world functional activity. There is an absence of data, however, to support this assumption. In inpatient settings, increased capacity did not result in improved performance outside of therapy sessions.[10] Likewise, in outpatient settings, clinical assessment of capacity (e.g. Functional Capacity Evaluation) was only weakly associated with economic predictors of return to work.[11] Clinical assessments may not accurately measure real-world performance, which is *the* outcome of most interest when the goal is functional recovery. In order to measure real-world performance, additional tools are necessary to assess UL function outside the clinic in an objective and reliable way. One such tool is the accelerometer.

Accelerometry can be used as an index of UL activity, defined as movement of the UL outside the clinic to complete functional and non-functional tasks. Accelerometry has been used to quantify hours of UL activity in individuals with stroke during inpatient and outpatient rehabilitation.[10,12-14] The validity and reliability of accelerometers to measure UL activity is well-established and correlates well with tests of UL function.[12,13,15-19] Furthermore, accelerometry is a useful substitute for self-report measures because it can reduce or eliminate reporting biases associated with self-report.[20,21]

The technology now exists to track UL activity in patients as they undergo rehabilitation, but data on UL activity from a referent sample of adults has not yet been gathered. Some data on UL activity are available, but sample sizes have been small[17,22,23] and limited to *healthy* participants aged 65-78.[10,22,24] Furthermore, there has been no investigation or control for factors that may influence UL activity. Studies have examined general physical activity by using hip-worn accelerometers as participants go about their day-to-day activities. Known factors associated with decreased general physical activity include increased time spent in sedentary activity,[25,26] cognitive impairment,[27] depression,[28] additive effects of comorbidities,[29,30] and increased age.[31,32] Additionally, the association between living alone and decreased general physical activity is inconclusive.[32-35] These same factors, which are often present in the rehabilitation population, may also influence UL activity; their association with duration of UL activity needs to be explored.

The purpose of this study, therefore, was to characterize hours of UL activity and potential modifiers of UL activity in a comprehensive sample of adults. We sampled a broad range of ages because upper limb impairment is a consequence of many conditions that affect adults of all ages. We hypothesized that decreased hours of UL activity would be associated with increased time spent in sedentary activity, severity of cognitive impairment, depressive symptomatology, number of comorbidities, and older ages. We also hypothesized that hours of UL activity would be greater in participants living alone. Referent data on hours of UL activity that accounts for the effect of modifying factors will provide clinicians with targeted values of UL activity for individual patients, given their unique pre-impairment demographic, social, and health characteristics. Overall, these data will help clinicians and patients set rehabilitation goals as well as track progress during rehabilitation of the ULs following impairment.

2.3 Methods

2.3.1 Participants

Seventy-four community-dwelling adults were recruited from the St. Louis metropolitan area through a community-based recruitment organization. Participants were enrolled who were 1) age 30 and older, and 2) able to follow commands. Participants were excluded if they had a self-reported history of a neurological condition or physical impairment of the UL. The Human Research Protection Office of Washington University approved the protocol for this study. Informed consent was obtained from all participants prior to data collection.

2.3.2 Study Protocol

This cross-sectional study was conducted at the Neurorehabilitation Lab at Washington University School of Medicine as well as the homes of study participants. Participants attended a one-hour office visit where they provided demographic information as well as social and medical histories, and completed self-report questionnaires on general physical activity, cognition, and depressive symptomatology. Next, accelerometers were placed on both wrists proximal to the head of the ulna to ensure capture of distal movement that might occur when more proximal joints were maintained relatively still (e.g. writing). Participants were asked to wear the accelerometers for the subsequent 25 hours, including sleep, while they went about their typical, daily routine.

Periods of sleep were included for several practical reasons. First, in order for accelerometry to be used by busy clinicians, analyzing data must be a user-friendly and efficient process. Tight schedules limit clinicians' ability to identify and subtract sleep time from accelerometry output. Second, deciding what constitutes non-functional movement (e.g. a tick or jerk) during quiescent periods is subjective. Movement during a nap or nighttime may be associated with functional movements such as an unconscious scratch or reaching for a glass of water and would be lost it if was removed because the subject was "asleep." Third, asking participants to remove the accelerometers during sleep would have increased the likelihood that participants would forget to replace them upon waking.

Twenty-five hours was chosen because it has been used in previous studies[17,23] and was a practical compromise between sufficient wearing time and participant willingness to wear the accelerometers. A subset (n = 5) of participants wore the accelerometers for a second 25 hour period, separated by at least 1 week, and demonstrated that UL activity values were reliable ($ICC_{(3,k)} = 0.93$, $p = 0.01$) and a good estimate of UL activity during an average day. At the conclusion of the 25 hour period, participants were queried to ensure that the accelerometers were worn for the entire period. Additionally, accelerometry data was visually inspected to verify that participants wore the accelerometers for 25 hours.

2.3.3 Measures

The primary outcome measure was *hours of UL activity*, as determined by accelerometry data. Wireless accelerometers (GT3X+ Activity Monitor, ActiGraph, Pensacola, FL) were used to quantify the duration of UL movement that occurred during the wearing period. The GT3X+ Activity Monitor contains a tri-axis, solid state digital accelerometer that detects acceleration in three planes. The accelerometer is small (4.6cm x 3.3cm x 1.5cm), waterproof, sensitive to -6 to +6 g-force, and contains 512 MB of internal storage. Acceleration was sampled at 30 Hz. The amount of acceleration that occurs per sample is measured in activity counts (0.001664g/count). For individual axes, sample activity counts were integrated for each second of data. Next, for each second of data, activity counts across the 3 axes were combined into a single value, called a vector magnitude, using the following equation: $\sqrt{(X^2 + Y^2 + Z^2)}$. Using a technique similar to that described by Uswatte et al.,[14] seconds where the vector magnitude was greater than or equal to 2 were categorized as "movement." Seconds where the vector magnitude was less than 2 were categorized as "non-movement." Seconds of movement were summed to determine hours of UL activity for the dominant and non-dominant ULs. Percent of UL activity was calculated by dividing the hours of UL activity by length of time the accelerometers were worn. The ratio of hours of UL activity between the non-dominant and dominant ULs was also calculated.

Predictor variables believed to potentially modify UL activity included time spent in sedentary activity, cognitive impairment, depressive symptomatology, number of comorbidities, cohabitation status, and age.

Sedentary activity was measured using levels A and B of the Physical Activity Scale,[36] a self-report measure that quantifies general physical activity during a typical 24-hour weekday. Activities are grouped into 9 levels that represent differing activity intensities measured by metabolic equivalents (METs). Time spent in Levels A (0 – 0.9 METS) and B (1.0 – 1.4 METs) were summed to determine time spent in sedentary activity, and activities included sleeping, reading, watching television, listening to music, and meditating. The Physical Activity Scale is strongly correlated with activity measured by activity diary ($r = 0.74$, $p < 0.01$).[36]

Cognitive impairment was measured using the Short Blessed Test, a test of cognitive function that screens for impairment in memory, orientation, and concentration. Errors on 6 items are scored and weighted with a total possible score of 28. Scores of 0-4 indicate normal cognition, 5-9 indicate questionable impairment, and 10 or more indicate impairment consistent with dementia.[37,38]

Depressive Symptomatology was measured using the Center for Epidemiological Studies-Depression Scale, which characterizes depressive symptomatology in the general population. Twenty items are scored on a four-point Likert scale (total score = 60). Higher scores indicate greater depressive symptomatology.[39-41]

Number of Self-Reported Comorbidities was obtained via self-report using a checklist of common medical conditions. Checklists improve memory recall of health conditions relative to open- and free-response methods.[42,43] The number of comorbidities was used as a potential modifier of UL activity instead of specific conditions because the additive effect of comorbidities was the factor of interest.[29,30]

Cohabitation status, obtained from the social history, determined if participants lived alone or with other people. *Age*, obtained from a demographic questionnaire, was our final predictor variable. Additional descriptive information was also collected according to routine laboratory procedures (e.g. demographics, handedness, etc.).

2.3.4 Data Analyses

Data were downloaded from each accelerometer, and subsequently processed using MATLAB R2011B (Mathworks, Natick, MA) software. A custom-written program was used to dichotomize each second of accelerometry data into periods of movement or non-movement, and to calculate hours of UL activity, percent of UL activity, and ratio of UL activity.

Statistical analyses were performed using IBM SPSS Statistics 19 and the criterion for statistical significance was $p < 0.05$. Descriptive statistics of each variable of interest were computed. Predictor variables were assessed for normality using Kolmogorov-Smirnov tests. Examination of residuals was performed visually as well as using Cook's distance. Time spent in sedentary activity and depressive symptomatology scores were log-transformed because they were right-skewed. Pearson correlation analyses were used to examine relationships between the outcome variable and continuous predictor variables. Cognitive impairment scores and number of comorbidities violated the parametric assumption of a normal distribution despite log transformation, and Spearman correlation analyses were used. Based on our sample size, correlation coefficients greater than 0.24 were significant at $p < 0.05$ and coefficients greater than 0.30 were significant at the $p < 0.01$ level. Correlation coefficients 0.60 and higher were considered to be strong, between 0.30 – 0.59 were moderate, and 0.29 and lower were weak.[44] Mann-Whitney U tests were used to examine the difference in UL activity between participants who were and were not working. A paired samples t-test was used to examine differences in hours of UL activity between participants based on hand dominance, and an independent samples t-test was used to examine differences in hours of UL activity based on cohabitation status.

2.4 Results

Demographic information and categorical predictor variables are presented in Table 2.1. Because there was no difference in hours of dominant UL activity between participants not working (9.1 ± 2.0) and the 12 participants who were working (9.0 ± 2.1, $p = 0.83$), all participants were grouped together for subsequent analyses. All participants wore the accelerometers for the entire recording period (mean 25.0 hours, range: 24.3-26.0 hours). No technical problems with the accelerometers were reported.

Table 2.1 Demographic information and categorical predictor variables

Variable	Value
Age (Years)	
Mean ± SD	54 ± 11
Range	30-83
Gender, n(%)	
Male	35 (47%)
Female	39 (53%)
Race, n(%)	
White	30 (40%)
African American	44 (60%)
Hand Dominance, n(%)	
Right	62 (84%)
Left	12 (16%)
Work Status, n(%)	
Not working	62 (84%)
<20 hours	7 (10%)
Part-time	4 (5%)
Full-time	1 (1%)
Cohabitation Status, n(%)	
Lives alone	27 (36%)
Lives with others	47 (64%)

Descriptive statistics of outcome variables and remaining continuous predictor variables are reported in Table 2.2. Hours of dominant UL activity was greater than hours of non-dominant UL activity ($p < 0.001$), though the absolute difference between extremities was only 30 minutes. Because Pearson correlations were excellent between dominant and non-dominant UL activity, between dominant and non-dominant percent of UL activity, and between UL activity and percent of UL activity (for all values, $r \geq 0.96$, $p < 0.001$), dominant UL activity was selected as the outcome variable for analyses of potential modifiers. The variability of the ratio of UL activity was very small despite a large range in hours of UL activity (Table 2.2). Figure 2.1 illustrates the absence of a relationship between hours of dominant UL activity and the ratio of UL activity ($r = 0.08$, $p = 0.51$).

Table 2.2 Mean, standard deviation, and range of outcome variable and other predictor variables

Variable	**Mean ± SD**	**Range**
Hours of UL Activity		
Dominant	9.1 ± 1.9	4.4 – 14.2
Non-dominant	8.6 ± 2.0	4.1 – 15.5
Ratio (non-dom/dom)	0.95 ± 0.06	0.79 – 1.1
Percent of UL Activity		
Dominant (%)	36.2 ± 7.8	17.7 – 56.8
Non-dominant (%)	34.5 ± 8.0	16.5 – 61.9
Sedentary Activity† (hours)	11.8 ± 2.7	7 – 20
Cognitive Impairment	2.0 ± 2.9	0 – 10
Depressive Symptomatology	8.9 ± 7.8	0 – 35
Number of Comorbidities†	1.4 ± 1.5	0 – 6

†Determined by self-report

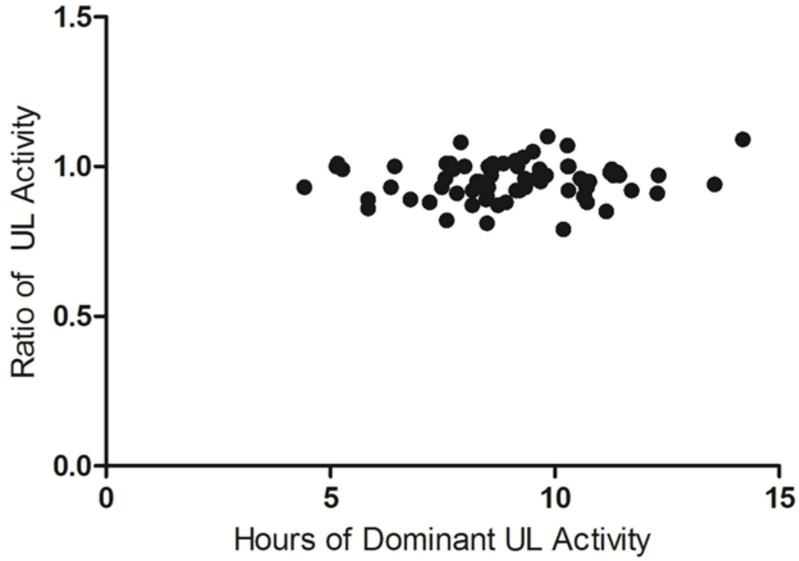

Figure 2.1 Scatterplot of ratio of UL activity versus hours of dominant UL activity. Despite variability in hours of dominant UL activity, the duration of activity between extremities is roughly equal, as indicated by a narrow range in the ratio of UL activity.

Hours of dominant UL activity was moderately correlated with time spent in sedentary activity (Fig. 2.2a, $r = -0.36$, $p < 0.01$). Correlations for hours of dominant UL activity versus cognitive impairment ($\rho = 0.20$, $p = 0.09$), depressive symptomatology (Fig. 2.2b, $r = 0.11$, $p = 0.37$), number of comorbidities ($\rho = -0.12$, $p = .32$), and age (Fig. 2.2c, $r = -0.002$, $p = 0.988$) were not significant. There was no difference in hours of dominant UL activity based on cohabitation status ($p = 0.85$). Secondary analyses indicated that there was no association between the ratio of UL activity and sedentary activity, cognitive impairment, depressive symptomatology, number of self-reported comorbidities, and age (for all values, r and $\rho < 0.13$, $p > 0.27$).

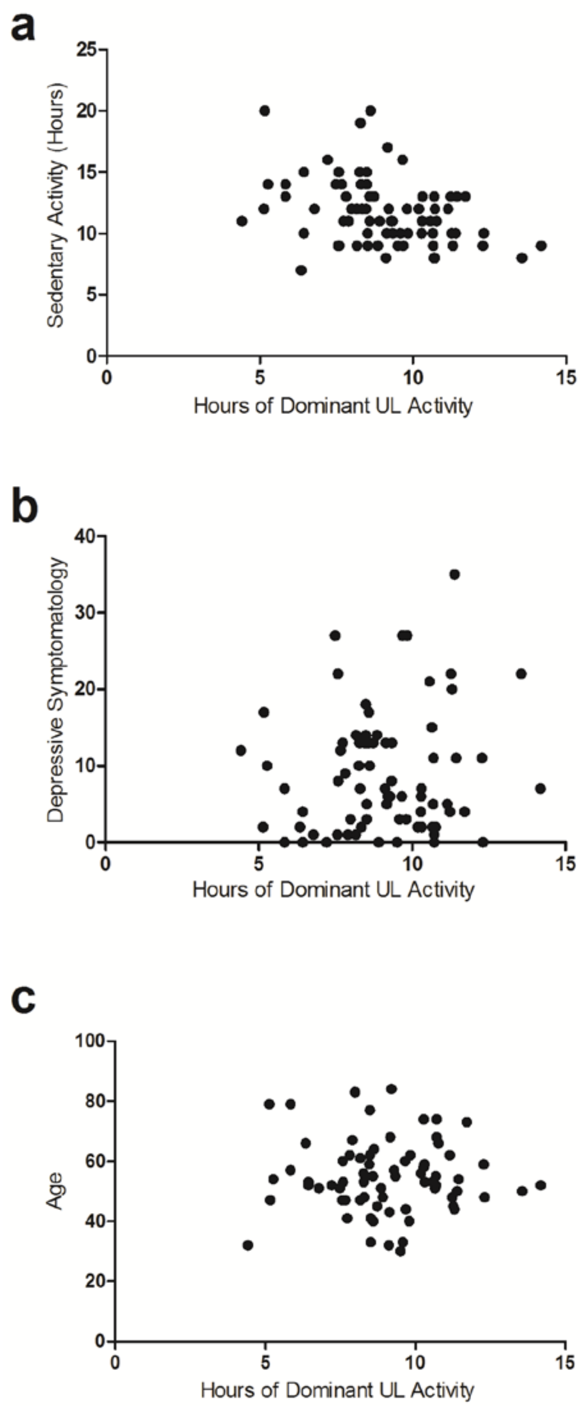

Figure 2.2 Scatterplots of hours of dominant UL activity versus time spent in sedentary activity (a), depressive symptomatology (b), and age (c). Time spent in sedentary activity, but not depressive symptomatology or age, was associated with hours of UL activity.

2.5 Discussion

Hours of UL activity during a typical day for community-dwelling adults was quantified using accelerometry in this study. Mean UL activity was 9.1 ± 1.9 hours and 8.6 ± 2.0 hours for dominant and non-dominant ULs, respectively. The ratio of UL activity (0.95 ± 0.06) indicates that the duration of UL activity between extremities was roughly equal, though quality of movements likely differed between extremities (e.g. stabilizing a bowl with one hand while stirring with the other hand). Potential modifiers of UL activity were examined for their association with hours of UL activity. In accordance with one of our hypotheses, decreased hours of UL activity was associated with increased time spent in sedentary activity. Hours of UL activity, however, was not associated with cognitive impairment, depressive symptomatology, number of comorbidities, or age, nor was there a difference in hours of UL activity between participants living alone versus with others.

These referent data build on previous studies that quantified the amount of arm activity in smaller samples of healthy, older adults[10,22-24] by categorizing hours of UL activity in a larger sample of adults of various ages. These data also indicate that time spent in sedentary activity may influence hours of UL activity. Other factors, that one might assume could influence UL activity, did not. Our results can now be used in conjunction with measures of UL functional capacity within the clinic to help clinicians set goals for individual patients as well as track progress during rehabilitation.

The ratio of UL activity is a valuable measure of function because it reflects activity of one limb relative to the other limb and accounts for general physical activity that affects both extremities.[13] General physical activity (e.g. walking) is accounted for because it likely affects both extremities equally.[12] A lower ratio of UL activity indicates increased asymmetry in duration of activity between the extremities, and in a clinical population, suggests decreased functionality of the limb in question. Our data indicate that the ratio of UL activity is a robust metric of real-world UL function in persons without UL impairment because its range and variability were relatively small in contrast with the range and variability in hours of UL activity. Additionally, the mean ratio of UL activity in our sample was similar to that in a sample of middle-aged adults (0.94),[23] and our range was similar to mean ratios reported in smaller samples of healthy, older adults (0.79 – 1.17).[10,22,24]

Only time spent in sedentary activity was associated with hours of UL activity, despite reported associations between general physical activity and the predictor variables chosen for exploration in this study. Time spent in sedentary activity is easily measured by self-report in the clinic and could be considered when identifying a post-rehabilitation target value for hours of UL activity. Individual goals for post-rehabilitation hours of UL activity could be adjusted to be consistent with pre-impairment levels of sedentary activity. Independent of the amount of expected or actual hours of UL activity that occurs as a result of rehabilitation, hours of UL activity of the impaired limb should be approximately 95% of the unimpaired UL activity when recovery has occurred, as indicated by the ratio of UL activity.

Cognitive impairment, depressive symptomatology, and number of self-reported comorbidities were not associated with hours of UL activity in our sample, even though studies show that these factors are associated with decreased general physical activity.[29,45,46] A possible reason for the lack of association between these factors and hours of UL activity is that our sample did not contain a wide distribution of values for some factors. The range of scores for cognitive impairment and number of comorbidities was low (Table 2.2). The range of scores for depressive symptomatology was larger, but still not associated with hours of UL activity (Figure 2.2b). In the clinic, patients often complete assessments that screen for cognitive impairment, depression and comorbidities. Our data suggest that low to moderate levels of cognitive impairment, depressive symptomatology, and comorbidities are not associated with hours of UL activity, and may not affect post-impairment hours of UL activity.

Two additional potential modifiers were unexpectedly unrelated to UL activity. First, there was no difference in hours of UL activity between participants living alone and those living with others (Table 2.1). We hypothesized that participants living alone would have higher UL activity, possibly as a result of increased domestic demands that cannot be completed by a partner or children. The data indicate that this is not the case. This finding is consistent with two studies that show no difference in levels of general physical activity between persons living alone versus with other people,[33,34] but not with two other studies.[32,35] Second, there was no association between hours of dominant UL activity and age. We hypothesized that decreased hours of UL activity would be associated with increased age because other studies demonstrated that decreased general physical activity is associated with increased age.[31,47,48] These disparate findings may be explained by the possibility that aging adults exchange more vigorous activities for less vigorous activities that require similar hours of UL activity. In sum, our data indicate that hours of UL activity is not associated with cohabitation status or age.

As accelerometer technology becomes more wide-spread, clinicians can use this tool to set specific goals, such as increasing a low ratio of UL activity, or achieving a ratio of UL activity in the referent range of 0.79 – 1.1. These data can help clinicians modify expectations of hours of UL activity based on pre-impairment, self-reported time spent in sedentary activity, but not self-reported cognitive impairment or depressive symptomatology. For example, consider a patient who receives care from a hand therapist following a traumatic injury to the hand. The patient reports spending a large amount of time in sedentary activity prior to sustaining the injury. The therapist should reduce the outcome goal for hours of UL activity to less than 9 hours because increased time spent in sedentary activity is associated with decreased UL activity. Similarly, the therapist can track the change in the ratio of UL activity over time. If the patient's initial ratio is 0.50 and increases to 0.80, the therapist can be confident that movement of the impaired limb has increased from 50% to 80% of movement of the unimpaired limb during the course of rehabilitation.

Beyond the clinical implications of this study, the methods and tools used in this study will be useful for rehabilitation researchers. The use of accelerometry to measure duration of UL activity could replace assessments that require significant administration time as well as eliminate reporting biases associated with self-report questionnaires. Some manufacturers offer accelerometers that transmit real-time data, which could be used to engineer systems that provide patients feedback to enhance performance as activity occurs. Additionally, as technology continues to improve and devices become more compact, it may be possible to place accelerometers on individual digits to capture skilled finger movements.

2.5.1 Limitations

Given the observational nature of this study, only association, not causation, between potential modifying factors and hours of UL activity can be determined. A prospective study examining the relationship between hours of UL activity and modifying factors would be necessary to determine causation. Second, the time spent in sedentary activity and number of comorbidities were obtained via self-report and may have been subjected to reporting bias. Future studies could more accurately quantify time spent in sedentary activity using wrist-worn accelerometry, once thresholds corresponding to sedentary activity have been validated. In order to accurately capture the number of comorbidities experienced by each study participant, data from participants' medical charts could be used. This was not feasible in the present study, however, because participants were recruited from the community and not from a single health organization.

A final comment is that most study participants were not employed. Patients with significant UL impairments are likely to not be working, therefore these findings generalize well to a rehabilitation population. It is possible that UL activity may differ for individuals who work. Hours of UL activity in a working population should be determined.

2.5.2 Conclusions

This study reported data on hours of UL activity in a comprehensive sample of community-dwelling adults and explored the associations between hours of UL activity and factors that could have potentially modified hours of UL activity. These referent values provide objective information on real-world UL activity that has previously been available only through self-report assessments. Hours of UL activity and the ratio of UL activity reflect the amount of real-world movement that occurs outside the clinic, and can be used by clinicians in conjunction with clinical assessments of UL function to set outcome goals and evaluate treatment progress for rehabilitation of the ULs.

2.6 Acknowledgments

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2.7 References

1. Webster BS, Snook SH. The Cost of Compensable Upper Extremity Cumulative Trauma Disorders. *Occup Environ Med.* 1994;36(7):713-717.

2. Zorowitz RD, Chen E, Tong KB, Laouri M. Costs and rehabilitation use of stroke survivors: a retrospective study of Medicare beneficiaries. *Top Stroke Rehabil.* 2009;16(5):309-320.

3. Yelin E, Wanke LA. An assessment of the annual and long-term direct costs of rheumatoid arthritis: the impact of poor function and functional decline. *Arthritis Rheum.* 1999;42(6):1209-1218.

4. Fabrizio AJ. Work-related upper extremity injuries: prevalence, cost and risk factors in military and civilian populations. *Work.* 2002;18(2):115-121.

5. Keogh JP, Nuwayhid I, Gordon JL, Gucer PW. The impact of occupational injury on injured worker and family: outcomes of upper extremity cumulative trauma disorders in Maryland workers. *Am J Ind Med.* 2000;38(5):498-506.

6. Baldwin ML, Butler RJ. Upper extremity disorders in the workplace: costs and outcomes beyond the first return to work. *J Occup Rehabil.* 2006;16(3):303-323.

7. Pransky G, Benjamin K, Hill-Fotouhi C, et al. Outcomes in work-related upper extremity and low back injuries: results of a retrospective study. *Am J Ind Med.* 2000;37(4):400-409.

8. Roger VL, Go AS, Lloyd-Jones DM, et al. Heart Disease and Stroke Statistics--2012 Update: A Report From the American Heart Association. *Circulation.* 2012;125(1):e2-e220.

9. Pincus T, Callahan LF, Sale WG, Brooks AL, Payne LE, Vaughn WK. Severe functional declines, work disability, and increased mortality in seventy-five rheumatoid arthritis patients studied over nine years. *Arthritis Rheum.* 1984;27(8):864-872.

10. Rand D, Eng JJ. Disparity Between Functional Recovery and Daily Use of the Upper and Lower Extremities During Subacute Stroke Rehabilitation. *Neurorehabil Neural Repair.* 2011;26(1):76-84.

11. Gross DP, Battie MC. Does functional capacity evaluation predict recovery in workers' compensation claimants with upper extremity disorders? *Occup Environ Med.* 2006;63(6):404-410.

12. Uswatte G, Foo WL, Olmstead H, Lopez K, Holand A, Simms LB. Ambulatory monitoring of arm movement using accelerometry: an objective measure of upper-extremity rehabilitation in persons with chronic stroke. *Arch Phys Med Rehabil.* 2005;86(7):1498-1501.

13. Uswatte G, Giuliani C, Winstein C, Zeringue A, Hobbs L, Wolf SL. Validity of accelerometry for monitoring real-world arm activity in patients with subacute stroke: evidence from the extremity constraint-induced therapy evaluation trial. *Arch Phys Med Rehabil.* 2006;87(10):1340-1345.

14. Uswatte G, Miltner WH, Foo B, Varma M, Moran S, Taub E. Objective measurement of functional upper-extremity movement using accelerometer recordings transformed with a threshold filter. *Stroke.* 2000;31(3):662-667.

15. Welk GJ, Schaben JA, Morrow JR, Jr. Reliability of accelerometry-based activity monitors: a generalizability study. *Med Sci Sports Exerc.* 2004;36(9):1637-1645.

16. Welk GJ. Principles of design and analyses for the calibration of accelerometry-based activity monitors. *Med Sci Sports Exerc.* 2005;37(11 Suppl):S501-511.

17. Lang CE, Wagner JM, Edwards DF, Dromerick AW. Upper extremity use in people with hemiparesis in the first few weeks after stroke. *J Neurol Phys Ther.* 2007;31(2):56-63.

18. Seitz RJ, Hildebold T, Simeria K. Spontaneous arm movement activity assessed by accelerometry is a marker for early recovery after stroke. *J Neurol.* 2011;258(3):457-463.

19. van der Pas SC, Verbunt JA, Breukelaar DE, van Woerden R, Seelen HA. Assessment of arm activity using triaxial accelerometry in patients with a stroke. *Arch Phys Med Rehabil.* 2011;92(9):1437-1442.

20. Burdick KE, Endick CJ, Goldberg JF. Assessing cognitive deficits in bipolar disorder: are self-reports valid? *Psychiatry Res.* 2005;136(1):43-50.

21. Adams SA, Matthews CE, Ebbeling CB, et al. The effect of social desirability and social approval on self-reports of physical activity. *Am J Epidemiol.* 2005;161(4):389-398.

22. Kilbreath SL, Heard RC. Frequency of hand use in healthy older persons. *Aust J Physiother.* 2005;51:119-122.

23. Michielsen ME, Selles RW, Stam HJ, Ribbers GM, Bussmann JB. Quantifying nonuse in chronic stroke patients: a study into paretic, nonparetic, and bimanual upper-limb use in daily life. *Arch Phys Med Rehabil.* 2012;93(11):1975-1981.

24. Rand D, Eng JJ. Arm-hand use in healthy older adults. *Am J Occup Ther.* 2010;64(6):877-885.

25. Martinez-Gonzalez MA, Martinez JA, Hu FB, Gibney MJ, Kearney J. Physical inactivity, sedentary lifestyle and obesity in the European Union. *Int J Obes Relat Metab Disord.* 1999;23(11):1192-1201.

26. Mokdad AH, Marks JS, Stroup DF, Gerberding JL. Actual causes of death in the United States, 2000. *JAMA.* 2004;291(10):1238-1245.

27. Yaffe K, Barnes D, Nevitt M, Lui LY, Covinsky K. A prospective study of physical activity and cognitive decline in elderly women: women who walk. *Arch Intern Med.* 2001;161(14):1703-1708.

28. Penninx BW, Leveille S, Ferrucci L, van Eijk JT, Guralnik JM. Exploring the effect of depression on physical disability: longitudinal evidence from the established populations for epidemiologic studies of the elderly. *Am J Public Health.* 1999;89(9):1346-1352.

29. Fultz NH, Ofstedal MB, Herzog AR, Wallace RB. Additive and interactive effects of comorbid physical and mental conditions on functional health. *J Aging Health.* 2003;15(3):465-481.

30. Rijken M, van Kerkhof M, Dekker J, Schellevis FG. Comorbidity of chronic diseases: effects of disease pairs on physical and mental functioning. *Qual Life Res.* 2005;14(1):45-55.

31. Caspersen CJ, Pereira MA, Curran KM. Changes in physical activity patterns in the United States, by sex and cross-sectional age. *Med Sci Sports Exerc.* 2000;32(9):1601-1609.

32. Hallal PC, Victora CG, Wells JC, Lima RC. Physical inactivity: prevalence and associated variables in Brazilian adults. *Med Sci Sports Exerc.* 2003;35(11):1894-1900.

33. Michael YL, Berkman LF, Colditz GA, Kawachi I. Living arrangements, social integration, and change in functional health status. *Am J Epidemiol.* 2001;153(2):123-131.

34. Aday RH, Kehoe GC, Farney LA. Impact of senior center friendships on aging women who live alone. *J Women Aging.* 2006;18(1):57-73.

35. Hull EE, Rofey DL, Robertson RJ, Nagle EF, Otto AD, Aaron DJ. Influence of marriage and parenthood on physical activity: a 2-year prospective analysis. *J Phys Act Health.* 2010;7(5):577-583.

36. Aadahl M, Jorgensen T. Validation of a new self-report instrument for measuring physical activity. *Med Sci Sports Exerc.* 2003;35(7):1196-1202.

37. Katzman R, Brown T, Fuld P, Peck A, Schechter R, Schimmel H. Validation of a short Orientation-Memory-Concentration Test of cognitive impairment. *Am J Psychiatry.* 1983;140(6):734-739.

38. Heun R, Papassotiropoulos A, Jennssen F. The validity of psychometric instruments for detection of dementia in the elderly general population. *Int J Geriatr Psychiatry.* 1998;13(6):368-380.

39. Andresen EM, Malmgren JA, Carter WB, Patrick DL. Screening for depression in well older adults: evaluation of a short form of the CES-D (Center for Epidemiologic Studies Depression Scale). *Am J Prev Med.* 1994;10(2):77-84.

40. Radloff LS. The CES-D scale: A self-report depression scale for research in the general population. *APPL PSYCH MEAS.* 1977;1:385-401.

41. Shinar D, Gross CR, Price TR, Banko M, Bolduc PL, Robinson RG. Screening for depression in stroke patients: the reliability and validity of the Center for Epidemiologic Studies Depression Scale. *Stroke.* 1986;17(2):241-245.

42. Schwarz N, Oyserman D. Asking questions about behavior: Cognition, communication, and questionnaire construction. *Am J Eval.* 2001;22(2):127-160.

43. Cohen G, Java R. Memory for Medical History - Accuracy of Recall. *Appl Cognitive Psych.* 1995;9(4):273-288.

44. Cohen J. *Statistical power analysis for the behavioral sciences*. 2nd ed. Hillsdale, N.J.: L. Erlbaum Associates; 1988.

45. Tatemichi TK, Desmond DW, Stern Y, Paik M, Sano M, Bagiella E. Cognitive impairment after stroke: frequency, patterns, and relationship to functional abilities. *J Neurol Neurosurg Psychiatry.* 1994;57(2):202-207.

46. Roshanaei-Moghaddam B, Katon WJ, Russo J. The longitudinal effects of depression on physical activity. *Gen Hosp Psychiatry.* 2009;31(4):306-315.

47. Bijnen FC, Feskens EJ, Caspersen CJ, Mosterd WL, Kromhout D. Age, period, and cohort effects on physical activity among elderly men during 10 years of follow-up: the Zutphen Elderly Study. *J Gerontol A Biol Sci Med Sci.* 1998;53(3):M235-241.

48. Troiano RP, Berrigan D, Dodd KW, Masse LC, Tilert T, McDowell M. Physical activity in the United States measured by accelerometer. *Med Sci Sports Exerc.* 2008;40(1):181-188.

Chapter 3: Real-World Affected Upper Limb Activity in Chronic Stroke: An Examination of Potential Modifying Factors

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3.1 Abstract

Background: Despite improvement in motor function after intervention, adults with chronic stroke experience disability in everyday activity. Factors other than motor function may influence affected upper limb (UL) activity. **Objective:** To characterize affected UL activity and examine potential modifying factors of affected UL activity in community-dwelling adults with chronic stroke. **Methods:** Forty-six adults with chronic stroke wore accelerometers on both ULs for 25 hours and provided information about potential modifying factors (time spent in sedentary activity, cognitive impairment, depressive symptomatology, number of comorbidities, motor dysfunction of the affected UL, age, activities of daily living (ADL) status, and living arrangement). Accelerometry was used to quantify duration of affected and unaffected UL activity. The ratio of affected-to-unaffected UL activity was also calculated. Associations within and between accelerometry-derived variables and potential modifying factors were examined. **Results:** Mean hours of affected and unaffected UL activity were 5.0 ± 2.2 and 7.6 ± 2.1 hours, respectively. The ratio of affected-to-unaffected UL activity was 0.64 ± 0.19, and hours of affected and unaffected UL activity were strongly correlated (r=0.78). Increased severity of motor dysfunction and dependence in ADLs were associated with decreased affected UL activity. No other factors were associated with affected UL activity. **Conclusions:** Severity of motor dysfunction and ADL status should be taken into consideration when setting goals for UL activity in people with chronic stroke. Given the strong, positive correlation between affected and unaffected UL activity, encouragement to increase activity of the unaffected UL may increase affected UL activity.

3.2 Introduction

Despite participation in rehabilitation regimens, paresis of the affected upper limb (UL) after stroke results in impaired motor function (e.g. coordination, strength) that persists for more than six months in a majority of people.[1] The focus of many physical rehabilitation approaches, such as constraint-induced movement therapy (CIMT),[2] task-specific training,[3] and robot-assisted training,[4] is to improve motor function of the affected UL because early recovery of UL function is a strong predictor for later recovery.[5] Even with improvements in motor function following intervention, adults with chronic stroke continue to experience disability in everyday activity,[6] which indicates that *additional* factors influence real-world use of the affected UL. If these additional factors can be identified, they can be targeted as part of treatment intervention to further increase affected UL activity.

Many factors, including sedentary activity, cognitive impairment, depression, multiple comorbidities, and age, are associated with reduced levels of physical activity and increased levels of disability in nondisabled adults[7-11] and adults with stroke,[12-16] and could potentially modify affected UL activity. We recently examined the relationship between these potential modifying factors and UL activity in nondisabled adults, and demonstrated that only the amount of time spent in sedentary activity was associated with activity of both ULs.[17] It is important to know if similar relationships exist in adults with chronic stroke.

Additional factors related to stroke, including dependence in Activities of Daily Living (ADL),[18] whether the dominant UL was affected by stroke,[19] and severity of motor dysfunction,[20] are associated with affected UL motor function as measured by clinical tests, and might also influence affected UL activity in adults with chronic stroke. Furthermore, living with others compared to living alone is associated with better perceived general health,[21] and could influence

UL activity. The association between these factors and affected UL activity in chronic stroke has not yet been explored.

It is also important to distinguish real-world activity (i.e. activity that occurs in an individual's home, work, and community settings) from rehabilitation-related activity that occurs inside hospital or clinical settings. In clinical settings, rehabilitation approaches that target the affected UL (e.g. CIMT and robot-assisted training) often require the affected UL to be used in a way that the limb is not typically used outside of the clinic. This is done because it is expected that gains made in therapy will translate into increased use of the affected UL in real-world settings. To ascertain if this translation truly occurs, affected UL activity needs to be measured in both real-world *and* clinical settings.

The purpose of this cross-sectional study was to characterize real-world affected UL activity, and potential modifying factors of affected UL activity, in community-dwelling adults with chronic stroke. We hypothesized that increased time spent in sedentary activity, cognitive impairment, depressive symptomatology, number of comorbidities, age, and severity of motor dysfunction would be associated with decreased real-world affected UL activity. We also hypothesized that real-world affected UL activity would be greater in participants who lived alone, and who were independent in ADLs.

3.3 Methods

3.3.1 Participants

Data from forty-six adults with chronic stroke were examined in this study. Participants were enrolled in a randomized control trial (NCT 01146379) between April 2011 and December 2013. The randomized control trial examines the dose-response effect of task-specific training on UL function in adults with mild-to-moderate chronic stroke. Only baseline (i.e. pretreatment) data were analyzed for this study. Participants were recruited from the Cognitive Rehabilitation Research Group and the Brain Recovery Core databases at Washington University School of Medicine. These databases contain contact information for patients with stroke admitted to Barnes Jewish Hospital or The Rehabilitation Institute of St. Louis in St. Louis, Missouri, USA, who consented to being contacted for potential participation in future research studies. Participants were also recruited from the community via word of mouth and flyers. All participants provided informed consent for participation in the randomized control trial, which was approved by the Human Research Protection Office at Washington University in St. Louis.

Inclusion criteria at time of consent included 1) ischemic or hemorrhagic stroke as determined by a stroke neurologist, 2) cognitive skills sufficient to participate, determined by a score of 0-1 on items 1b and 1c of the National Institutes of Health Stroke Scale (NIHSS),[22] 3) mild to moderate unilateral UL weakness, defined by a score of 1-3 on item 5 of the NIHSS, 4) ability to actively move the affected UL, determined by an Action Research Arm Test (ARAT, see Measures section of Methods for description) score of 10-49,[23] and 5) ability to provide informed consent. Exclusion criteria included 1) inability to follow commands, 2) psychiatric diagnosis, 3) current participation in stroke treatment (e.g. therapy, botox), 4) other neurological diagnosis, and 5) pregnancy.

3.3.2 Procedure

Participants completed a one-hour office visit at the Neurorehabilitation Lab at Washington University School of Medicine in St. Louis, where they provided demographic and medical information. Accelerometers were used to record duration of UL activity, and were placed on both wrists, proximal to the ulnar styloid, at the beginning of the office visit. Participants completed a battery of study assessments that measured potential modifying factors of affected UL activity. Participants were then instructed to wear the accelerometers for the subsequent 24 hours while they went about their normal daily routines, with permission to remove the devices when bathing or showering. Participants returned the accelerometers on a subsequent visit, at which time accelerometry data were visually inspected to ensure that patients wore the accelerometers during the designated wearing period.

3.3.3 Measures

Accelerometry-Derived Variables that Quantify UL Activity

Real-world activity of the ULs was captured using accelerometers. The GT3X Activity Monitor (Actigraph; Pensacola, Florida) measures acceleration in three axes with a dynamic range of ± 6 gravitational units. Data is stored on an on-board microchip that can be downloaded at a later time. Due to its small (38 x 37 x 18 mm) size and portability, the GT3X Activity Monitor is ideal for measuring activity that occurs in real-world settings. Use of accelerometry to measure real-world UL activity in people with stroke has established validity and reliability.[24-26]

Acceleration was sampled in all three axes at 30Hz. Raw acceleration was integrated into 1 second samples, and converted into activity counts (0.001664g/count) using ActiLife 6 software (ActiGraph; Pensacola, FL). Data were then processed using MATLAB R2011b (Mathworks; Natick, MA). A custom-written program combined activity counts from all three axes into a single value, called the vector magnitude, using the following equation: $\sqrt{(x^2 + y^2 + z^2)}$. Vector magnitudes were calculated for each second of activity. Vector magnitude values were then dichotomized into two categories using a filter threshold.[17,27] Seconds when the vector magnitude was ≥2 were defined as "activity," and seconds when the vector magnitude was <2 were defined as "no activity." Seconds of activity were summed to determine hours of affected and unaffected UL activity. The activity ratio was calculated by dividing hours of affected UL activity by hours of unaffected UL activity.[17,27]

Two accelerometry-derived variables quantify real-world affected UL activity: hours of affected UL activity and the activity ratio. Hours of affected UL activity directly reflects duration of real-world affected UL activity. The activity ratio, which is also referred to in the literature as the "ratio of more- to-less-impaired arm acceleration,"[24] reflects affected UL activity with respect to unaffected UL activity. Importantly, the activity ratio is stable (mean ± SD = 0.95 ± 0.06) and independent of hours of UL activity in nondisabled adults (r = 0.08).[17]

Potential Modifiers of UL Activity

Factors hypothesized to modify affected UL activity included time spent in sedentary activity, cognitive impairment, depressive symptomatology, number of comorbidities, severity of stroke-induced motor dysfunction, age, ADL status, and living arrangement (see Introduction).

Time spent in sedentary activity during a typical weekday, quantified in hours, was assessed using the Physical Activity Scale, a valid self-report measure of daily physical activity.[28,29] Sedentary activity was defined as activity of 1.4 METS (Metabolic Equivalent of Task[30]) or less, and includes activities such as sleeping, reading, and watching television.

Cognitive impairment was quantified using the Short Blessed Test, a cognitive screening test used to assess memory, orientation, and concentration.[31] This tool has been used to assess cognitive impairment in adults with stroke.[13,32,33] Errors on six questions are weighted (total score = 28), with higher scores indicating more-impaired cognition. Scores ≥6 indicate probable cognitive impairment.[34]

Depressive symptomatology was assessed using the Center for Epidemiological Studies Depression Scale, a screening test for depression and depressive disorder[35] that has been validated for use in adults with stroke.[36,37] Twenty questions are scored on a 4-point Likert scale (total score = 60), with higher scores indicating increased depressive symptomatology. Scores ≥ 16 indicate probable clinical depression.[35,38]

Number of comorbidities was obtained using a checklist of common medical conditions. Self-reported recall of health conditions is more accurate with checklists than with open- or free-response methods.[39,40]

Severity of stroke-induced motor dysfunction was assessed using the ARAT, a performance-based assessment with established reliability that quantifies the capacity to reach, grasp, move/manipulate, and release objects (total score = 57).[41-43] Higher scores indicate less motor dysfunction.

Age was obtained from the recruitment databases. ADL status (i.e. independent versus dependent for bathing, grooming, or dressing) and living arrangement (i.e. lives with others versus alone) were collected via self-report.

Additional self-reported demographic and health characteristics (i.e. education, employment, hand dominance, side affected by stroke, time since most-recent stroke, number of strokes) were collected according to routine clinical practice, and where appropriate, examined to see if they influenced potential modifiers of affected UL activity (i.e. moderating effects were examined).

3.3.4 Statistical Analysis

Statistical analyses were performed using IBM SPSS Statistics for Windows, Version 21 (IBM Corp., Armonk, NY). All data were checked for normality using Shapiro-Wilk tests and variance was assessed using Levene's test.[44] Means and standard deviations were calculated for normally-distributed variables, and medians and interquartile ranges (IQR) were calculated for non-normally-distributed variables. Correlation analyses (Pearson, Spearman, and biserial[44]) were used to examine associations among and between hours of affected UL activity, hours of unaffected UL activity, the activity ratio, and potential modifiers of affected UL activity. Correlation coefficients <0.30 were weak, between 0.30 and 0.60 were moderate, and ≥0.60 were considered strong.[45] Independent t-tests were used to examine differences in hours of affected and unaffected UL activity; and to examine differences in hours of affected UL activity and the activity ratio based on ADL status, living arrangement, and whether the dominant versus the nondominant UL was affected. All significance tests were two-tailed and criteria for significance was set at alpha = 0.05.

3.4 Results

Forty-six subjects participated in this study. Mean age was 60 ± 11 years. Sex (male: n=30/46), race (African American: n=24/46; Caucasian: n=22/46), and side affected by stroke (dominant: n=24/46) were well-represented across participants. The median time since most-recent stroke was 0.9 (IQR = 1.4) years, and the median number of strokes was 1 (IQR = 1). Participants wore the accelerometers for the designated wearing period (median: 24.9 hours, IQR: 1.55 hours). No technical problems with the accelerometers were observed.

Descriptive statistics of potential modifiers of affected UL activity are provided in Table 3.1. Participants spent 63% (15.8/25 hours) of their time during a typical weekday in sedentary activity. Scores for self-reported cognitive impairment, depressive symptomatology, number of comorbidities, and age exhibited a broad range of values. All participants experienced motor dysfunction of the affected UL, as indicated by Action Research Arm Test scores. A majority of participants were independent in ADLs and lived with others. The dominant UL was affected in approximately half of study participants.

Table 3.1 Descriptive statistics of, and correlations between, potential modifiers, hours of affected UL activity, and the activity ratio (n=46, except as noted)

Potential Modifiers	**Mean ± SD or Median (IQR)**	**Range**	**Correlations**	
			Hours of Affected UL Activity	Activity Ratio
Hours of Sedentary Activity†	15.8 ± 4.0	6 – 23	0.00	0.27
Cognitive Impairment†	2 (7)	0 – 28	-0.09	0.17
Depressive Symptomatology	9 (17)	0 – 52	0.15	0.18
Number of Comorbidities	3 (2)	0 – 7	-0.02	-0.08
Motor Dysfunction of Affected UL	36 (15)	10 – 48	0.49*	0.63*
Age	60 ± 11	32 – 83	0.00	-0.02
	N (%)			
ADL Status (independent)	37 (80)			
Living Arrangement (lives with others)	34 (74)			
Dominant UL Affected	24 (52)			

†Assessment scores were missing for some participants; for Hours of Sedentary Activity, n = 36; for Cognitive Impairment, n = 45
*p < 0.01
Abbreviations: ADL = Activities of Daily Living, UL = Upper Limb

Hours of affected UL activity (5.0 ± 2.2, range: 0.8-10.4) were significantly less than hours of unaffected UL activity (7.6 ± 2.1, range: 2.0-11.6, $p < 0.01$). Hours of affected UL activity were positively associated with hours of unaffected UL activity ($r = 0.78$, $p < 0.01$), as illustrated in Figure 3.1. The activity ratio was 0.64 ± 0.19 (range: 0.32-1.00).

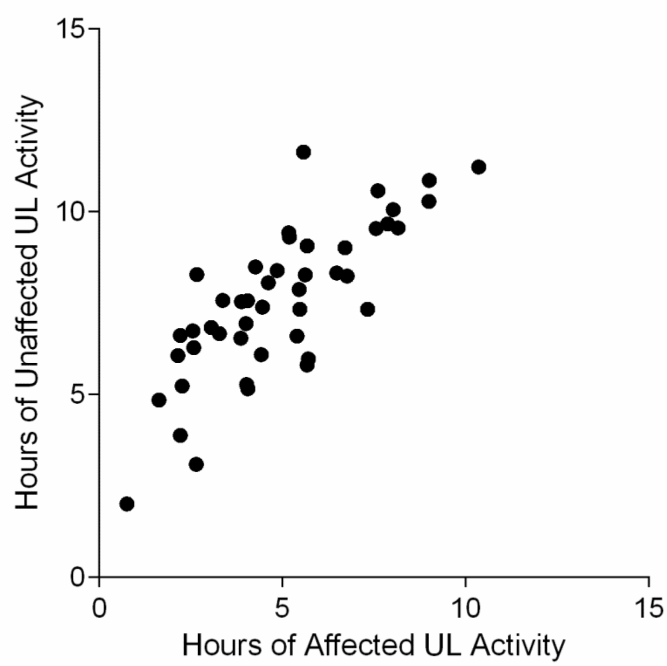

Figure 3.1 Scatterplot of hours of affected versus unaffected UL activity. The correlation between the two variables was strong (r=0.78).

Correlation coefficients between potential modifiers and both hours of affected UL activity and the activity ratio are provided in Table 3.1. Severity of motor dysfunction of the affected UL was moderately associated with hours of affected UL activity, and strongly associated with the activity ratio. Correlation coefficients between the remaining potential modifiers listed in Table 3.1 and both hours of affected UL activity and the activity ratio were weak and lacked significance (for all values, $p > 0.12$). Affected UL activity was greater in participants who were independent in ADLs (5.4 ± 2.1 hours) than in participants who received assistance for bathing, grooming, or dressing (3.0 ± 1.3 hours, $p < 0.01$, Figure 3.2a). The activity ratio also was greater in participants who were independent in ADLs (0.68 ± 0.18) than in participants who received assistance (0.48 ± 0.13, $p < 0.01$, Figure 3.2b). For living arrangement, there was no difference between participants who lived alone versus those who lived with others in hours of affected UL activity (mean difference: 0.09 hours, $p = 0.9$) or the activity ratio (mean difference: 0.02, $p = 0.78$).

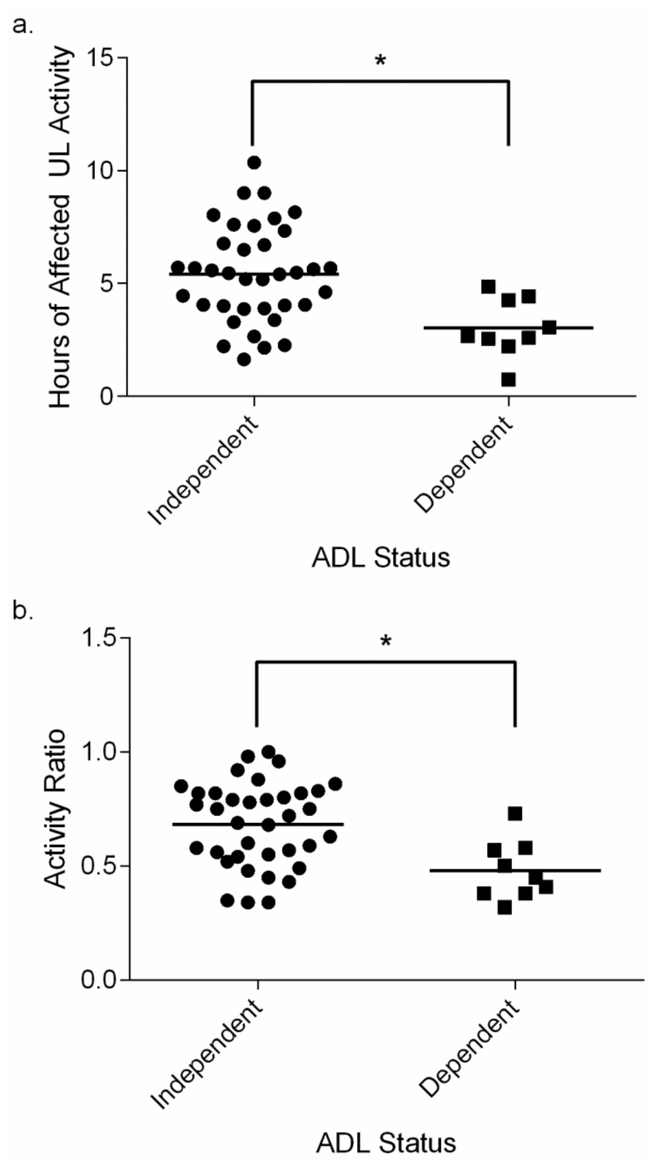

Figure 3.2 ADL status versus real-world affected UL activity. Each symbol represents a single subject. Horizontal lines represent mean values. Hours of affected UL activity (a) and the activity ratio (b) were significantly higher in participants who were independent for bathing, grooming, or dressing than in participants who were dependent.
$*p < 0.01$

Secondary analyses explored the relationship between additional stroke-related variables and both hours of affected UL activity and the activity ratio to see if the additional stroke-related variables influenced the correlations described above (i.e. moderating effects were examined). Time since most-recent stroke and number of strokes were not correlated with either hours of affected UL activity or the activity ratio (for all values, $\rho < 0.23$, $p > 0.60$). There was no difference in hours of affected UL activity based on whether the dominant UL was affected (mean difference: 0.75 hours, $p=0.25$). The activity ratio was higher, however, in participants whose dominant UL was affected (0.70 ± 0.18) than in participants whose nondominant UL was affected (0.57 ± 0.18, $p = 0.02$). Statistical tests investigating the relationship between potential modifiers and the activity ratio were therefore re-examined while controlling for whether the dominant UL was affected using partial correlations; no significant changes in correlation coefficients or t-test statistics were observed. Last of all, the association between ADL status and motor dysfunction of the affected UL was examined because both modifiers were associated with accelerometry-derived variables. The biserial correlation between ADL status and severity of motor dysfunction of the affected UL was not significant ($r = -0.32$, $p = 0.12$).

3.5 Discussion

The purpose of this study was to characterize real-world affected UL activity, and examine potential modifiers of UL activity, in community-dwelling adults with chronic stroke. Hours of affected UL activity were strongly correlated with hours of unaffected UL activity ($r = 0.78$), even though duration of affected UL activity was 2.6 hours less than unaffected UL activity. That the affected UL was less active than the unaffected UL was confirmed by an activity ratio of 0.64 ± 0.19. The activity ratio was higher in participants whose dominant UL was affected than in participants whose nondominant UL was affected; whether the dominant UL was affected, however, did not confound associations between the activity ratio and potential modifiers of affected UL activity. In accordance with our hypotheses, increased severity of motor dysfunction and dependence in ADLs were associated with decreased hours of affected UL activity and activity ratios. The participants' time spent in sedentary activity, cognitive impairment, depressive symptomatology, number of comorbidities, age, and living arrangement were not associated with hours of affected UL activity or the activity ratio.

Our findings confirm that real-world activity of both affected and unaffected ULs is lower in adults with chronic stroke than in adults without stroke, where real-world activity of the dominant and nondominant ULs averages 9.1 and 8.6 hours, respectively.[17] Michielsen et al. also found that activity of the ULs in adults with chronic stroke (unaffected UL: 5.3 hours, affected UL: 2.4 hours) was lower than in nondisabled adults (dominant UL: 5.4 hours, nondominant UL: 5.1 hours).[46] The authors acknowledge that the inconvenience of wearing their accelerometry-based system (consisting of 5 accelerometers across the thighs, trunk, and ULs) may have resulted in underestimation of real-world UL activity in their sample, which likely explains the difference in hours of affected and unaffected UL activity observed between this study and theirs.

While it is known that activity of both ULs is reduced immediately after stroke,[47] it is alarming that unaffected UL activity remains reduced in chronic stroke (7.6 hours compared to 9.1 hours of dominant UL activity in nondisabled adults).[17] Even though only one UL is affected at the level of impairment (i.e. hemiparesis), *both* ULs are affected at the level of activity in everyday life. The strong correlation between hours of affected and unaffected UL activity in our study indicates that decreased affected UL activity is associated with decreased unaffected UL activity. This phenomenon may be explained by the fact that many daily activities are performed bilaterally, and require both ULs to work together (e.g. stacking boxes, stabilizing a piece of paper with one hand while writing with the other hand). [48,49] Hence, reduced affected UL activity might lead to reduced unaffected UL activity. Viewed from the opposite direction, the correlation suggests that affected UL activity might be increased by increasing activity of the unaffected UL because of the bilateral nature of everyday tasks. If such a causal relationship exists, increasing unaffected UL activity in order to increase affected UL activity could be an alternative intervention strategy for patients who do not respond to, or meet entry criteria for, other interventions, such as CIMT or robotic-assisted therapy. Furthermore, it would address the issue of reduced unaffected UL activity in chronic stroke.

Whether the dominant versus nondominant UL is affected should also be considered when addressing real-world affected UL activity. This study demonstrated greater activity ratios in participants whose dominant UL was affected than in participants whose nondominant UL was affected. This finding is consistent with studies that demonstrated less motor impairment,[19] and greater recovery after bilateral arm training,[50] of the affected UL in chronic stroke patients whose dominant UL was affected. As a whole, these results suggest that people whose *nondominant* ULs are affected by stroke may need more encouragement to use their affected ULs.

Increased severity of motor dysfunction was associated with decreased hours of affected UL activity and decreased activity ratios. That better motor function and increased real-world affected UL activity are associated is unsurprising, given the positive relationship observed between tests of motor ability (e.g. Fugl-Meyer Assessment) and global function (i.e. Functional Independence Measure).[20,51,52] On the other hand, the associations between ADL status, and both hours of affected UL activity and the activity ratio are not as straightforward. While it is reasonable to assume that dependence in ADLs can occur as a result of UL motor dysfunction, it is not the sole contributor to dependence in ADLs. Paresis of the lower limb, poor balance, and cognitive status, among other factors, can also contribute to dependence in ADLs. Interventions other than increasing motor function of the affected UL, such as use of adaptive equipment, might allow a person to be independent in ADLs while indirectly contributing to increased affected UL activity (e.g. use of adaptive equipment could encourage use of both ULs to complete many tasks).

Time spent in sedentary activity, cognitive impairment, depressive symptomatology, number of comorbidities, age, and living arrangement were not associated with hours of affected UL activity or the activity ratio. In nondisabled adults, these same factors were not associated with hours of real-world UL activity, with the exception of time spent in sedentary activity, which showed a modest correlation (r = -0.36).[17] In the present study, the parameters used to assess time spent in sedentary activity, hours of affected UL activity, and the activity ratio were sufficiently broad to detect correlations, had they existed. The range of values for cognitive impairment, depressive symptomatology, number of comorbidities, and age were also broad, and would have demonstrated significant correlations with either hours of affected UL activity or the activity ratio, had they existed. Regarding living arrangement, even though previous research indicates that living alone offers protective effects against self-perceived morbidity and poor health status,[21] living arrangement was not associated with affected UL activity in study participants. While the factors described above are associated with physical activity[12-16] and perceived general health,[21] they were not associated with real-world affected UL activity. Goals related to affected UL activity therefore need not be reduced in the presence of these factors.

3.5.1 Limitations

Because of its observational design, the main limitation of this study is its inability to demonstrate a cause-effect relationship between potential modifying factors and real-world affected UL activity. A longitudinal design would be necessary to demonstrate such a relationship. A second limitation is that accelerometry is a useful *index* of UL function in daily life, rather than a direct quantification of function itself. As used here, accelerometry cannot distinguish between volitional (i.e. reaching) and non-volitional (i.e. arm-swing during gait) movements. The effect of this on our data would be to possibly inflate the duration of UL activity, but would not likely influence the activity ratio. With advances in technology, this weakness will likely be rectified. Despite this inherent limitation at present, accelerometry is one of the best tools available for objectively measuring UL activity in real-world settings.

3.5.2 Conclusions

This study characterized real-world affected UL activity in community-dwelling adults with chronic stroke, and examined associations between affected UL activity and numerous factors hypothesized to modify affected UL activity. Increased severity of motor dysfunction and dependence in ADLs were associated with decreased hours of affected UL activity and decreased activity ratios, and should be considered when designing treatment interventions and setting goals to improve real-world affected UL activity in adults with chronic stroke. Because real-world affected and unaffected UL activity were strongly correlated, increasing real-world activity of the *unaffected* UL could be a potential strategy for increasing affected UL activity in adults with chronic stroke, and deserves further exploration.

3.6 Acknowledgments

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3.7 References

1. Wade DT, Hewer RL. Functional abilities after stroke: measurement, natural history and prognosis. *J Neurol Neurosurg Psychiatry.* Feb 1987;50(2):177-182.

2. Wolf SL, Winstein CJ, Miller JP, et al. Effect of constraint-induced movement therapy on upper extremity function 3 to 9 months after stroke: the EXCITE randomized clinical trial. *JAMA.* Nov 1 2006;296(17):2095-2104.

3. Birkenmeier RL, Prager EM, Lang CE. Translating animal doses of task-specific training to people with chronic stroke in 1-hour therapy sessions: a proof-of-concept study. *Neurorehabil Neural Repair.* Sep 2010;24(7):620-635.

4. Fasoli SE, Krebs HI, Stein J, Frontera WR, Hogan N. Effects of robotic therapy on motor impairment and recovery in chronic stroke. *Arch Phys Med Rehabil.* Apr 2003;84(4):477-482.

5. Nijland RH, van Wegen EE, Harmeling-van der Wel BC, Kwakkel G. Presence of finger extension and shoulder abduction within 72 hours after stroke predicts functional recovery: early prediction of functional outcome after stroke: the EPOS cohort study. *Stroke.* Apr 2010;41(4):745-750.

6. Bonita R, Solomon N, Broad JB. Prevalence of stroke and stroke-related disability. Estimates from the Auckland stroke studies. *Stroke.* Oct 1997;28(10):1898-1902.

7. Martinez-Gonzalez MA, Martinez JA, Hu FB, Gibney MJ, Kearney J. Physical inactivity, sedentary lifestyle and obesity in the European Union. *Int J Obes Relat Metab Disord.* Nov 1999;23(11):1192-1201.

8. Yaffe K, Barnes D, Nevitt M, Lui LY, Covinsky K. A prospective study of physical activity and cognitive decline in elderly women: women who walk. *Arch Intern Med.* Jul 23 2001;161(14):1703-1708.

9. Penninx BW, Leveille S, Ferrucci L, van Eijk JT, Guralnik JM. Exploring the effect of depression on physical disability: longitudinal evidence from the established populations for epidemiologic studies of the elderly. *Am J Public Health.* Sep 1999;89(9):1346-1352.

10. Fultz NH, Ofstedal MB, Herzog AR, Wallace RB. Additive and interactive effects of comorbid physical and mental conditions on functional health. *J Aging Health.* Aug 2003;15(3):465-481.

11. Caspersen CJ, Pereira MA, Curran KM. Changes in physical activity patterns in the United States, by sex and cross-sectional age. *Med Sci Sports Exerc.* Sep 2000;32(9):1601-1609.

12. Rand D, Eng JJ, Tang PF, Jeng JS, Hung C. How active are people with stroke?: use of accelerometers to assess physical activity. *Stroke.* Jan 2009;40(1):163-168.

13. Tatemichi TK, Desmond DW, Stern Y, Paik M, Sano M, Bagiella E. Cognitive impairment after stroke: frequency, patterns, and relationship to functional abilities. *J Neurol Neurosurg Psychiatry.* Feb 1994;57(2):202-207.

14. Whyte EM, Mulsant BH. Post stroke depression: epidemiology, pathophysiology, and biological treatment. *Biol Psychiatry.* Aug 1 2002;52(3):253-264.

15. Karatepe AG, Gunaydin R, Kaya T, Turkmen G. Comorbidity in patients after stroke: impact on functional outcome. *J Rehabil Med.* Nov 2008;40(10):831-835.

16. Kelly-Hayes M, Beiser A, Kase CS, Scaramucci A, D'Agostino RB, Wolf PA. The influence of gender and age on disability following ischemic stroke: the Framingham study. *J Stroke Cerebrovasc Dis.* May-Jun 2003;12(3):119-126.

17. Bailey RR, Lang CE. Upper-limb activity in adults: referent values using accelerometry. *J Rehabil Res Dev.* 2013;50(9):1213-1222.

18. Mercier L, Audet T, Hebert R, Rochette A, Dubois MF. Impact of motor, cognitive, and perceptual disorders on ability to perform activities of daily living after stroke. *Stroke.* Nov 2001;32(11):2602-2608.

19. Harris JE, Eng JJ. Individuals with the dominant hand affected following stroke demonstrate less impairment than those with the nondominant hand affected. *Neurorehabil Neural Repair.* Sep 2006;20(3):380-389.

20. Duncan PW, Goldstein LB, Matchar D, Divine GW, Feussner J. Measurement of motor recovery after stroke. Outcome assessment and sample size requirements. *Stroke.* Aug 1992;23(8):1084-1089.

21. Joung IM, van de Mheen H, Stronks K, van Poppel FW, Mackenbach JP. Differences in self-reported morbidity by marital status and by living arrangement. *Int J Epidemiol.* Feb 1994;23(1):91-97.

22. National Institue of Neurological Disorders and Stroke. Stroke Scales and Related Information. http://www.ninds.nih.gov/disorders/stroke/strokescales.htm. Accessed July 17, 2014.

23. Yozbatiran N, Der-Yeghiaian L, Cramer SC. A standardized approach to performing the action research arm test. *Neurorehabil Neural Repair.* Jan-Feb 2008;22(1):78-90.

24. Uswatte G, Foo WL, Olmstead H, Lopez K, Holand A, Simms LB. Ambulatory monitoring of arm movement using accelerometry: an objective measure of upper-extremity rehabilitation in persons with chronic stroke. *Arch Phys Med Rehabil.* Jul 2005;86(7):1498-1501.

25. van der Pas SC, Verbunt JA, Breukelaar DE, van Woerden R, Seelen HA. Assessment of arm activity using triaxial accelerometry in patients with a stroke. *Arch Phys Med Rehabil.* Sep 2011;92(9):1437-1442.

26. Lang CE, Bland MD, Bailey RR, Schaefer SY, Birkenmeier RL. Assessment of Upper Extremity Impairment, Function, and Activity After Stroke: Foundations for Clinical Decision Making. *J Hand Ther.* Sep 10 2012.

27. Uswatte G, Miltner WH, Foo B, Varma M, Moran S, Taub E. Objective measurement of functional upper-extremity movement using accelerometer recordings transformed with a threshold filter. *Stroke.* Mar 2000;31(3):662-667.

28. Aadahl M, Jorgensen T. Validation of a new self-report instrument for measuring physical activity. *Med Sci Sports Exerc.* Jul 2003;35(7):1196-1202.

29. Andersen LG, Groenvold M, Jorgensen T, Aadahl M. Construct validity of a revised Physical Activity Scale and testing by cognitive interviewing. *Scand J Public Health.* Nov 2010;38(7):707-714.

30. Ainsworth BE, Haskell WL, Herrmann SD, et al. 2011 Compendium of Physical Activities: a second update of codes and MET values. *Med Sci Sports Exerc.* Aug 2011;43(8):1575-1581.

31. Katzman R, Brown T, Fuld P, Peck A, Schechter R, Schimmel H. Validation of a short Orientation-Memory-Concentration Test of cognitive impairment. *Am J Psychiatry.* Jun 1983;140(6):734-739.

32. Edwards DF, Hahn MG, Baum CM, Perlmutter MS, Sheedy C, Dromerick AW. Screening patients with stroke for rehabilitation needs: validation of the post-stroke rehabilitation guidelines. *Neurorehabil Neural Repair.* Mar 2006;20(1):42-48.

33. Dromerick AW, Lang CE, Birkenmeier RL, et al. Very Early Constraint-Induced Movement during Stroke Rehabilitation (VECTORS): A single-center RCT. *Neurology.* Jul 21 2009;73(3):195-201.

34. Carr DB, Gray S, Baty J, Morris JC. The value of informant versus individual's complaints of memory impairment in early dementia. *Neurology.* Dec 12 2000;55(11):1724-1726.

35. Radloff LS. The CES-D scale: A self-report depression scale for research in the general population. *APPL PSYCH MEAS.* 1977;1:385-401.

36. Shinar D, Gross CR, Price TR, Banko M, Bolduc PL, Robinson RG. Screening for depression in stroke patients: the reliability and validity of the Center for Epidemiologic Studies Depression Scale. *Stroke.* Mar-Apr 1986;17(2):241-245.

37. Agrell B, Dehlin O. Comparison of six depression rating scales in geriatric stroke patients. *Stroke.* Sep 1989;20(9):1190-1194.

38. Lewinsohn PM, Seeley JR, Roberts RE, Allen NB. Center for Epidemiologic Studies Depression Scale (CES-D) as a screening instrument for depression among community-residing older adults. *Psychol Aging.* Jun 1997;12(2):277-287.

39. Schwarz N, Oyserman D. Asking questions about behavior: Cognition, communication, and questionnaire construction. *Am J Eval.* Spr-Sum 2001;22(2):127-160.

40. Cohen G, Java R. Memory for Medical History - Accuracy of Recall. *Appl Cognitive Psych.* Aug 1995;9(4):273-288.

41. Hsieh CL, Hsueh IP, Chiang FM, Lin PH. Inter-rater reliability and validity of the action research arm test in stroke patients. *Age Ageing.* Mar 1998;27(2):107-113.

42. Van der Lee JH, De Groot V, Beckerman H, Wagenaar RC, Lankhorst GJ, Bouter LM. The intra- and interrater reliability of the action research arm test: a practical test of upper extremity function in patients with stroke. *Arch Phys Med Rehabil.* Jan 2001;82(1):14-19.

43. van der Lee JH, Beckerman H, Lankhorst GJ, Bouter LM. The responsiveness of the Action Research Arm test and the Fugl-Meyer Assessment scale in chronic stroke patients. *J Rehabil Med.* Mar 2001;33(3):110-113.

44. Field AP. *Discovering statistics using SPSS : (and sex, drugs and rock 'n' roll)*. 3rd ed. Los Angeles: SAGE Publications; 2009.

45. Cohen J. *Statistical power analysis for the behavioral sciences*. 2nd ed. Hillsdale, N.J.: L. Erlbaum Associates; 1988.

46. Michielsen ME, Selles RW, Stam HJ, Ribbers GM, Bussmann JB. Quantifying nonuse in chronic stroke patients: a study into paretic, nonparetic, and bimanual upper-limb use in daily life. *Arch Phys Med Rehabil.* Nov 2012;93(11):1975-1981.

47. Lang CE, Wagner JM, Edwards DF, Dromerick AW. Upper extremity use in people with hemiparesis in the first few weeks after stroke. *J Neurol Phys Ther.* Jun 2007;31(2):56-63.

48. McCombe Waller S, Whitall J. Bilateral arm training: why and who benefits? *NeuroRehabilitation.* 2008;23(1):29-41.

49. Bailey RR, Klaesner, J.W., Lang, C.E. An Accelerometry-Based Methodology for Assessment of Real-World Bilateral Upper Extremity Activity. *PLoS One.* 2014.

50. McCombe Waller S, Whitall J. Hand dominance and side of stroke affect rehabilitation in chronic stroke. *Clin Rehabil.* Aug 2005;19(5):544-551.

51. Chae J, Johnston M, Kim H, Zorowitz R. Admission motor impairment as a predictor of physical disability after stroke rehabilitation. *Am J Phys Med Rehabil.* May-Jun 1995;74(3):218-223.

52. Fong KN, Chan CC, Au DK. Relationship of motor and cognitive abilities to functional performance in stroke rehabilitation. *Brain Inj.* May 2001;15(5):443-453.

Chapter 4: An Accelerometry-Based Methodology for Assessment of Real-World Bilateral Upper Extremity Activity

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4.1 Abstract

Background: The use of both upper extremities (UE) is necessary for the completion of many everyday tasks. Few clinical assessments measure the abilities of the UEs to work together; rather, they assess unilateral function and compare it between affected and unaffected UEs. Furthermore, clinical assessments are unable to measure function that occurs in the real-world, outside the clinic. This study examines the validity of an innovative approach to assess real-world bilateral UE activity using accelerometry. **Methods:** Seventy-four neurologically intact adults completed ten tasks (donning/doffing shoes, grooming, stacking boxes, cutting playdough, folding towels, writing, unilateral sorting, bilateral sorting, unilateral typing, and bilateral typing) while wearing accelerometers on both wrists. Two variables, the Bilateral Magnitude and Magnitude Ratio, were derived from accelerometry data to distinguish between high- and low-intensity tasks, and between bilateral and unilateral tasks. Estimated energy expenditure and time spent in simultaneous UE activity for each task were also calculated. **Results:** The Bilateral Magnitude distinguished between high- and low-intensity tasks, and the Magnitude Ratio distinguished between unilateral and bilateral UE tasks. The Bilateral Magnitude was strongly correlated with estimated energy expenditure ($\rho = 0.74$, $p < 0.02$), and the Magnitude Ratio was strongly correlated with time spent in simultaneous UE activity ($\rho = 0.93$, $p < 0.01$) across tasks. **Conclusions:** These results demonstrate face validity and construct validity of this methodology to quantify bilateral UE activity during the performance of everyday tasks performed in a laboratory setting, and can now be used to assess bilateral UE activity in real-world environments.

4.2 Introduction

Upper extremity (UE) function is necessary for the performance of many everyday tasks. Some tasks are performed using symmetrical movements between the UEs where kinetic and kinematic parameters are matched (e.g. carrying a heavy object).[1] Other tasks are performed unilaterally (e.g. typing with one hand). Most tasks, including many "unilateral" tasks, actually occur in between these two extremes. Classified as bilateral complimentary activity, these tasks require both extremities to work together to accomplish a goal even though one extremity may be "functionally inactive." An example of this is writing, where one hand is used to stabilize a piece of paper while the other hand manipulates a pen to write on the paper. Because most everyday tasks are completed using bilateral actions, bilateral UE function should be assessed in patients with UE impairment receiving rehabilitation services.

Surprisingly, few clinical assessments measure bilateral UE function. Many assessments measure UE function of the impaired extremity and compare it to function of the unimpaired extremity (e.g. Action Research Arm Test, Jebsen-Taylor Hand Function Test).[2] Some assessments use bilateral tasks to measure UE function. The Chedoke Arm and Hand Inventory,[3] for example, measures the ability to use both UEs to complete a task, but scoring is determined by the amount of assistance required to complete the task rather than any inherent characteristic of motor ability (e.g. speed, intensity). A further limitation of clinical assessments is that they do not measure free-living or real-world UE activity, defined as use of the UEs *outside of the clinic* to complete functional and non-functional tasks. For practical reasons, a clinician cannot personally track the activity of a patient 24 hours a day. Self-report measures of physical activity may be used to overcome this barrier, but self-reported activity is known to vary greatly with direct measures of activity[4] for many reasons, including desire for social approval[5] and cognitive impairment.[6] Clearly, existing clinical assessments are insufficient for measuring real-world bilateral UE function following UE impairment.

In an effort to measure real-world UE function, accelerometry has been introduced as an objective method to quantify real-world UE activity in healthy[7] and patient[8] populations. While accelerometry cannot distinguish arm movements that are functional (e.g. getting dressed) from non-functional (e.g. arm swing while ambulating), they serve as a useful *index* of real-world UE function (i.e. UE activity).[9] Accelerometry has been used to quantify duration and intensity of UE activity of individual extremities, as well as duration and intensity of one extremity relative to the other extremity. This approach is the same as that described for clinical assessment: unilateral activity of each UE is assessed separately and then compared. Unfortunately, UE activity of one extremity *relative* to the other extremity is not the same thing as bilateral UE activity.

As a result of these challenges, this study examined the validity of an innovative approach that uses accelerometry data to quantify bilateral UE activity during the performance of every-day tasks. Participants completed 10 everyday tasks while wearing accelerometers. Two variables were calculated from the accelerometry data, the Bilateral Magnitude and Magnitude Ratio, to reflect bilateral activity intensity and the contribution of each UE to activity. We hypothesized that these variables would distinguish high intensity tasks from low intensity tasks, and bilateral tasks from unilateral tasks. We also hypothesized that the variables would be associated with estimated energy expenditure and time spent in activity when both UEs were simultaneously active.

4.3 Methods

4.3.1 Participants

Participants for this cross-sectional study were recruited through HealthStreet, a community-based effort of the Institute of Clinical and Translational Sciences at Washington University School of Medicine in St. Louis between May and September 2012. Inclusion criteria were (a) age > 30 years, (b) ability to follow commands, and (c) dwelling in the community. Exclusion criteria were (a) self-reported history of a neurological condition and (b) self-reported history of significant UE impairment. This study was approved by the Human Research Protection Office of Washington University and conformed to the Declaration of Helsinki. A total of 74 adults provided written informed consent, participated in the study, and were compensated for their time.

4.3.2 Procedure

Participants completed a one-hour office visit at the Neurorehabilitation Lab at Washington University School of Medicine, where they provided demographic information, including self-reported hand dominance. Accelerometry was used to measure UE activity during task performance. The validity and reliability of accelerometry to measure UE activity is well-established.[8,10-13] The GT3X+ Activity Monitor (Actigraph, Pensacola, FL) contains a solid state, digital accelerometer that is capable of measuring acceleration along three axes, contains 512 MB of internal storage, and has ± 6g dynamic range. Acceleration was sampled at 30 Hz. Two accelerometers (one on each UE) were placed on distal forearms, proximal to the styloid process of the ulna, which allowed both proximal (i.e. upper arm) and distal (i.e. forearm) movements to be captured. Small movements of the hands and fingers that occur in isolation of more proximal segments, as occurs when one types on a computer but rests the forearms on a table surface, may be missed by accelerometers worn at the wrists; thus, wrist-worn accelerometry may slightly *underestimate* the actual amount of UE activity that occurs during task performance.

Participants performed eight UE tasks. The tasks were chosen to encompass a variety of UE movement patterns, including unilateral activity, symmetrical bilateral activity (where temporal, kinetic, and kinematic parameters were similar between UEs), and complementary bilateral activity (where the UEs were used in an asymmetrical but cooperative fashion to complete a task), that might be performed in real-world environments.[1] Tasks included donning/doffing shoes, grooming, stacking boxes, cutting playdough, folding towels, writing, sorting items into a tackle box, and typing. Some participants completed typing and sorting tasks predominantly one-handed (i.e. unilateral), while others completed the tasks using both hands (i.e. bilateral), resulting in ten tasks that were analyzed. A brief description of each task is given in Table 4.1. Task order was randomized using a custom-written program in MATLAB R2011b (Mathworks, Natick, MA), and task performance was video-recorded.

Table 4.1 Description of upper extremity tasks

Task	Description
Shoes	Donning and doffing shoes, including tying laces if applicable.
Grooming	Tasks requiring bilateral UE activity that occurs around the head (e.g. combing/styling hair, removing/replacing earrings, mimed make-up application, shaving in front of a mirror).
Boxes	Transferring boxes (0.91 kg; 24 cm x 15 cm x 9.5cm) between shelves located at shoulder- and waist-heights.
Cutting	Cutting playdough on a cutting board using a knife and fork.
Towels	Folding large bath towels and placing them into a pile.
Writing	Writing a short story on a piece of paper using a pencil.
Unilateral Sorting	Sorting small objects into a tackle box *with one hand* using a 3 point pinch (3-jaw-chuck).
Bilateral Sorting	Sorting small objects into a tackle box *with both hands* using a 3 point pinch (3-jaw-chuck).
Unilateral Typing	Typing a short story on a laptop computer using *one hand*.
Bilateral Typing	Typing a short story on a laptop computer using *both hands*.

To approximate movement patterns that might occur during real-world activity, participants were instructed to complete each task in a self-selected manner until the task was completed, which took between one and two minutes. Because participants were allowed to complete tasks in a self-selected manner, participants performed Bilateral Typing and Bilateral Sorting using a variety of symmetrical and complementary actions. For example, some participants were skilled typists who used both hands to type in a symmetric manner, while others were less skilled and typed by using the index fingers of both hands in a hunt-and-peck fashion. For Bilateral Sorting, some participants sorted objects using both hands at the same time, while others sorted objects by either using one hand at a time or using one hand continuously and occasionally using the other hand to help.

Participants wore the accelerometers for the next 24 hours while they went about their normal, daily routine at home. Summary analysis of accelerometry data collected during the 24 hours is reported elsewhere[14] and is not provided within this manuscript. Accelerometers were returned to the Neurorehabilitation Lab at the conclusion of the wear period, where accelerometry data were downloaded to a computer using ActiLife 6 proprietary software (ActiGraph, Pensacola, FL). ActiLife 6 software band-pass filters acceleration data between frequencies of 0.25 – 2.5 Hz, removes the effect of gravity, down-samples 30 Hz data into one second intervals by summing acceleration across samples, and converts acceleration into units called Activity Counts (1 Activity Count = 0.001664g = 0.0163m*s^{-2}).[15] Activity Counts for each task and each participant can be found in an online data repository at http://digitalcommons.wustl.edu/open_access_pubs/2901/. ActiLife 6 was also used to visually inspect accelerometry data to ensure that the accelerometers functioned properly during the recording period.

4.3.3 Variables of Interest

Accelerometry data were used to calculate two primary variables of interest, the *Magnitude Ratio* and *Bilateral Magnitude*. Figure 4.1 illustrates how data were processed and primary variables calculated for one task to assist in explanation of the methods described below. Accelerometry data were exported from ActiLife 6 to MATLAB R2011b, and variables of interest were calculated using a custom-written program. First, for each second of data, activity counts across the three axes were combined into a single value, called a vector magnitude, using the equation: $\sqrt{(x^2 + y^2 + z^2)}$ (Fig. 4.1A).[8] This was done separately for each UE. Second, vector magnitudes were smoothed using a 5-sample moving average to reduce the variability of vector magnitude amplitudes (Fig. 4.1B).

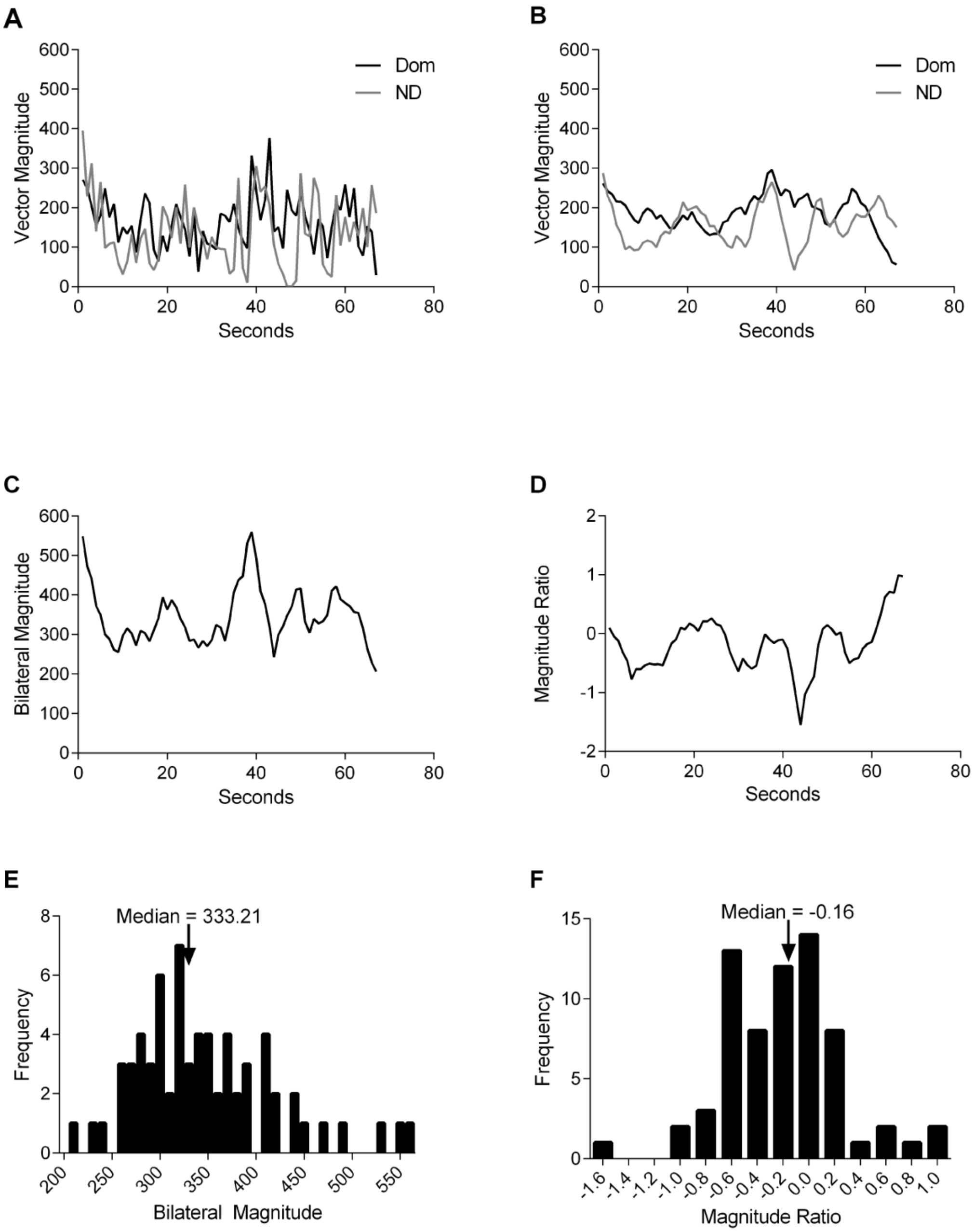

Figure 4.1 Example of data processing for one participant and one task, Grooming. A. Vector magnitude (measured in activity counts) for the dominant and nondominant UEs. B. Vector magnitudes were smoothed using a 5-sample moving average, resulting in decreased amplitudes. C. The Bilateral Magnitude (measured in activity counts) was calculated for each second of activity. D. The Magnitude Ratio was calculated for each second of activity. E & F. Histograms of Bilateral Magnitude and Magnitude Ratio values, respectively. The median values are identified by arrows.

Third, smoothed vector magnitudes were isolated for each task and were used to calculate the Bilateral Magnitudes and the Magnitude Ratios for each second of activity. We considered multiple options to quantify bilateral UE activity, but chose these primary variables because they most directly and intuitively reflected the constructs of interest, i.e. how the UEs are used together to accomplish tasks.

The Bilateral Magnitude reflects the intensity of activity across both UEs, and was calculated by summing the smoothed vector magnitude of the nondominant and dominant UEs for each second of activity (Fig. 4.1C). Bilateral Magnitude values of 0 indicate that no activity occurred, and increasing Bilateral Magnitude values indicate increasing intensity of bilateral UE activity.

The Magnitude Ratio reflects the ratio of acceleration between UEs. It was calculated for each second of activity by 1) adding one activity count to the smoothed vector magnitude of both UEs, 2) dividing the smoothed vector magnitude of the nondominant UE by the smoothed vector magnitude of the dominant UE, and 3) log-transforming the calculated values (Fig. 4.1D). The addition of one activity count was done to prevent dividing by zero for seconds when the dominant UE was inactive (i.e. denominator = 0). Log-transformation using a natural logarithm was performed to prevent positive skewness of untransformed ratio values greater than 1.0.[8] Magnitude Ratio values of 0 indicate equivalent activity contribution from both UEs; positive values indicate more nondominant UE activity and negative values indicate more dominant UE activity, relative to the opposite extremity.

After calculating the Bilateral Magnitude and Magnitude Ratio for each second of each task, seconds when no activity in either extremity occurred (i.e. the Bilateral Magnitude was equal to zero) were removed for statistical analysis. Thus, only seconds when activity occurred in at least one extremity are reflected in the results. Seconds when no activity occurred were removed from statistical analysis because the purpose of this accelerometry-based methodology is to quantify bilateral UE activity *when UE activity occurs*, and inclusion of time when no activity occurred would influence statistical analyses.

In order to establish convergent validity of the primary variables, secondary variables were calculated that were expected to correlate with the primary variables. Secondary variables included *Estimated Energy Expenditure* and *Time Spent in Simultaneous Activity*. Estimated Energy Expenditure for each task was obtained from the 2011 Compendium of Physical Activities,[16] which provides MET (Metabolic Equivalent of Task) values for various activities. One MET is defined as the amount of energy expended at rest, and equals 1.0 $kcal*kg^{-1}*h^{-1}$. MET values from 0-3 indicate light intensity activity, from 3-6 indicate moderate intensity activity, and above 6 indicates vigorous intensity activity.[17,18] This secondary variable was expected to correlate with the Bilateral Magnitude.

Time Spent in Simultaneous Activity was defined as the percentage of time that both UEs were simultaneously active, and was calculated by dividing the number of seconds when the smoothed vector magnitudes of *both* UEs were simultaneously greater than 0 activity counts by the number of seconds when the smoothed vector magnitude of *either* UE was greater than 0 activity counts. Put more simply, Time Spent in Simultaneous Activity was calculated by dividing the number of seconds that both UEs were active by the number of seconds that at least one UE was active. Time Spent in Simultaneous Activity was expected to correlate with the Magnitude Ratio because these variables quantify bilateral UE activity in different, but related, ways (i.e. duration of simultaneous UE activity vs. ratio of acceleration between UEs).

In eight cases, few (n=6) of the left-handed participants used their nondominant UE to complete tasks, even though all right-handed *and* half of the left-handed participants used their dominant UE to complete the same tasks. These cases are consistent with studies showing that left-handed adults complete some tasks with the nondominant UE more frequently than right-handed adults.[19,20] For these eight cases, the inverse of the Magnitude Ratio values were used to correct for this inconsistency.

4.3.4 Statistics

Statistical analyses were performed using IBM SPSS Statistics for Windows, Version 21 (IBM Corp., Armonk, NY). All variables at all stages of analysis were assessed for normality using Kolmogorov-Smirnov tests. Despite log transformation, all variables were not normally distributed; therefore, median values were calculated for participant- and sample-level analyses.

For each task and each participant, median Bilateral Magnitude (Fig. 4.1E) and median Magnitude Ratio (Fig. 4.1F) values were computed. Sample-level statistics were then calculated. For each task, the median and interquartile range of the median Bilateral Magnitude, median Magnitude Ratio, and Time Spent in Simultaneous Activity were computed. Outlying values were investigated but not removed because their effect on calculated median values was minimal.

Spearman correlation analyses were used to examine relationships between primary and secondary variables across all tasks. The correlation between the median Bilateral Magnitude and Estimated Energy Expenditure was examined using sample-level data because Estimated Energy Expenditure values were constant within tasks. The correlation between the median Magnitude Ratio and Time Spent in Simultaneous Activity was examined two ways: 1) using sample-level data for consistency with the approach used for the median Bilateral Magnitude and

Estimated Energy Expenditure, and 2) using participant-level data to examine if the association was maintained across participants. We computed the median and interquartile range of the correlations coefficients across participants because the values were not normally distributed. Correlation coefficients 0.60 and higher were considered to be strong, between 0.30 - 0.59 were moderate, and 0.29 and lower were weak.[21]

4.4 Results

4.4.1 Participants

Participants had a mean age of 54 (SD 11) years. Sex (female: n=39/74) and race (African-American: n=44/74, White: 30/74) were well-represented. The majority of participants were right-hand dominant (n=62/74). Video-recordings of task performance were available for all but five typing tasks due to camera misplacement. No technical problems with the accelerometers occurred during the recording period.

4.4.2 Analysis of Primary and Secondary Variables

Results for one participant, with a focus on a single task (Grooming), are presented first to facilitate understanding of sample-level data. The Magnitude Ratio and the Bilateral Magnitude both varied during the 70 seconds of task performance (Fig. 4.2A). Median values for each variable were calculated (see Figs. 4.1E, 4.1F, and 4.2A) to represent the bilateral UE activity of the task as a whole. Overall, this task was performed at a relatively high intensity (median Bilateral Magnitude = 333.21 activity counts), and the dominant UE was slightly more active than the nondominant UE (Magnitude Ratio = -0.16). Compared to Grooming, this participant performed some tasks more unilaterally as indicated by large, negative, median Magnitude Ratios (e.g. Writing & Cutting), and performed other tasks at both higher (e.g. Boxes) and lower (e.g. Cutting) intensities (Fig. 4.2B).

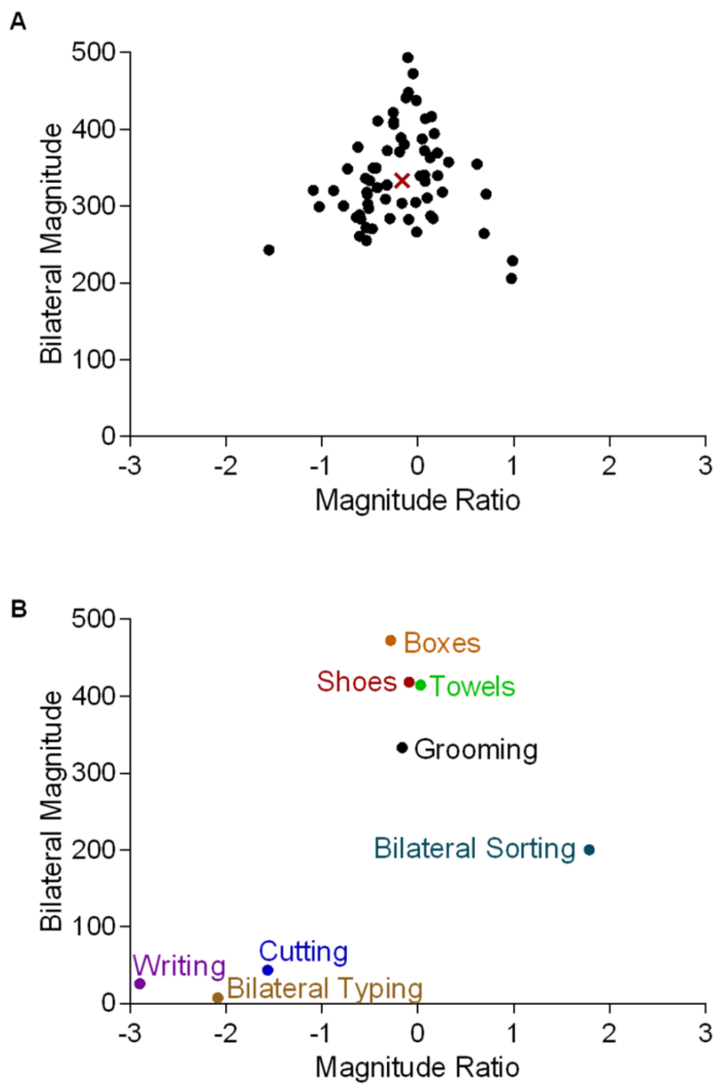

Figure 4.2 Example data for a single participant. A. Scatterplot illustrating the relationship between the Magnitude Ratio and Bilateral Magnitude (measured in activity counts) for each second of data (filled circles) for one task, Grooming. The median value of both variables is indicated by the red 'X.' B. Scatterplot illustrating how the different tasks compare to Grooming with respect to median Bilateral Magnitude and median Magnitude Ratio values. The median Magnitude Ratio for Bilateral Sorting and Bilateral Typing deviated from 0, despite these being bilateral tasks. For Bilateral Sorting, the participant used her nondominant UE to complete half of the task before using both UEs together. For Bilateral Typing, the participant frequently used her dominant UE to press the "Backspace" key, even though she used both UEs to type in a hunt-and-peck fashion.

Median and interquartile range values of primary variables for all participants are presented in Table 4.2. Median Bilateral Magnitudes ranged from 5.63 to 463.36, indicating that the tasks were performed along a continuum of low to high bilateral UE intensity. Similarly, median Magnitude Ratio values ranged from -4.68 (Unilateral Sorting) where the dominant UE was used almost exclusively to complete the task, to 0.01 (Shoes & Towels) where both UEs contributed equivalently to task performance.

Table 4.2 Median and interquartile range of median Bilateral Magnitudes and median Magnitude Ratios for each task

Activity (n*)	Bilateral Magnitude	Magnitude Ratio
	Median (IQR)	
Shoes (74)	281.32 (133.72)	0.01 (0.18)
Grooming (74)	309.69 (153.04)	-0.05 (0.28)
Boxes (74)	463.36 (78.27)	-0.05 (0.20)
Cutting (74)	50.39 (33.82)	-1.43 (1.19)
Towels (74)	426.60 (100.80)	0.01 (0.14)
Writing (74)	5.63 (6.56)	-1.95 (0.96)
Unilateral Sorting (38)	109.41 (30.19)	-4.68 (0.20)
Bilateral Sorting (36)	186.08 (183.06)	-0.14 (0.65)
Unilateral Typing (9)	19.09 (22.42)	-2.99 (1.50)
Bilateral Typing (60)	10.15 (12.58)	-0.39 (0.93)

*n=number of observations for each task, see Methods
Abbreviations: IQR, interquartile range

The middle 50 percent (25th to 75th percentiles) of median Bilateral Magnitude and median Magnitude Ratio values for each task across all participants are displayed in Figure 4.3. For the majority of tasks, median Bilateral Magnitudes and median Magnitude Ratios varied greatly across participants, indicating that the same task was performed very differently among individual participants. Despite the variability observed within tasks, tasks one might assume to be performed at higher intensities (e.g. Boxes) had high median Bilateral Magnitudes relative to tasks one might assume to be performed at lower intensities (e.g. Writing). Similarly, tasks one might assume to be performed with equal contribution from both UEs (e.g. Shoes) had median Magnitude Ratios near 0, while tasks that one might assume to be performed predominantly with the dominant hand (e.g. Unilateral Sorting) had large, negative, median Magnitude Ratios.

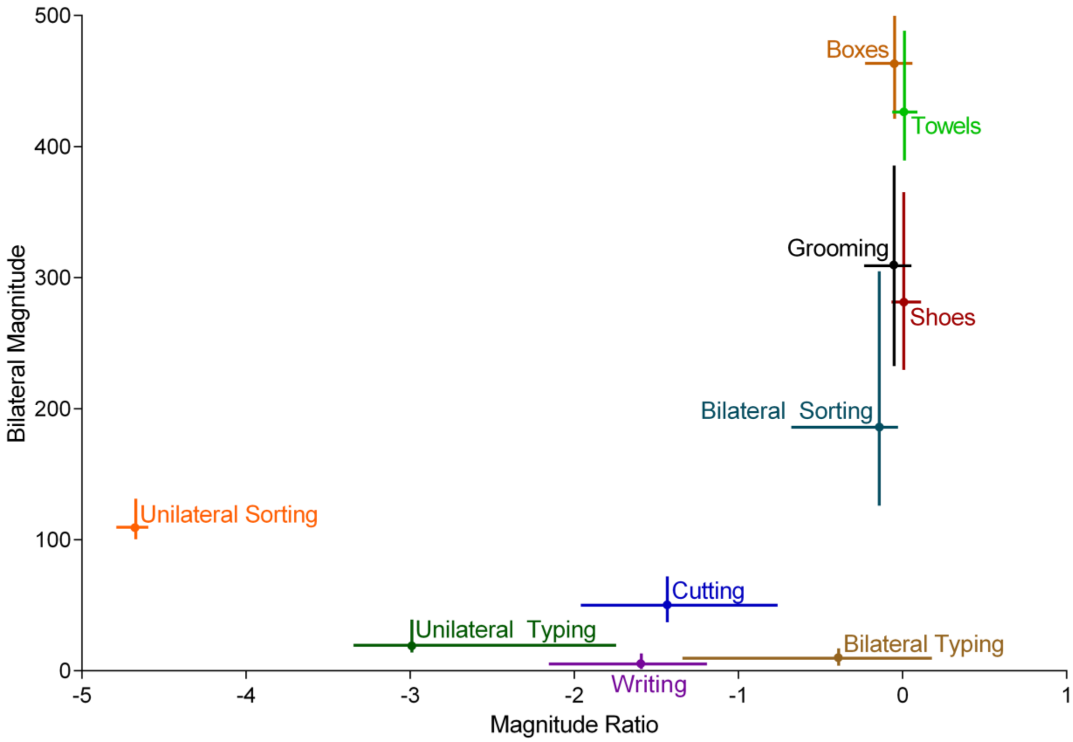

Figure 4.3 Sample data across all tasks. Values are the middle 50% (25 – 75 percentiles) of median Bilateral Magnitude (vertical bars, measured in activity counts) and median Magnitude Ratio (horizontal bars) values. Differences between tasks and variability within tasks are evident.

Values of secondary variables for each task across all participants are presented in Table 4.3. Estimated Energy Expenditure was low to moderate for the ten tasks. Nine out of ten tasks were categorized as light-intensity tasks (i.e. MET values less than 3), while one task (Boxes) was categorized as moderate intensity (MET values between 3 and 6). Both UEs were simultaneously active for a majority of tasks as indicated by a high percentage of Time Spent in Simultaneous Activity, while few tasks were completed relatively one-handed (e.g. Writing, Unilateral Sorting) as indicated by a low percentage.

Table 4.3 Values for Estimated Energy Expenditure and Time Spent in Simultaneous Activity for each task

Activity (n*)	**Estimated Energy Expenditure**†	**Percent of Time Spent in Simultaneous Activity**
	Median (IQR)	
Shoes (74)	2.50	100.00 (0.00)
Grooming (74)	2.00	100.00 (0.00)
Boxes (74)	3.30	100.00 (0.00)
Cutting (74)	2.00	94.25 (21.72)
Towels (74)	2.00	100.00 (0.00)
Writing (74)	1.30	8.75 (16.11)
Unilateral Sorting (38)	2.50	8.89 (11.16)
Bilateral Sorting (36)	2.50	98.31 (32.03)
Unilateral Typing (9)	1.30	26.74 (35.61)
Bilateral Typing (60)	1.30	62.68 (47.47)

*n=number of observations for each task, see Methods
†As measured by MET values
Abbreviations: IQR, interquartile range

Spearman correlations were calculated between primary and secondary variables across all tasks. Estimated Energy Expenditure was strongly correlated with the median Bilateral Magnitude ($\rho = 0.74$, $p < 0.02$). Time Spent in Simultaneous Activity was strongly correlated with the median Magnitude Ratio. This was true when correlations were examined using sample-level data ($\rho = 0.93$, $p < 0.01$) and participant-level data (median $\rho = 0.73$, IQR = 0.28; correlation coefficients > 0.71 were significant at $p < 0.05$).

4.5 Discussion

4.5.1 General

The purpose of this study was to examine the validity of using the Bilateral Magnitude and Magnitude Ratio to quantify bilateral UE activity during the performance of everyday tasks. Visual inspection of Figure 4.3 provides face validity for the primary variables Bilateral Magnitude and Magnitude Ratio. Higher median Bilateral Magnitude values were observed for tasks where the UEs were used more intensively (e.g. Boxes, Towels) than when the UEs were used less intensely (e.g. Writing, Cutting). Median Magnitude Ratio values close to 0 occurred during tasks when both UEs contributed equally to task performance (e.g. Boxes, Towels), while large, negative Magnitude Ratios occurred during tasks when the dominant UE was predominantly used (e.g. Writing & Unilateral Sorting).

Strong correlations between primary and secondary variables were also demonstrated; that is, construct validity for the Bilateral Magnitude and Magnitude Ratio as metrics of real-world bilateral UE activity has been established. The strong correlation between median Bilateral Magnitudes and Estimated Energy Expenditure indicates that the Bilateral Magnitude is related to task intensity, which was expected given that activity intensity and activity magnitude are related measurements (i.e. intensity = magnitude per unit of time). The strong correlation between median Magnitude Ratios and Time Spent in Simultaneous Activity was also expected because both serve as indices of bilateral UE activity. The strong correlations between primary and secondary variables across tasks also indicate that the Bilateral Magnitude and the Magnitude Ratio quantify UE activity *independently* of the task performed. These data demonstrate validity of this methodology to quantify bilateral UE activity that occurs during the performance of everyday activity.

Methods that attempt to assess bilateral UE activity by calculating unilateral activity and then computing the ratio of activity between UEs provide an incomplete understanding of bilateral UE activity. For example, if both UEs are active for 12 hours each during a 24 hour period, the ratio of activity duration would be 1.0 (e.g. 12 hours/12 hours = 1.0). This value, however, could be obtained if both extremities were simultaneously active for 12 hours (i.e. bilateral activity), or if the extremities were unilaterally active for 12 hours each. In this situation, the ratio of activity duration does not provide accurate information about *bilateral* UE activity. Similarly, if the ratio of activity intensity during a 24 hour period were calculated, a similar situation would arise. In contrast, the methodology described in this study provides quantitative information on intensity of bilateral UE activity and the contribution of each UE to activity, *when activity occurs*. This is illustrated in Figure 4.2A, where one can appreciate that the intensity of bilateral UE activity and the contribution of each UE to activity *varies* over time.

Approaches that categorize UE activity using computer-based algorithms provide important information about UE activity, but not specifically about *bilateral* UE activity. Using accelerometry data, Schasfoort et al.[13] categorized UE activity into active and passive functional categories using multiple accelerometers placed on the thighs, trunk, and forearms with moderate to high accuracy. While data from both forearms was utilized by their algorithm to identify activity, no distinction was made between unilateral and bilateral activity.

Using a different approach, Bao & Intille[22] used five accelerometers placed on the ankle, thigh, hip, forearm, and upper arm to identify 20 *specific* UE tasks, including several performed exclusively with the UEs (e.g. scrubbing, eating). As in the previous example, bilateral activity was not distinguished from unilateral activity. Additionally, the algorithm was developed to identify only 20 tasks, which is a limiting factor because real-world activity consists of many more than 20 tasks. Furthermore, previous research[23,24] has demonstrated that movement patterns across repetitions of the same task vary within individuals, which affects the accuracy of algorithms that are designed to identify specific tasks.[25,26] Because movement patterns vary *within* individuals, one might also assume that movement patterns vary *across* individuals. Examination of the variability across participants for the median Bilateral Magnitude (see Fig. 4.3), median Magnitude Ratio (see Fig. 4.3), and Time Spent in Simultaneous Activity (see Table 4.3) confirms this assumption.

The methodology described in this study does not share the limitations outlined above because the Bilateral Magnitude and Magnitude Ratio quantify bilateral UE intensity and the contribution of each UE to activity when activity occurs, and is not limited to performance of specific tasks. Furthermore, only two accelerometers are needed to calculate the Bilateral Magnitude and Magnitude Ratio, which is an important consideration because wearing fewer accelerometers may improve wearing compliance in patient populations.[27]

4.5.2 Possible Applications

Analysis of UE activity using the Bilateral Magnitude and the Magnitude Ratio provides information about both the intensity of bilateral UE activity and relative contribution of each UE to activity performance. When the Bilateral Magnitude and Magnitude Ratio are calculated for known periods of time, such as during occupational or physical therapy treatment sessions, bilateral UE activity can be assessed within and across sessions to see if increases occur. Similarly, the Bilateral Magnitude and Magnitude Ratio can be calculated for activity that occurs outside of the clinic (e.g. while a patient is at home). The values can then be compared across time to see if increases occur. If increases do not occur, either across treatment sessions or across periods of real-world activity, a clinician may conclude that the treatment approach being used is not effective and that another one should be selected. Conversely, if values increase over time, evidence is provided that the treatment approach is effective in increasing UE activity. In this way, accelerometry-based measures of bilateral UE activity can be used in conjunction with clinical tests to assess recovery of UE function and real-world UE activity.

4.5.3 Limitations

One limitation of this study is that small, observed finger movements in some participants may not have been recorded by the wrist-worn accelerometers, despite the established validity of accelerometers for measuring UE activity.[8,10-13] This potential underestimation of actual activity likely occurred because some hand movements can be made when the wrist and forearm are held still while the fingers move, as occurs in skilled typing. Many UE tasks, however, require coordinated movement of the fingers, hands, and forearm, as occurs when moving a computer mouse or reaching for and grasping a cup. This type of multi-joint activity will be captured by wrist-worn accelerometers. Additionally, the lack of recorded accelerometry data may have also resulted from the filtering algorithms utilized by the ActiLife software. If fine motor tasks are being studied, then the sensitivity of body-worn sensors and associated software for detecting small movements should be verified. This situation has a low probability of occurring in neurologic patient populations where large UE movements accompany fine-motor finger movements due to the inability to individuate joint movements.[28]

A second limitation is that validation of the methodology described in this study is limited to tasks performed in a laboratory setting. This first stage of validation, however, is consistent with approaches used by other researchers. Both Uswatte[10] and Schasfoort[13] initially validated their methodologies using standardized laboratory tasks before applying their methodologies to real-world activity. Having demonstrated construct validity in this study, future studies will use the described methodology to examine real-world bilateral UE activity in healthy and patient populations. This will allow for comparison with existing accelerometry-based approaches (i.e. duration, intensity, and ratio of UE activity during a 24 hour period).

A final limitation is that participants performed sorting and typing tasks differently. Some tasks were performed unilaterally while others were performed bilaterally. Furthermore, participants performed bilateral tasks using a variety of symmetrical and complementary actions. In hindsight, this oversight was actually appropriate because in the real-world, the same task is performed differently within and across individuals. Importantly, the Magnitude Ratio was able to distinguish tasks performed using predominantly one extremity from those performed using both extremities.

4.5.4 Conclusion

This study establishes the validity of an innovative methodology using accelerometry to assess bilateral UE activity during the performance of everyday tasks. The ability to quantify intensity of bilateral UE activity and the contribution of each UE to activity for real-world activity can be used by researchers and clinicians to select intervention approaches and evaluate the effectiveness of rehabilitation interventions. This is especially important in patient populations where bilateral UE function is impaired due to neurologic or orthopedic injury. Assessment of real-world bilateral UE activity can now be used in conjunction with clinical tests of function and patient-centered outcome measures to assess recovery of bilateral UE function in patient populations.

4.6 Acknowledgements

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4.7 References

1. McCombe Waller S, Whitall J. Bilateral arm training: why and who benefits? *NeuroRehabilitation.* 2008;23(1):29-41.

2. Lang CE, Bland MD, Bailey RR, Schaefer SY, Birkenmeier RL. Assessment of Upper Extremity Impairment, Function, and Activity After Stroke: Foundations for Clinical Decision Making. *J Hand Ther*. 2012.

3. Barreca S, Gowland CK, Stratford P, et al. Development of the Chedoke Arm and Hand Activity Inventory: theoretical constructs, item generation, and selection. *Top Stroke Rehabil.* 2004;11(4):31-42.

4. Prince SA, Adamo KB, Hamel ME, Hardt J, Gorber SC, Tremblay M. A comparison of direct versus self-report measures for assessing physical activity in adults: a systematic review. *Int J Behav Nutr Phys Act.* 2008;5:56.

5. Adams SA, Matthews CE, Ebbeling CB, et al. The effect of social desirability and social approval on self-reports of physical activity. *Am J Epidemiol.* 2005;161(4):389-398.

6. Jobe JB. Cognitive processes in self report. In: A.A. S, Turkann JS, Bachrach CA, Jobe JB, Kurtzman HS, Cain VS, eds. *The science of self-report: implications for research and practice*. Mahwah: Lawrence Erlbaum Associates; 2000:25-28.

7. Rand D, Eng JJ. Arm-hand use in healthy older adults. *Am J Occup Ther.* 2010;64(6):877-885.

8. van der Pas SC, Verbunt JA, Breukelaar DE, van Woerden R, Seelen HA. Assessment of arm activity using triaxial accelerometry in patients with a stroke. *Arch Phys Med Rehabil.* 2011;92(9):1437-1442.

9. Uswatte G, Giuliani C, Winstein C, Zeringue A, Hobbs L, Wolf SL. Validity of accelerometry for monitoring real-world arm activity in patients with subacute stroke: evidence from the extremity constraint-induced therapy evaluation trial. *Arch Phys Med Rehabil.* 2006;87(10):1340-1345.

10. Uswatte G, Miltner WH, Foo B, Varma M, Moran S, Taub E. Objective measurement of functional upper-extremity movement using accelerometer recordings transformed with a threshold filter. *Stroke.* 2000;31(3):662-667.

11. Welk GJ. Principles of design and analyses for the calibration of accelerometry-based activity monitors. *Med Sci Sports Exerc.* 2005;37(11 Suppl):S501-511.

12. Welk GJ, Schaben JA, Morrow JR, Jr. Reliability of accelerometry-based activity monitors: a generalizability study. *Med Sci Sports Exerc.* 2004;36(9):1637-1645.

13. Schasfoort FC, Bussmann JB, Stam HJ. Ambulatory measurement of upper limb usage and mobility-related activities during normal daily life with an upper limb-activity monitor: a feasibility study. *Med Biol Eng Comput.* 2002;40(2):173-182.

14. Bailey RR, Lang CE. Upper-limb activity in adults: referent values using accelerometry. *J Rehabil Res Dev.* 2013;50(9):1213-1222.

15. Hawk L. ActiGraph Data Conversion Process. https://help.theactigraph.com/entries/21702957-ActiGraph-Data-Conversion-Process. Accessed January 14, 2015.

16. Ainsworth BE, Haskell WL, Herrmann SD, et al. 2011 Compendium of Physical Activities: a second update of codes and MET values. *Med Sci Sports Exerc.* 2011;43(8):1575-1581.

17. Freedson PS, Melanson E, Sirard J. Calibration of the Computer Science and Applications, Inc. accelerometer. *Med Sci Sports Exerc.* 1998;30(5):777-781.

18. Haskell WL, Lee IM, Pate RR, et al. Physical activity and public health: updated recommendation for adults from the American College of Sports Medicine and the American Heart Association. *Med Sci Sports Exerc.* 2007;39(8):1423-1434.

19. Borod JC, Caron HS, Koff E. Left-handers and right-handers compared on performance and preference measures of lateral dominance. *Br J Psychol.* 1984;75 (Pt 2):177-186.

20. Steenhuis RE. The relation between hand preference and hand performance: what you get depends on what you measure. *Laterality.* 1999;4(1):3-26.

21. Cohen J. *Statistical power analysis for the behavioral sciences*. 2nd ed. Hillsdale, N.J.: L. Erlbaum Associates; 1988.

22. Bao L, Intille SS. Activity recognition from user-annotated acceleration data. *LECT NOTES COMPUT SC.* 2004;3001/2004:1-17.

23. Slifkin AB, Newell KM. Is variability in human performance a reflection of system noise? *Curr Dir Psychol Sci.* 1998;7(6):170-177.

24. Stergiou N, Decker LM. Human movement variability, nonlinear dynamics, and pathology: is there a connection? *Hum Mov Sci.* 2011;30(5):869-888.

25. Preece SJ, Goulermas JY, Kenney LP, Howard D. A comparison of feature extraction methods for the classification of dynamic activities from accelerometer data. *IEEE Trans Biomed Eng.* 2009;56(3):871-879.

26. Staudenmayer J, Pober D, Crouter S, Bassett D, Freedson P. An artificial neural network to estimate physical activity energy expenditure and identify physical activity type from an accelerometer. *J Appl Physiol (1985).* 2009;107(4):1300-1307.

27. Michielsen ME, Selles RW, Stam HJ, Ribbers GM, Bussmann JB. Quantifying nonuse in chronic stroke patients: a study into paretic, nonparetic, and bimanual upper-limb use in daily life. *Arch Phys Med Rehabil.* 2012;93(11):1975-1981.

28. Lang CE, Beebe JA. Relating movement control at 9 upper extremity segments to loss of hand function in people with chronic hemiparesis. *Neurorehabil Neural Repair.* 2007;21(3):279-291.

Chapter 5: Quantifying Real-World Upper Limb Activity in Nondisabled Adults and Adults with Chronic Stroke

This chapter has been accepted for publication:

Bailey RR, Klaesner JW, & Lang CE. Quantifying real-world upper limb activity in nondisabled adults and adults with chronic stroke. *Neurorehabil Neural Repair, (in press)*.

5.1 Abstract

Background. Motor capability is commonly assessed inside the clinic, but motor performance in real-world settings (i.e. outside of the clinic) is seldom assessed because measurement tools are lacking. **Objective.** To quantify real-world bilateral upper limb (UL) activity in nondisabled adults and adults with stroke using a recently-developed accelerometry-based methodology. **Methods.** Nondisabled adults (n=74) and adults with chronic stroke (n=48) wore accelerometers on both wrists for 25-26 hours. Motor capability was assessed using the Action Research Arm Test (ARAT). Accelerometry-derived variables were calculated to quantify intensity of bilateral UL activity (i.e. Bilateral Magnitude) and the contribution of both ULs to activity (Magnitude Ratio) for each second of activity. Density plots were used to examine each second of bilateral UL activity throughout the day. **Results.** Nondisabled adults demonstrated equivalent use of dominant and nondominant ULs, indicated by symmetrical density plots and a median Magnitude Ratio of -0.1 (Interquartile Range: 0.3) where a value of 0 indicates equal activity between ULs. Bilateral UL activity intensity was lower ($p<0.001$) and more lateralized in adults with stroke as indicated by asymmetrical density plots and a lower median Magnitude Ratio (-2.2, Interquartile Range: 6.2, $p<0.001$). Density plots were similar between many stroke participants who had different ARAT scores, indicating that real-world bilateral UL activity was similar despite different motor capabilities. **Conclusions.** Quantification and visualization of real-world bilateral UL activity can be accomplished using this novel accelerometry-based methodology, and complements results obtained from clinical tests of function when assessing recovery of UL activity following neurologic injury.

5.2 Introduction

Many daily tasks require that both upper limbs (ULs) work together in a complementary fashion to accomplish a goal (e.g. writing with one hand while stabilizing a piece of paper with the other hand).[1,2] As such, recovery of bilateral UL function after stroke is desirable. In order to assess bilateral UL function, valid and reliable measures are required. Kinematic analyses are commonly used in laboratory settings to assess UL movement parameters (e.g. velocity, accuracy, efficiency),[3,4] while standardized assessments (e.g. Jebsen Hand Function Test,[5] Action Research Arm Test[6]) are commonly used in clinical settings to measure UL function.

These approaches assess motor *capabilities* (i.e. what a person "can do") in structured research and clinical settings, but they do not measure motor *performance* (i.e. what a person actually does) in unstructured environments (e.g. at home, work, and in the community. The distinction between capability and performance has been shown in previous studies where participants were more likely to use their non-paretic limb during spontaneous task conditions (i.e. motor performance) despite adequate motor capability of the paretic UL observed during forced-use conditions.[7,8] Thus, motor capability and motor performance are different constructs and should be assessed separately.[9]

One approach to measuring motor performance is the use of self-report questionnaires. Unfortunately, self-report questionnaires can be subject to report bias due to cognitive impairment following stroke (e.g. impaired comprehension, memory recall, and attention[10-12]) and social desirability (e.g. desire to please the doctor or therapist, embarrassment over not completing more activity[13]). Furthermore, often only moderate correlations are observed between self-reported and direct measurement (e.g. heart rate monitoring, double-labeled water, accelerometry) of physical activity.[14]

As an alternative to self-report questionnaires, wrist-worn accelerometry has emerged as a tool to assess motor performance that occurs throughout the day. We refer to this activity as real-world UL activity to emphasize that it occurs outside of structured settings.[15] The small size and portability make it possible for accelerometers to be worn while individuals go about their day-to-day activities. Although one cannot determine the specific actions performed from accelerometry recordings, (e.g. cutting with a fork and knife vs. writing[16]), it nevertheless is a useful *index* of real-world UL function.[17] To date, accelerometry has been used to quantify duration and intensity of daily UL activity of the ULs separately, and then compare UL activity between limbs.[17-21] While this practice provides general information about how active one limb is relative to the other (e.g. paretic UL relative to the non-paretic UL), it does not provide information about how both ULs are used together during task performance.

Recently, we developed an accelerometry-based methodology that quantifies bilateral UL activity by calculating two variables, the Bilateral Magnitude and the Magnitude Ratio, to respectively quantify intensity of bilateral UL activity and the contribution of each UL to activity, on a second-by-second basis.[16] Using tasks performed in a laboratory setting, these variables were able to distinguish high-intensity tasks from low-intensity tasks, and tasks that were completed using both hands from tasks that were completed relatively one-handed. This methodology has potential use for measuring bilateral UL activity in real-world settings.

The purpose of the current study was to examine real-world bilateral UL activity in nondisabled adults and adults with chronic stroke as they went about their normal, daily routine. We examined both summary statistics and second-by-second values for the Bilateral Magnitude and Magnitude Ratio because we hypothesized that second-by-second values would vary greatly with respect to the summary statistics. Using density plots to visualize each second of data, we show that bilateral UL activity varies throughout the day and that bilateral UL activity differs between nondisabled adults and adults with chronic stroke.

5.3 Methods

5.3.1 Participants

Nondisabled adults and adults with chronic stroke participated in this cross-sectional study. Nondisabled adults were recruited through HealthStreet, a community-based recruitment program operated by Washington University School of Medicine in St. Louis. Inclusion criteria were 1) age > 30 years, 2) ability to follow commands, and 3) dwelling in the community. Exclusion criteria included a self-reported history of neurological condition or significant UL impairment.

Adults with chronic stroke participated in a randomized controlled trial (NCT 01146379) investigating the dose-response effect of task-specific training on UL function. Adults with stroke were recruited from the Cognitive Rehabilitation Research Group and the Brain Recovery Core databases at Washington University School of Medicine in St. Louis, which contain contact information for adults with stroke who consented to being contacted for participation in research studies. This study analyzed only pretreatment (i.e. baseline) data.

Inclusion criteria were 1) diagnosis of an ischemic or hemorrhagic stroke, 2) sufficient cognitive skills to participate as determined by a score of 0-1 on items 1b and 1c of the National Institutes of Health Stroke Scale (NIHSS),[22] 3) unilateral UE weakness defined by a score of 1-3 on item 5 of the NIHSS, 4) motor capability as determined by a score of 10-48 on the Action Research Arm Test (ARAT, max score = 57 and indicates normal motor ability),[6,23] 5) dwelling in the community, and 6) at least six months poststroke. Exclusion criteria included 1) inability to follow 2-step commands, 2) psychiatric diagnosis, 3) other neurological diagnosis, and 4) pregnancy.

All participants provided informed consent and were compensated for their time. This study was approved by the Human Research Protection Office of Washington University and conformed to the Declaration of Helsinki.

5.3.2 Procedure

Participants completed a 1-2 hour lab visit. They provided demographic and health information and completed study assessments that examined factors related to UL activity, which have been reported elsewhere.[15,24] Specific factors of interest for the present study included self-reported hand dominance (pre-stroke hand dominance for adults with stroke), and motor capability of the paretic UL (as measured by the ARAT). Accelerometers were placed on both wrists, proximal to the ulnar styloid. Accelerometers were initialized and synchronized using ActiLife 6 proprietary software (ActiGraph, Pensacola, FL). Participants were instructed to wear the accelerometers for the subsequent 24 hours (including sleep) while they went about their normal, daily routines, with permission to remove the devices when bathing or showering. Accelerometers were returned to the lab during a subsequent visit.

5.3.3 Accelerometry

Wrist-worn accelerometry has established validity and reliability for measuring UL activity in nondisabled adults and adults with stroke.[19,20,25,26] GT3X+ Activity Monitors (Actigraph, Pensacola, FL) were used to measure activity. These wireless devices are small (38 x 37 x 18 mm), contain a solid-state accelerometer that has a dynamic range of ± 6 gravitational units, and store data locally. Accelerations were recorded along three axes at 30 Hz. Accelerometry data were downloaded using ActiLife 6 software, which band-pass filtered data between frequencies of 0.25-2.5 Hz, used a proprietary process to remove acceleration due to gravity, down-sampled data to 1 Hz (i.e. one second) samples, and converted acceleration into activity counts (0.001664g/count).[27] ActiLife 6 was also used to visually inspect the accelerometry data to ensure that the accelerometers functioned properly during the recording period.

5.3.4 Primary Variables of Interest

Accelerometry data were used to calculate two primary variables of interest: the *Bilateral Magnitude* and the *Magnitude Ratio*. The Bilateral Magnitude quantifies the intensity of activity across both ULs, whereas the Magnitude Ratio quantifies the contribution of each UL to activity. Validation of these variables as measures of bilateral UL activity and a description of how they are calculated has been reported previously.[16] Briefly, accelerometry data were exported from ActiLife 6 software to MATLAB R2011b (Mathworks; Natick, MA) and processed using custom-written software. For each second of data, accelerations were combined across axes into a single vector magnitude value using the equation $\sqrt{(x^2 + y^2 + z^2)}$. The *Bilateral Magnitude* was calculated for each second of activity by summing the vector magnitude of both ULs.[16] Bilateral Magnitude values of 0 indicate that no activity occurred across either UL, while increasing Bilateral Magnitude values indicate increasing UL activity intensity.

The *Magnitude Ratio* was calculated for each second of activity by dividing the vector magnitude of one UL by the vector magnitude of the contralateral UL.[16] For nondisabled adults, the nondominant UL was divided by the dominant UL; for adults with stroke, the paretic UL was divided by the non-paretic UL. The calculated values were then transformed using a natural logarithm to prevent skewness of positive, untransformed values.[20] Magnitude Ratios could not be accurately calculated for seconds when unilateral UL activity occurred (because 0 would appear in the numerator or denominator), therefore seconds when unilateral dominant/nonparetic UL activity occurred were assigned a constant value of -7 while seconds when unilateral nondominant/paretic UL activity occurred were assigned a value of +7. Magnitude Ratio values of 0 indicate that both ULs contributed equally to activity. Negative values indicate more dominant/non-paretic UL activity relative to the nondominant/paretic UL, while the opposite is true for positive values. Because examination of UL activity was the purpose of this study, seconds when neither UL was active (i.e. the Bilateral Magnitude was equal to 0) were removed from analysis.

5.3.5 Secondary Variables of Interest

Four secondary variables were calculated: duration of 1) dominant/non-paretic unilateral, 2) nondominant/paretic unilateral, 3) simultaneous, and 4) total UL activity, to summarize general UL activity that occurred during a typical day. Data were dichotomized into "active" or "not active" based on whether or not an activity count was recorded for each second. Unilateral UL activity was defined as seconds when only *one* UL was active, and simultaneous UL activity was defined as seconds when *both* ULs were active. Duration of total UL activity was obtained by summing the duration of unilateral and simultaneous UL activity, thus reflecting the duration of time when *either* UL was active.

5.3.6 Statistics and Examination of Accelerometry-Derived Variables

IBM SPSS Statistics for Windows, Version 21 (IBM Corp., Armonk, NY) was used. Normality of accelerometry-derived variables was assessed using Kolmogorov-Smirnov tests. For individual-level data, median values for the Bilateral Magnitude and Magnitude Ratio were calculated because these variables were not normally distributed. For group-level data, summary statistics (i.e. means and standard deviations or medians and interquartile ranges (IQR)) were calculated for each variable. Note that the IQR represents the range of the middle 50% of data values for a given variable. Parametric (i.e. independent samples t-tests) and non-parametric (i.e. Pearson's chi-Square tests, Mann-Whitney U tests) analytical tests were used to examine relationships among demographic variables within and between groups, and differences in study variables between groups. Differences in study variables within groups based on hand dominance (nondisabled adults) and side affected by stroke (adults with stroke) were also examined. Spearman correlations were used to investigate the association between motor capability (i.e. ARAT scores) and primary variables of interest. All tests of significance were two-tailed and the criterion for significance was alpha < 0.05.

Two-dimensional density plots were created using bivariate histograms to examine the Bilateral Magnitude (y-axis, bin width: 20 activity seconds) and Magnitude Ratio (x-axis, bin width: 0.2 units) for each second of real-world UL activity. The duration (i.e. number of seconds) with which a given Bilateral Magnitude-Magnitude Ratio combination occurred is depicted by color. Increasing Bilateral Magnitude values indicate increasing intensity of UL activity across one limb (unilateral activity) or both limbs (simultaneous activity). Magnitude Ratio values of -7 depict seconds when dominant/non-paretic unilateral UL activity occurred and values of +7 depict seconds when nondominant/paretic unilateral UL activity occurred. Magnitude Ratios from -6 to +6 depict seconds when simultaneous UL activity occurred. A Magnitude Ratio of 0 indicates equal contribution from both ULs. Increasing negative values indicate increasing dominant/nonparetic UL activity relative to the contralateral limb, while increasing positive values indicate increasing nondominant/paretic UL activity relative to the contralateral limb.

5.4 Results

5.4.1 Description of Participants

Accelerometry data were available for 74 non-disabled adults and 48 adults with stroke.

Demographic information and stroke-specific characteristics are displayed in Table 5.1. Adults with stroke were 5 years older on average than nondisabled adults (p=0.01). There were no differences in sex, race, or hand dominance between groups (for all values, $X^2<2.7$, p>0.10). Stroke subjects can be characterized as having mild-to-moderate deficits, based on ARAT scores. Median time since most-recent stroke was 0.9 (IQR: 1.3) years, and median number of strokes was 1 (IQR 0). Nondisabled adults wore accelerometers for 25.0 (IQR: 0) hours and adults with stroke wore accelerometers for 26.0 (IQR: 0) hours (p<0.001).

Table 5.1 Demographic and stroke-specific characteristics of nondisabled adults (n=74) and adults with stroke (n=48)

Variable	Nondisabled Adults	Adults with Stroke
	Mean ± SD or % (n)	
Age, years	54.3 ± 11.3	59.7 ± 10.9
Sex, female	53% (39)	38% (18)
Race		.
African-American	59% (44)	50% (24)
Caucasian	41% (30)	48% (23)
Asian		2% (1)
Hand Dominance, right	84% (62)	88% (42)
Side Affected by Stroke, right		58% (28)
Dominant Side Affected		54% (26)
Action Research Arm Test		31.3 ± 119

5.4.2 Primary Variables of Interest

Nondisabled Adults

Data for three individual participants are first presented to facilitate interpretation of the Bilateral Magnitude, Magnitude Ratio, and the density plots. Figure 5.1A displays data for a participant whose median Bilateral Magnitude was 98.3 activity counts (IQR: 128.5) and median Magnitude Ratio was -0.49 (IQR: 7.47), indicating that he performed a great deal of low-intensity UL activity and dominant UL activity slightly exceeded nondominant UL activity. The magnitude of the IQRs indicate that second-by-second Bilateral Magnitude and Magnitude Ratio values varied greatly with respect to median values; this is also illustrated by the spread of values in Figure 5.1A. Dominant unilateral activity (left-side of figure) slightly exceeded nondominant unilateral UL activity (right side of figure), and low-intensity (i.e. Bilateral Magnitude < 200 activity counts) unilateral activity occurred often (i.e. red color). The majority of total UL activity consisted of simultaneous UL activity (middle of figure). Patterns of activity between ULs were similar as indicated by the roughly-symmetrical appearance of the middle portion of Figure 5.1A.

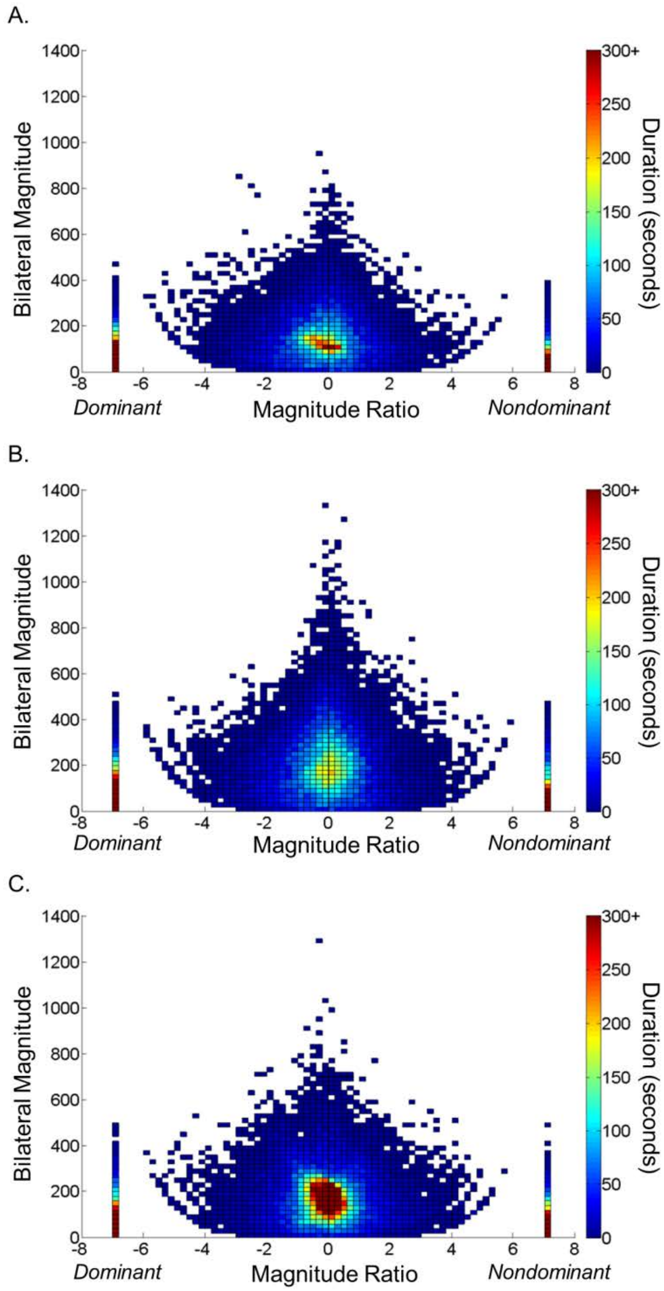

Figure 5.1 Density plots showing 25 hours of real-world bilateral upper limb activity in three nondisabled adults. A: Total UL activity (9.6 hours) was low in this participant. B: Total UL Activity (11.9 hours) and median Bilateral Magnitude and median Magnitude Ratio values were higher in this participant. C: Total UL Activity (13.7) and median Bilateral Magnitude and Magnitude Ratio values were highest in this participant. Despite differences in total UL activity, each density plot was symmetrical in overall shape indicating that patterns of dominant and nondominant UL activity were similar.

Figure 5.1B provides data from a second participant whose median Bilateral Magnitude was a little higher (141.6 activity counts, IQR: 194.5) and median Magnitude Ratio was closer to 0 (-0.13, IQR: 2.63). Figure 5.1C displays a third example participant whose median Bilateral Magnitude was even higher (152.2 activity counts, IQR: 128.4) and median Magnitude Ratio was nearly 0 (-0.06, IQR: 1.30). Figures 5.1B and 5.1C are closer to symmetry than 5.1A, though the differences are slight. This pattern of slightly asymmetrical to nearly pure symmetry was consistent across the 74 non-disabled adults.

Three additional features of the density plots require explanation. First, the "rounded" or "bowl-shaped" bottoms of the density plots occur when activity is of low intensity and one UL is moving at a relatively greater intensity than the opposite UL. The rims of the bowl shape represent increasing intensity of activity, where one hand is accelerating and the other is relatively but not completely still. An example of this would be sorting objects with one hand while the other secures the container.[16] Second, the "warm glow" in the bottom center of each plot indicates that real-world dominant and nondominant UL activity is often closely matched to perform activities of low-to-moderate intensity. Examples of such activity include cutting food with a knife and fork and sorting small objects using both hands.[16] Third, the "concavity" that occurs when the Magnitude Ratio approaches 0 as the Bilateral Magnitude increases occurs when UL activity becomes increasingly symmetrical and intense as a result of shared kinematic and kinetic properties between ULs. Examples of this kind of activity include folding towels and placing an object on a shelf with both hands.[16]

Group-level data for nondisabled adults are presented in the upper half of Table 5.2. Group median values indicate that a large portion of real-world UL activity consisted of low intensity activity that was completed using both ULs to a similar degree. Interquartile range values for the

Bilateral Magnitude (median: 176.5, IQR: 34.3 activity counts) and the Magnitude Ratio (median: 2.66, IQR: 1.53) demonstrate that the middle 50% of second-by-second values varied with respect to median values. Within-group analysis indicated that neither the median Bilateral Magnitude (Mann Whitney U Test: U=349.0, Z=-0.3, p=0.5) nor the median Magnitude Ratio (Mann Whitney U Test: U=306.0, Z=-01.0 p=0.3) differed based on whether nondisabled adults were right- (n=62) or left-hand (n=12) dominant.

Table 5.2 Values of accelerometry-derived variables for nondisabled adults (n=74) and adults with stroke (n=48)

Variable	**Nondisabled Adults**	**Adults with Stroke**	**p-value**
Primary Variables of Interest	Mean ± SD		
Median Bilateral Magnitude	136.2 (36.6)	82.4 (27.6)	<0.001†
Median Magnitude Ratio	-0.1 (0.3)	-2.2 (6.2)	<0.001†
Secondary Variables of Interest	Median (IQR)		
Unilateral UL Activity, hours			
Dominant/Non-Paretic	1.9 ± 0.5	3.4 ± 1.2	<0.001‡
Nondominant/Paretic	1.5 ± 0.5	0.8 ± 0.5	<0.001‡
Simultaneous UL Activity, hours	7.2 ± 1.9	4.1 ± 1.7	<0.001‡
Total UL Activity, hours	10.7 ± 2.1	8.4 ± 2.2	<0.001‡

†p-value obtained using Mann Whitney U test

‡p-value obtained using independent samples t-test

Abbreviations: UL, upper limb

Adults with Stroke

Data for six individual participants with stroke are presented in Figure 5.2. The left half of Figure 5.2 displays data for participants with a paretic dominant UL and the right half displays data for participants with a paretic nondominant UL. Each row displays data for participants with lower (top row), moderate (middle row), and higher (bottom row) motor capability as indicated by ARAT scores. Figure 5.2A shows data for a participant with low motor capability (ARAT=10) whose median Bilateral Magnitude was 89.7 (IQR: 116.0) activity counts and median Magnitude Ratio was -7.0 (IQR: 5.85), indicating that real-world UL activity for this participant was of low-intensity and completed mostly with the nonparetic UL. The interquartile range also indicates that second-by-second values varied with respect to median values. Visual inspection of the density plot reveals that both unilateral and simultaneous activity consisted mainly of nonparetic UL activity (Magnitude Ratio from -7 to 0). Paretic UL activity during unilateral (Magnitude Ratio =7) and simultaneous activity (Magnitude Ratios from 0 to +6) was low.

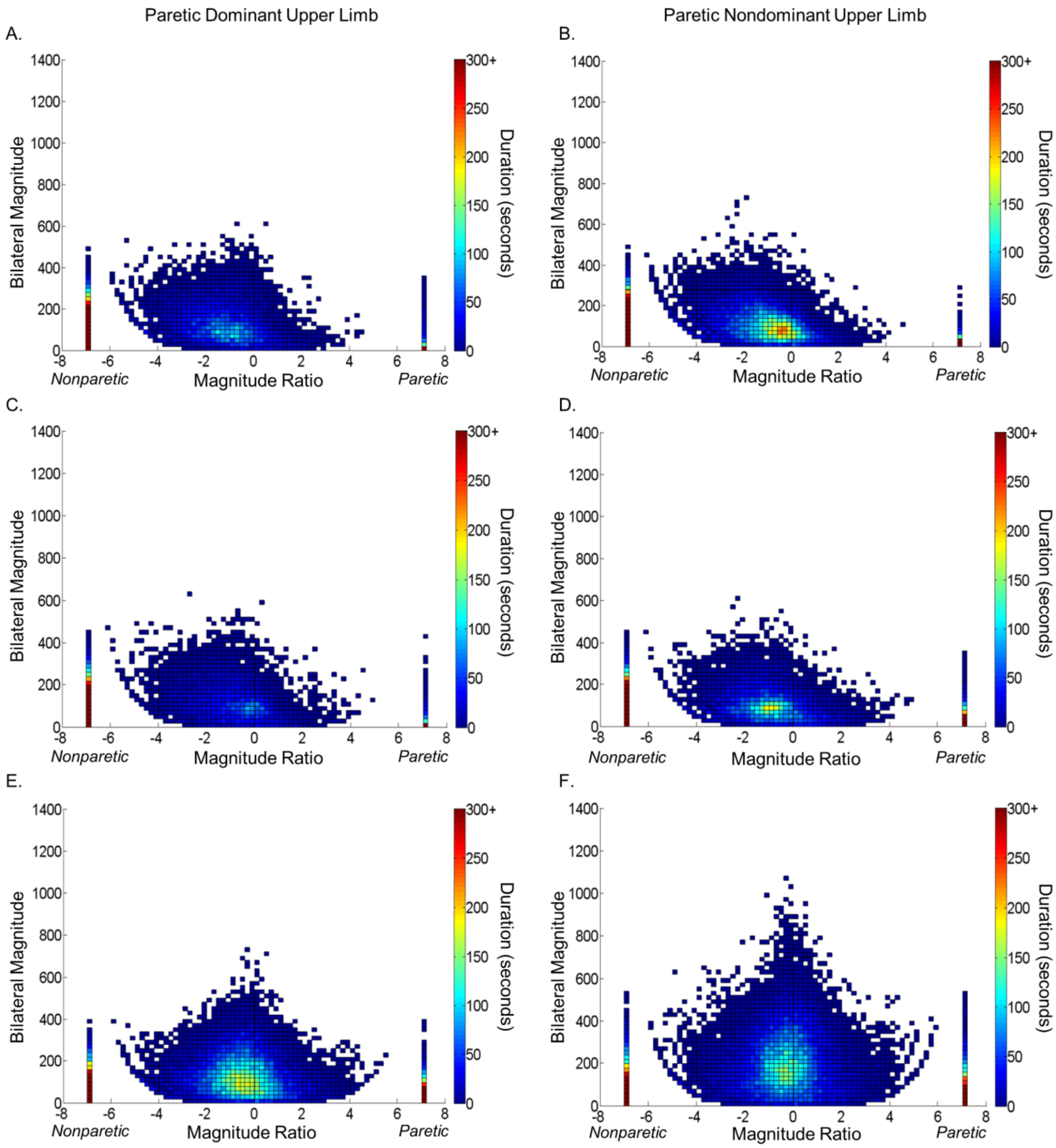

Figure 5.2 Density plots showing 26 hours of real-world bilateral upper limb activity in 6 adults with stroke. Participants in the left-side column had paretic dominant ULs, while participants in the right-side column had paretic nondominant ULs. Individual data are displayed from participants with lower (A: ARAT=10, B: ARAT=10), moderate (C: ARAT=36, D: ARAT=38), and higher motor capabilities (E: ARAT=46, F: ARAT=48). Despite higher ARAT scores, the participants in C & D have similar density plots to the participants in A & B.

Figure 5.2B shows data for another participant with the same motor capability (ARAT=10), similar median Bilateral Magnitude (77.3 activity counts, IQR: 98.9) and Magnitude Ratio (-7.0, IQR: 6.03) values, but whose non-dominant side was affected by stroke. Figures 5.2A and 5.2B are similar.

Figures 5.2C and 5.2D show data from participants with moderate motor capabilities, affected on the dominant (Figure 5.2C; ARAT=36; median Bilateral Magnitude= 77.5 activity counts, IQR: 111.6; median Magnitude Ratio= -7.0, IQR: 6.0), and non-dominant sides (Figure 5.2D; ARAT=38; median Bilateral Magnitude=66.3 activity counts, IQR: 87.0; median Magnitude Ratio= -7.0, IQR: 6.20), respectively. Despite greater motor capabilities, the data in Figures 5.2C and 5.2D look very similar to those in 5.2A and 5.2B.

Figures 5.2E and 5.2F show data from participants with higher motor capabilities, affected on the dominant (Figure 5.2E; ARAT=46; median Bilateral Magnitude= 86.6 activity counts, IQR: 115.8; median Magnitude Ratio= -0.80, IQR: 5.24) and non-dominant sides, (Figure 5.2F; ARAT=48; median Bilateral Magnitude=133.4 activity counts, IQR: 186.6; median Magnitude Ratio=-0.5, IQR: 3.65), respectively. These statistics and the more symmetrical density plots more closely resemble data from non-disabled individuals in Figure 5.1. In additional to engaging in more simultaneous UL activity, the participant in Figure 5.2F also performed UL activity at greater intensities.

Group-level statistics, displayed in the upper half of Table 5.2, support visual examination of Figure 5.2. Median Bilateral Magnitude values in adults with stroke were lower than in nondisabled adults, indicating lower intensity of real-world UL activity. Median Magnitude Ratio values in adults with stroke were more negative than in nondisabled adults, indicating increased activity of the nonparetic UL relative to the paretic UL. Interquartile range values for the Bilateral Magnitude (median: 115.9 activity counts, IQR: 34.3) and the Magnitude Ratio (median: 6.62, IQR: 1.2) demonstrate that the middle 50% of second-by-second values varied with respect to median values.

Differences were seen in one of the two primary variables based on whether the participants' pre-stroke dominant UL was affected by stroke. There were no differences in median Bilateral Magnitude values between participants with paretic dominant (n=26) versus nonparetic dominant (n=22) ULs (Mann Whitney U Test: U=225.0, Z=-1.3, P=0.2). The median Magnitude Ratio was more negative, however, in participants with a paretic nondominant UL (median: -5.0, IQR: 5.6) than a paretic dominant UL (median: -0.88, IQR: 2.5; Mann Whitney U Test: U=148.5, Z=-2.9, p<0.01). Motor capability (ARAT score) was weakly correlated[28] with median Bilateral Magnitude values (r_s=0.30, p=0.04) and moderately correlated with median Magnitude Ratio values (r_s=0.66, p<0.001; Figure 5.3). Visual analysis of Figure 5.3, however, illustrates that 33% (16/48) of participants had a median Magnitude Ratio of -7 (i.e. at least 50% of total UL activity consisted of unilateral nonparetic UL activity) despite variable ARAT scores (range: 10-42), which underscores the distinction between capability and performance.

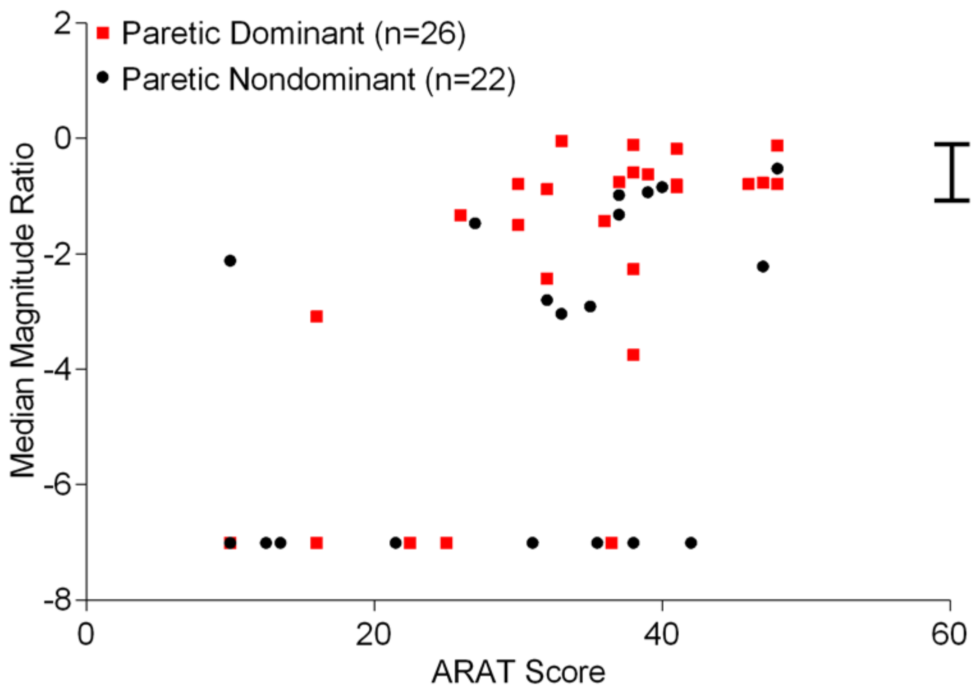

Figure 5.3 Scatterplot of ARAT score versus the median Magnitude Ratio for adults with stroke. Median Magnitude Ratio values were more negative in participants with a paretic nondominant UL (black circles) than in participants with a paretic dominant UL (red squares). There were 5 participants with a Magnitude Ratio of -7 and an ARAT score of 10. Despite a Spearman correlation of 0.66, 16/48 (33%) participants had a median Magnitude Ratio of -7, indicating that at least 50% of total UL activity consisted of nonparetic unilateral UL activity. The vertical hatched bar specifies the middle 50% (i.e. 25^{th} and 75^{th} percentiles) of median Magnitude Ratio values in nondisabled adults.

5.4.3 Secondary Variables of Interest

Additional variables that quantified duration of UL activity by group are displayed in the lower half of Table 5.2. Duration of unilateral dominant/nonparetic UL activity was greater in adults with stroke than in nondisabled adults, while duration of unilateral nondominant/paretic UL activity was less. Simultaneous UL activity made up 67% (7.2/10.7 hours) of total UL activity in nondisabled adults, but only 49% (4.1/8.4 hours) of total UL activity in adults with stroke. Even though nondisabled adults wore the accelerometers for 1 hour *less* (25 vs. 26 hours), duration of simultaneous and total UL activity were *greater* in nondisabled adults than in adults with stroke.

5.5 Discussion

This study quantified real-world bilateral UL activity during a typical day in nondisabled adults and adults with chronic stroke using wrist-worn accelerometry. We calculated summary statistics that demonstrated that intensity of bilateral UL activity (Bilateral Magnitude) was lower, and bilateral UL activity was more lateralized (the Magnitude Ratio was more negative), in adults with stroke than in nondisabled adults. Examination of individual- and group-level descriptive statistics (i.e. median and interquartile ranges) for Bilateral Magnitude and Magnitude Ratio values confirmed our hypothesis that second-by-second values varied greatly with respect to summary statistics. Visual representation of second-by-second UL activity using density plots supported this finding as well. Furthermore, the density plots clearly show that patterns of real-world bilateral UL activity differed between nondisabled adults and adults with stroke, and importantly, between adults with stroke despite similar motor capabilities.

It was striking that in nondisabled adults, the dominant and nondominant ULs were active to a similar degree. This trend was observed in individual- and group-level (see Table 5.2) data. This observation challenges the assumption that the nondominant UL is used only to assist the dominant UL. Our results do not dispute the laboratory findings of others indicating increased dominant UL accuracy during the performance of dynamic tasks (e.g. manipulating) and increased nondominant UL accuracy during the performance of static tasks (e.g. stabilizing),[29,30] or that the dominant UL can execute complex tasks more efficiently than the nondominant UL.[31] Rather, our results extend these laboratory results to provide evidence that complementary, usually simultaneous actions of the ULs make up a significant portion of real-world, everyday UL activity.

It was not surprising that real-world bilateral UL activity was less symmetrical (lower Magnitude Ratios) and less intense (lower Bilateral Magnitudes) in adults with stroke compared to nondisabled adults. Inside the laboratory, Han et al.[8] demonstrated increased use of the nonparetic UL during a spontaneous reaching task. Similarly, Uswatte et al.[17] used accelerometry to calculate the ratio of paretic-to-nonparetic UL movement in adults with stroke and demonstrated that *duration* of paretic UL movement was less than nonparetic UL movement (i.e. ratio of paretic-to-nonparetic movement = 0.56). Uswatte et al.'s observation has now been confirmed across many studies.[20,21,32] The lower duration of simultaneous UL activity and higher duration of non-paretic unilateral UL activity in adults with stroke compared to nondisabled adults in this study is a further indication that real-world bilateral UL activity is reduced in adults with stroke.

At first glance, one may wonder if the reduction in bilateral UL activity is a direct result of the severity of paretic UL motor dysfunction. While we observed moderate associations between ARAT scores and median Bilateral Magnitude and Magnitude Ratio values, we also observed similar density plots from participants with varying ARAT scores. These results imply that motor capabilities are not necessarily a direct reflection of real-world performance, and may be an objective quantification of the phenomenon of learned non-use described by Taub and others.[15,33-35] The findings here from people living in the community are consistent with findings from an inpatient rehabilitation setting,[36] where improvements in paretic UL motor function, as measured by clinical tests of function, were not associated with increased daily use of the paretic UL, as measured by accelerometry. Together, our results and others highlight the critical point that objective quantification of real-world performance is imperative in both rehabilitation research and clinical practice.

Pre-stroke hand dominance affected real-world bilateral UL activity in this study. Paretic UL activity was lower than nonparetic UL activity to a *greater degree* (i.e. median Magnitude Ratios were more negative) in participants with a paretic nondominant UL. We speculate that this was because participants still had full functional use of their dominant UL to complete daily activity and therefore were less motivated to use their paretic nondominant UL, whereas individuals whose dominant UL was affected by stroke were more motivated to regain functional use of their dominant UL. A similar explanation was given by Harris and Eng[37] after observing less impairment in the paretic UL of adults with chronic stroke when the dominant side was affected. These explanations are also consistent with our earlier observation that duration of paretic UL activity was greater in adults whose dominant UL was affected (i.e. ratio of paretic-to-nonparetic UL activity = 0.70) than in adults whose nondominant UL was affected (ratio = 0.57).[15]

5.5.1 Limitations

Three limitations may alter the interpretation of our data. First, adults with stroke wore the accelerometers for 1 hour longer than did nondisabled adults for practical reasons. Despite the longer wearing duration, we still observed clear differences between groups. It is possible that the magnitude of those differences likely would have been greater had nondisabled adults worn the accelerometers for an additional hour. Second, despite ActiLife 6's 0.25-2.5 Hz filter, abrupt accelerations while a passenger in a moving car were recorded during preliminary tasks (unpublished data), resulting in potential overestimation of UL activity. The risk of overestimation is small, however, because the participants in this study spent a majority of their time in sedentary activity.[15,24] Third, the effect of walking on UL activity was not reported in this study. Because walking was included, the values presented here might be considered overestimations of real-world UL activity, though overestimation is likely to be low due to the sedentary nature of the participants. There are distinct advantages related to cost, availability of accelerometers, patient and clinician compliance, and simplifying data processing when only wrist-worn accelerometers are used. Future research, however, should examine the effect of walking on real-world UL activity.

5.5.2 Conclusion

Simultaneous UL activity makes up a significant portion of daily activity in nondisabled adults. This finding alone has significant implications for how interventions are selected and delivered to patients with stroke (e.g. task-specific training with both hands instead of just one). Results from community-dwelling participants with stroke highlight the importance of assessing UL activity *outside* of the clinic, and not simply motor capability *inside* the clinic or laboratory. If the goal of rehabilitation following stroke is to improve daily function, then UL activity in a patient's real-world environment must be assessed. We show that this can feasibly be accomplished via calculation of the Bilateral Magnitude, Magnitude Ratio, and density plots obtained from accelerometry data. Finally, measuring real-world UL activity over time will help patients, clinicians, and researchers assess recovery of real-world UL motor performance.

5.6 Acknowledgments

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5.7 References

1. Kilbreath SL, Heard RC. Frequency of hand use in healthy older persons. *Aust J Physiother.* 2005;51:119-122.

2. McCombe Waller S, Whitall J. Bilateral arm training: why and who benefits? *NeuroRehabilitation.* 2008;23(1):29-41.

3. Lang CE, Wagner JM, Dromerick AW, Edwards DF. Measurement of upper-extremity function early after stroke: properties of the action research arm test. *Arch Phys Med Rehabil.* 2006;87(12):1605-1610.

4. Lang CE, Wagner JM, Edwards DF, Dromerick AW. Upper extremity use in people with hemiparesis in the first few weeks after stroke. *J Neurol Phys Ther.* 2007;31(2):56-63.

5. Jebsen RH, Taylor N, Trieschmann RB, Trotter MJ, Howard LA. An objective and standardized test of hand function. *Arch Phys Med Rehabil.* 1969;50(6):311-319.

6. Lyle RC. A performance test for assessment of upper limb function in physical rehabilitation treatment and research. *Int J Rehabil Res.* 1981;4(4):483-492.

7. Sterr A, Freivogel S, Schmalohr D. Neurobehavioral aspects of recovery: assessment of the learned nonuse phenomenon in hemiparetic adolescents. *Arch Phys Med Rehabil.* 2002;83(12):1726-1731.

8. Han CE, Kim S, Chen S, et al. Quantifying arm nonuse in individuals poststroke. *Neurorehabil Neural Repair.* 2013;27(5):439-447.

9. Young NL, Williams JI, Yoshida KK, Bombardier C, Wright JG. The context of measuring disability: does it matter whether capability or performance is measured? *J Clin Epidemiol.* 1996;49(10):1097-1101.

10. Bradburn NM, Rips LJ, Shevell SK. Answering autobiographical questions: the impact of memory and inference on surveys. *Science.* 1987;236(4798):157-161.

11. Tatemichi TK, Desmond DW, Stern Y, Paik M, Sano M, Bagiella E. Cognitive impairment after stroke: frequency, patterns, and relationship to functional abilities. *J Neurol Neurosurg Psychiatry.* 1994;57(2):202-207.

12. Jobe JB. Cognitive processes in self report. In: A.A. S, Turkann JS, Bachrach CA, Jobe JB, Kurtzman HS, Cain VS, eds. *The science of self-report: implications for research and practice*. Mahwah: Lawrence Erlbaum Associates; 2000:25-28.

13. Adams SA, Matthews CE, Ebbeling CB, et al. The effect of social desirability and social approval on self-reports of physical activity. *Am J Epidemiol.* 2005;161(4):389-398.

14. Prince SA, Adamo KB, Hamel ME, Hardt J, Gorber SC, Tremblay M. A comparison of direct versus self-report measures for assessing physical activity in adults: a systematic review. *Int J Behav Nutr Phys Act.* 2008;5:56.

15. Bailey R, Birkenmeier R, Lang C. Real-World affected upper limb activity in chronic stroke: An examination of potential modifying factors. *Top Stroke Rehabil.* 2015;22(1):26-33.

16. Bailey RR, Klaesner JW, Lang CE. An accelerometry-based methodology for assessment of real-world bilateral upper extremity activity. *PLoS One.* 2014;9(7):e103135.

17. Uswatte G, Giuliani C, Winstein C, Zeringue A, Hobbs L, Wolf SL. Validity of accelerometry for monitoring real-world arm activity in patients with subacute stroke: evidence from the extremity constraint-induced therapy evaluation trial. *Arch Phys Med Rehabil.* 2006;87(10):1340-1345.

18. de Niet M, Bussmann JB, Ribbers GM, Stam HJ. The stroke upper-limb activity monitor: its sensitivity to measure hemiplegic upper-limb activity during daily life. *Arch Phys Med Rehabil.* 2007;88(9):1121-1126.

19. Gebruers N, Truijen S, Engelborghs S, Nagels G, Brouns R, De Deyn PP. Actigraphic measurement of motor deficits in acute ischemic stroke. *Cerebrovasc Dis.* 2008;26(5):533-540.

20. van der Pas SC, Verbunt JA, Breukelaar DE, van Woerden R, Seelen HA. Assessment of arm activity using triaxial accelerometry in patients with a stroke. *Arch Phys Med Rehabil.* 2011;92(9):1437-1442.

21. Michielsen ME, Selles RW, Stam HJ, Ribbers GM, Bussmann JB. Quantifying nonuse in chronic stroke patients: a study into paretic, nonparetic, and bimanual upper-limb use in daily life. *Arch Phys Med Rehabil.* 2012;93(11):1975-1981.

22. Brott T, Adams HP, Jr., Olinger CP, et al. Measurements of acute cerebral infarction: a clinical examination scale. *Stroke.* 1989;20(7):864-870.

23. van der Lee JH, Beckerman H, Lankhorst GJ, Bouter LM. The responsiveness of the Action Research Arm test and the Fugl-Meyer Assessment scale in chronic stroke patients. *J Rehabil Med.* 2001;33(3):110-113.

24. Bailey RR, Lang CE. Upper-limb activity in adults: referent values using accelerometry. *J Rehabil Res Dev.* 2013;50(9):1213-1222.

25. Chen KY, Acra SA, Majchrzak K, et al. Predicting energy expenditure of physical activity using hip- and wrist-worn accelerometers. *Diabetes Technol Ther.* 2003;5(6):1023-1033.

26. Uswatte G, Foo WL, Olmstead H, Lopez K, Holand A, Simms LB. Ambulatory monitoring of arm movement using accelerometry: an objective measure of upper-extremity rehabilitation in persons with chronic stroke. *Arch Phys Med Rehabil.* 2005;86(7):1498-1501.

27. Hawk L. ActiGraph Data Conversion Process. https://help.theactigraph.com/entries/21702957-ActiGraph-Data-Conversion-Process. Accessed January 14, 2015.

28. Portney L, Watkins M. *Foundations of clinical research: Applications to pratice*. 2nd ed. Upper Saddle River, NJ: Prentic Hall Health; 2000.

29. Wang J, Sainburg RL. The dominant and nondominant arms are specialized for stabilizing different features of task performance. *Exp Brain Res.* 2007;178(4):565-570.

30. Przybyla A, Good DC, Sainburg RL. Dynamic dominance varies with handedness: reduced interlimb asymmetries in left-handers. *Exp Brain Res.* 2012;216(3):419-431.

31. Peters M. Why the preferred hand taps more quickly than the non-preferred hand: Three experiments on handedness. *Canadian Journal of Psychology/Revue canadienne de psychologie.* 1980;34(1):62-71.

32. Thrane G, Emaus N, Askim T, Anke A. Arm use in patients with subacute stroke monitored by accelerometry: association with motor impairment and influence on self-dependence. *J Rehabil Med.* 2011;43(4):299-304.

33. Uswatte G, Taub E. Implications of the learned nonuse formulation for measuring rehabilitation outcomes: Lessons from contraint-induced movement therapy. *Rehabil Psychol.* 2005;50(1):34-42.

34. Andre JM, Didier JP, Paysant J. "Functional motor amnesia" in stroke (1904) and "learned non-use phenomenon" (1966). *J Rehabil Med.* 2004;36(3):138-140.

35. Johnson M, Paranjape R, Strachota E, Tchekanov G, McGuire J. Quantifying learned non-use after stroke using unilateral and bilateral steering tasks. *IEEE Int Conf Rehabil Robot.* 2011;2011:5975457.

36. Rand D, Eng JJ. Disparity Between Functional Recovery and Daily Use of the Upper and Lower Extremities During Subacute Stroke Rehabilitation. *Neurorehabil Neural Repair.* 2011;26(1):76-84.

37. Harris JE, Eng JJ. Individuals with the dominant hand affected following stroke demonstrate less impairment than those with the nondominant hand affected. *Neurorehabil Neural Repair.* 2006;20(3):380-389.

Chapter 6: Summary of Major Findings

6.1 Major Findings

Chapter 2 characterized the duration of UL activity during a typical day and potential modifying factors of UL activity in nondisabled adults. Our results showed that UL activity in nondisabled adults for the dominant and nondominant ULs was 9.1 ± 1.9 hours and 8.6 ± 2.0 hours, respectively. Furthermore, duration of dominant and nondominant UL activity were strongly correlated (r = 0.96). We also demonstrated that the ratio of activity duration between the ULs (i.e. the Activity Ratio, 0.95 ± 0.06) was a robust metric, as evidenced by its narrow standard deviation and independence from duration of dominant UL activity, and may be useful in distinguishing between individuals with and without UL impairment. As hypothesized, self-reported time spent in sedentary activity was moderately associated with duration of UL activity. Contrary to our hypotheses, cognitive impairment, depressive symptomatology, number of comorbidities, age, and living arrangement were not associated with duration of dominant UL activity.

Chapter 3 characterized the duration of UL activity during a typical day and potential modifying factors of UL activity in adults with chronic stroke. Our results showed that duration of affected UL activity was strongly correlated with duration of unaffected UL activity (r = 0.78), even though duration of affected UL activity (5.0 ± 2.2 hours) was 2.6 hours lower than unaffected UL activity (7.6 ± 2.1 hours). The Activity Ratio was 0.64 ± 0.19 across all participants, but was lower in participants whose pre-stroke nondominant UL was affected. As hypothesized, lower motor capacity and dependence in ADLs were associated with decreased duration of affected UL activity. Contrary to our hypotheses, self-reported time spent in sedentary activity, cognitive impairment, depressive symptomatology, number of comorbidities, age, and living arrangement were not associated with duration of affected UL activity.

Chapter 4 examined the validity of an accelerometry-based methodology to quantify bilateral UL activity using two accelerometry-derived variables: the Bilateral Magnitude and the Magnitude Ratio. Our results showed that during the performance of 8 everyday tasks performed inside the laboratory, median Bilateral Magnitudes were higher for high-intensity tasks and lower for low-intensity tasks. Median Magnitude Ratios approximated a value of 0.0 (indicating equal contribution from both ULs) for tasks completed using both hands, while large, negative values (indicating increased activity of the dominant UL relative to the nondominant UL) were observed for tasks completed using mainly the dominant UL. Additionally, for each task, strong correlations were observed between the median Bilateral Magnitude and Estimated Energy Expenditure ($r_s = 0.74$), indicating that the Bilateral Magnitude is related to activity intensity. Strong correlations were also observed between the median Magnitude Ratio and percentage of time spent in simultaneous UL activity ($r_s = 0.93$), indicating that the Magnitude Ratio is a measure of bilateral UL activity. These strong correlations existed across tasks, indicating that the Bilateral Magnitude and Magnitude Ratio quantified UL activity independently of the task performed, and are thus useful metrics of bilateral UL activity.

Chapter 5 used the methodology developed in Chapter 4 to characterize bilateral UL activity during a typical day in nondisabled adults and adults with chronic stroke. Our results showed that both the median Bilateral Magnitude and the median Magnitude Ratio were lower in adults with stroke than in nondisabled adults, indicating that real-world UL activity intensity is lower and that activity is less bilateral in adults with stroke. Examination of density plots and secondary variables (i.e. duration of unilateral, simultaneous, and total UL activity) indicated that real-world UL activity was symmetrical between the ULs in nondisabled adults, but lateralized (i.e. unaffected UL activity was greater) in adults with stroke. Further examination of the results revealed that 33% of adults with stroke used only their unaffected UL for a majority of real-world UL activity, and this occurred across a wide range of motor capacity scores. These results highlight the distinction between motor *capacity* and motor *performance*. Last of all, median Magnitude Ratios were lower in adults with stroke whose pre-stroke nondominant UL was affected, which mirrors the results in Chapter 3 regarding lower Activity Ratios in adults whose nondominant side was affected by stroke.

6.2 Limitations

Across all studies, limitations include sample selection, limitations inherent to accelerometry, procedural use of accelerometers, and not controlling for lower limb activity.

First of all, generalizability of our findings is limited based on the criteria used to select our participant samples. The majority of nondisabled adults were not working. The few who did work were employed in office-based jobs. As such, our research findings may not generalize to adults who work full-time, or to adults who work in non-office environments (e.g. hospital-based employment, manual labor, etc.), and should be explored in future studies. The results from our nondisabled adults do, however, generalize to the rehabilitation population who are often not working. Regarding adults with stroke, the participants enrolled in our studies were at least 6 months post-stroke, had at least minimal motor capacity, and were cognitively intact (i.e. normal to mild-cognitive impairment). Our findings may not generalize to adults in the acute or subacute stages of stroke, who have no motor capacity of the affected UL, or who have moderate-to-severe cognitive impairment.

Secondly, limitations inherent to accelerometry must be acknowledged. Accelerometers detect movement, regardless of the source. For this reason, it is not possible to distinguish between intentional and non-intentional movements, and thus real-world UL activity, our index of motor performance, may actually slightly overestimate intentional activity. Furthermore, it is possible that intentional UL activity may be underestimated in cases where wrist-worn accelerometry does not detect fine motor activity of the digits and hand. For example, across all study participants in Chapter 4, we were unable to detect fine motor activity that occurred in 7% (38/549) of tasks because participants held their wrist still while their hand manipulated objects when typing, writing, or cutting (unpublished data). Because most UL activities are performed across multiple UL segments and joints (e.g. reaching for a cup to take a drink requires coordinated movement of the upper arm, forearm, wrist, hand and digits), omission of UL activity due to isolated fine motor movements is likely minimal. As accelerometry technology improves and the devices become smaller, the ability to detect fine motor movements using accelerometry will be improved. An additional concern is that non-human-movement (e.g. acceleration in a car) could have been detected by the accelerometers, also resulting in an overestimation of intentional activity. Because ActiLife software band-pass filtered the accelerometry data to isolate and exclude non-human movement from analysis, this threat to validity was minimized.[1]

Thirdly, procedural use of accelerometry may influence our results. We collected data over a 25-26 hours period. If UL activity during that period differed from “typical” everyday activity for some reason, our results could be biased. For this reason, it is recommended that 3-5 days of accelerometry data be collected.[2] This is a long time for participants to wear multiple devices, and may lead to decreased compliance.[3,4] We chose to collect data during a 25-26 hour period to improve adherence to the wearing protocol. In Chapter 2, we demonstrated that UL activity was reliable across two separate 25-hour periods in a subset of participants. Additionally, the majority of study participants reported that compared to a “typical” day, their activity during the accelerometry monitoring period was “the same” or only “slightly more than normal” (unpublished data), indicating that our accelerometry data were valid.

Last of all, we were not able to control for UL activity that occurred due to arm swing when walking. It is desirable to control for UL activity due to walking because it could inflate values of UL activity. We attempted to control for UL activity due to walking in our studies, but were unsuccessful in adults with stroke. For all studies, participants wore accelerometers on both upper and both lower limbs. We developed an algorithm to identify periods of walking based on lower limb accelerometry data (see Appendix B). Our algorithm accurately identified walking 98% of the time in nondisabled adults when applied to known periods of walking. In adults with stroke, however, accuracy was only 50%. For consistency across studies, we included walking because we were unable to accurately detect walking in adults with stroke. It is unlikely that inclusion of UL activity when walking biased the results reported in our studies. Another study of adults with stroke has already shown the Activity Ratio to be similar between analyses where walking was first excluded and then included from analysis.[3] This is consistent with the results obtained for nondisabled adults in our studies (unpublished data, see Appendix B). Similarly, the median Bilateral Magnitude and Magnitude Ratio values did not differ in a clinically meaningful way when walking was included versus excluded in our studies, suggesting that inclusion of walking did not bias our results for nondisabled adults (unpublished data, see Appendix B). Based on these findings and because walking activity is lower in adults with stroke than in nondisabled adults,[5] it is unlikely that the results for adults with stroke were biased by including periods of walking in the analysis.

6.3 Clinical Implications and Significance

The most significant contribution of this dissertation is the development of an accelerometry-based methodology to objectively quantify real-world UL activity in a clinically-relevant manner. Across Chapters 2, 4, and 5 we obtained "referent values" for several metrics of UL activity in nondisabled adults. These referent values can be used to either set outcome goals related to UL activity for patients with UL impairment or used as a reference point to gauge recovery of UL motor performance. The methodology can also be used at different time points (e.g. baseline assessment, weekly treatment sessions, discharge assessment) to track changes in real-world UL activity over time. This latter point is especially important because it can help the clinician determine if the selected intervention leads to improved motor performance; if not, then the clinician might choose to modify the intervention. An additional benefit of the accelerometry-based methodology is the production of density plots, which allow for visualization of real-world UL activity. The density plots could be a useful tool for clinicians to use with patients in order to provide visual feedback about how patients use their ULs throughout the day.

The study in Chapter 5 emphasized the distinction between motor capacity and motor performance in adults with stroke, and highlighted why both domains of motor function must be assessed. Motor capacity, as measured by clinical tests of function, was only moderately associated with motor performance, as measured by wrist-worn accelerometry. Despite this moderate correlation, one-third of adults with stroke used their unaffected UL for at least half of total UL activity; furthermore, motor performance was low in these adults despite a wide range of motor capacities. These results not only underscore the need to assess motor capacity and motor performance separately, but they also highlight the need to identify factors in addition to motor capacity that can be targeted for intervention to improve motor performance above that which can be obtained by improvements in motor capacity alone.

Chapters 2 and 3 explored several potential modifying factors of real-world UL activity in nondisabled adults and in adults with stroke. We demonstrated that self-reported time spent in sedentary activity was inversely associated with duration of UL activity to a moderate degree in nondisabled adults but not in adults with stroke. This factor might be a useful rehabilitation target to improve real-world motor performance in patient populations that experience UL impairment other than stroke, and should be explored. In adults with stroke, we demonstrated that decreased motor capacity and dependence in ADLs were associated with decreased UL activity. Motor capacity is a common target of intervention in patients with stroke because it is often considered a surrogate measure of real-world motor performance. The ability to perform ADLs is often addressed by occupational therapists, but usually is not the sole focus of intervention during acute and subacute rehabilitation for practical reasons (e.g. short hospital stays, the patient or family members want treatment sessions to focus on issues other than ADLs). Our data, along with another study,[6] suggest that more attention should be given to the ability to perform ADLs. It is unlikely that the difference in duration of affected UL activity (i.e. 2.4 hours) between adults with stroke who are dependent versus independent for ADLs in Chapter 3 is wholly attributable to ADL status. Instead, it is possible that adults with stroke who are independent in ADLs approach other tasks throughout the day with the same ingenuity and creativeness that they use to complete ADLs (e.g. using compensatory strategies or adaptive equipment), and it is this factor rather than independence in ADLs that explains the difference in real-world UL activity. This should be explored in future studies. Other modifying factors should also be identified and explored for their potential influence on real-world UL activity.

The studies in Chapters 3 and 5 highlighted two additional clinical implications: both ULs are "affected" after stroke and pre-stroke hand dominance influences real-world UL activity. Duration of *both* dominant and nondominant UL activity in adults with stroke was lower than activity in *either* UL in nondisabled adults. This suggests that both ULs are "affected" after stroke at the level of everyday performance, though the nonparetic UL is "affected" less so than the paretic UL. This should come as little surprise because previous studies have demonstrated that after stroke, the nonparetic UL is slightly impaired at multiple levels: decreased strength,[7] impaired dexterity and coordination,[8] altered kinematic parameters of movement (e.g. velocity, trajectory),[9] and poorer performance on simulated activities of daily living.[8,10]

Pre-stroke hand-dominance also matters. In our studies, we demonstrated that both the Activity Ratio and the median Magnitude Ratio were lower in adults whose pre-stroke nondominant UL were affected by stroke, indicating that these participants used their paretic UL less than did participants whose dominant UL was affected by stroke at the level of real-world motor performance. Previous studies have demonstrated similar findings at the level of motor capacity: UL strength and Wolf Motor Function Test scores were lower in the paretic limb of adults whose nondominant side was affected by stroke.[11,12] We hypothesize that this occurs because adults whose nondominant UL was affected by stroke still have functional use of their dominant UL and therefore may be less inclined to use their paretic, nondominant UL; adults whose dominant UL was affected by stroke, however, might be more inclined to regain functional use of their paretic, dominant UL. Taken together, these findings suggest that individuals whose nondominant side is affected by stroke have an increased risk of experiencing impaired motor capacity and motor performance, and may benefit from special attention during rehabilitation.

6.4 Suggestions for Future Studies

Based on the findings across studies, the most practical question that needs to be explored is, "Does motor performance change as a result of rehabilitation?" Re-worded in more measurable terms, "Does rehabilitation-related improvement in motor capacity generalize to improved real-world UL activity?" This question is currently being examined as part of a randomized clinical trial (NCT 01146379, PI: C.E. Lang) that is investigating the dose-response effect of task-specific training on motor capacity and motor performance. This is an important question that needs to be answered because if the time and money invested in rehabilitation does not lead to improved motor performance, then those resources should be invested elsewhere.

In an attempt to improve motor performance, two additional questions should be investigated: "What other factors influence real-world UL activity," and "Can treatment intervention be administered differently to improve real-world UL activity?" We examined only a few of many factors that could potentially modify UL activity. Additional social (e.g. social networks), psychological (e.g. personality, mood), and physiological (e.g. pain) factors should be identified and explored to determine if motor performance can be improved when these factors are targeted for intervention.

Furthermore, it might be possible to deliver interventions differently in order to improve real-world motor performance. Theories of health behavior posit that long-lasting behavioral change can occur when a person is made accountable for their actions.[13] Additionally, health behavior theories identify individual (e.g. self-efficacy), interpersonal (e.g. social support), and environmental (e.g. built environment, policy, culture) factors that can be targeted as part of intervention to effect behavioral change.[13] Borrowing from these theories, greater improvement in motor capacity and self-reported motor performance was observed in adults with stroke when behavioral interventions (e.g. self-monitoring of daily UL use, completing a behavioral contract with a therapist to practice at home, weekly telephone calls from the therapist) were combined with "traditional" motor neurorehabilitation interventions compared to neurorehabilitation interventions alone.[14] Incorporation of different behavioral intervention approaches should be examined for their ability to improve motor performance above that which can be obtained by traditional neurorehabilitation alone.

A final recommendation regarding future studies is that UL activity due to walking should be quantified and examined. This might be accomplished through a pedometer, or hip- or ankle-worn accelerometers that are specifically designed to detect walking that can be time-synched with UL accelerometers. Many scholars in the research arena believe that it is important to control for UL activity due to arm swing when walking. We acknowledge their concerns, but also recognize that stroke is a cardiovascular disease and people with stroke have very low levels of physical activity,[15] which places them at risk for a recurrent stroke.[16] Therefore, we encourage any walking activity that people with stroke perform, and welcome the challenge to identify UL activity due to walking during these periods.

6.5 References

1. Hawk L. ActiGraph Data Conversion Process. https://help.theactigraph.com/entries/21702957-ActiGraph-Data-Conversion-Process. Accessed January 14, 2015.

2. Welk GJ. Principles of design and analyses for the calibration of accelerometry-based activity monitors. *Med Sci Sports Exerc.* 2005;37(11 Suppl):S501-511.

3. Uswatte G, Giuliani C, Winstein C, Zeringue A, Hobbs L, Wolf SL. Validity of accelerometry for monitoring real-world arm activity in patients with subacute stroke: evidence from the extremity constraint-induced therapy evaluation trial. *Arch Phys Med Rehabil.* 2006;87(10):1340-1345.

4. Barak S, Wu SS, Dai Y, Duncan PW, Behrman AL. Adherence to accelerometry measurement of community ambulation poststroke. *Phys Ther.* 2014;94(1):101-110.

5. Michael KM, Allen JK, Macko RF. Reduced ambulatory activity after stroke: the role of balance, gait, and cardiovascular fitness. *Arch Phys Med Rehabil.* 2005;86(8):1552-1556.

6. Thrane G, Emaus N, Askim T, Anke A. Arm use in patients with subacute stroke monitored by accelerometry: association with motor impairment and influence on self-dependence. *J Rehabil Med.* 2011;43(4):299-304.

7. McCrea PH, Eng JJ, Hodgson AJ. Time and magnitude of torque generation is impaired in both arms following stroke. *Muscle & Nerve.* 2003;28(1):46-53.

8. Desrosiers J, Bourbonnais D, Bravo G, Roy PM, Guay M. Performance of the 'unaffected' upper extremity of elderly stroke patients. *Stroke.* 1996;27(9):1564-1570.

9. Yarosh CA, Hoffman DS, Strick PL. Deficits in Movements of the Wrist Ipsilateral to a Stroke in Hemiparetic Subjects. *J Neurophysiol.* 2004;92(6):3276-3285.

10. Wetter S, Poole JL, Haaland KY. Functional implications of ipsilesional motor deficits after unilateral stroke. *Archives of Physical Medicine and Rehabilitation.* 2005;86(4):776-781.

11. Harris JE, Eng JJ. Individuals with the dominant hand affected following stroke demonstrate less impairment than those with the nondominant hand affected. *Neurorehabil Neural Repair.* 2006;20(3):380-389.

12. McCombe Waller S, Whitall J. Hand dominance and side of stroke affect rehabilitation in chronic stroke. *Clin Rehabil.* 2005;19(5):544-551.

13. Bandura A. Health promotion by social cognitive means. *Health Educ Behav.* 2004;31(2):143-164.

14. Taub E, Uswatte G, Mark VW, et al. Method for enhancing real-world use of a more affected arm in chronic stroke: transfer package of constraint-induced movement therapy. *Stroke.* 2013;44(5):1383-1388.

15. Rand D, Eng JJ, Tang PF, Jeng JS, Hung C. How active are people with stroke?: use of accelerometers to assess physical activity. *Stroke.* 2009;40(1):163-168.

16. Roger VL, Go AS, Lloyd-Jones DM, et al. Heart Disease and Stroke Statistics--2012 Update: A Report From the American Heart Association. *Circulation.* 2012;125(1):e2-e220.

Appendix A

Activity Counts result from summing filtered accelerometry data into user-defined periods of time called "epochs." Using a proprietary algorithm, Actigraph GT3X+ accelerometers (Actigraph, Pensacola, FL) were used in our studies to calculate the change in acceleration with respect to time for each sample of data by converting the analog acceleration signal to a digital value, and then dividing by the sampling rate. In performing these mathematical operations, acceleration is converted into an activity count, where 1 activity count = 0.001664g = .0163m/sec^2.[1] As such, activity counts *per sample* are a proportional measure of acceleration rather than a direct measure of acceleration. Activity counts per sample can then summed over a user-defined epoch using Actilife 6 software (Actigraph, Pensacola, FL). As a result, activity counts *per epoch* reflect intensity of upper limb movement as a function of acceleration. Activity counts were chosen as the output unit across studies in this dissertation because of their accepted use in studies using accelerometry and because it is an intuitive measurement unit for clinicians. We do recognize, however, that "g" or "m/sec^2" would be more intuitive for an engineering audience.

Actilife 6 software further processes the accelerometry data using a digital filter to band-limit acceleration data to the frequency range of 0.25 to 2.5 Hz to discriminate human motion from non-human motion (e.g. fluorescent lights, car- and elevator-based movement, etc.). A recent study demonstrated that arm and leg movements during walking in healthy, young men

[1] Hawk L. ActiGraph Data Conversion Process. https://help.theactigraph.com/entries/21702957-ActiGraph-Data-Conversion-Process. Accessed January 14, 2015.

(mean age: 25 years) occurred at frequencies near 1 Hz.[2] Because the participants in our studies were much older and some had experienced stroke, the frequency of movement in participants is unlikely to have exceeded 1 Hz. As such, the band-pass filter applied to the acceleration data in our studies was appropriate for capturing human movement.

[2] Wagenaar RC, van Emmerik RE. Resonant frequencies of arms and legs identify different walking patterns. *J Biomech.* 2000;33(7):853-861.

Appendix B

We attempted to control for UL activity due to arm swing when walking by analyzing accelerometry data obtained from ankle-worn accelerometers. For nondisabled adults, walking was defined as ≥ 5 seconds of continuous activity across both lower limbs that was ≥ 100 activity counts. These parameters correctly identified walking 98% of the time when applied to known periods of walking and incorrectly identified walking 0.7% of the time during a non-walking lower limb activity (i.e. donning shoes). Parameters were modified for adults with stroke because walking is slower and more asymmetrical after stroke. Walking was defined as ≥ 5 seconds of continuous activity across either lower limb that was ≥ 70 activity counts. These parameters correctly identified walking 50% of the time during a known period of walking in a subset (n=20) of participants. The lower accuracy in adults with stroke was likely due to increased heterogeneity in walking ability post-stroke.

Because our algorithm accurately identified walking in nondisabled adults, we examined whether UL activity due to arm swing in nondisabled adults biased study results. In nondisabled adults, the median duration of walking was 0.8 (IQR: 1.0) hours. Duration of simultaneous (i.e. bilateral) UL activity during walking was also 0.8 (IQR: 1.0) hours, indicating that walking was a bilateral UL activity, which was confirmed by an Activity Ratio of 1.0 (IQR: 0.0). The median Bilateral Magnitude value during walking was 190.3 (IQR: 83.9) activity counts, which indicates that UL activity was of low-to-moderate intensity during walking. The median Magnitude Ratio during walking was -0.14 (IQR: 0.73), which indicates that the dominant UL moved with slightly more intensity than did the nondominant UL during walking.

Wilcoxon Signed Rank Tests (i.e. the nonparametric equivalent of a paired-samples t-test) were used to examine differences between accelerometry-derived variables of UL activity when walking was included and excluded from analysis. Results are displayed in Table B.1. First, as noted previously, walking was a bilateral activity that lasted for 0.8 hours, which explains the difference in hours of simultaneous UL activity. Although the median values for the Bilateral Magnitude and Magnitude Ratio were statistically different, the differences were not clinically meaningful. A difference of 10 activity counts in the Bilateral Magnitude and a difference of 0.001 in the Magnitude Ratio are not clinically significant. Lastly, and consistent with previously reported literature, there was no difference in the Activity Ratio.

Table B.1 Comparison of upper limb activity in nondisabled adults when walking was included and excluded from analysis

	Walking Included	Walking Excluded	p-value*
	Median (IQR)		
Simultaneous UL Activity, hours	6.9 (2.5)	6.0 (2.3)	<0.001
Median Bilateral Magnitude	136.2 (36.6)	126.5 (32.6)	<0.001
Median Magnitude Ratio	-0.100 (0.29)	-0.099 (0.29)	<0.001
Activity Ratio	0.95 (0.08)	0.95 (0.09)	0.7

*P-Value determined using Wilcoxon Signed Rank Test (i.e. nonparametric equivalent of a paired t-test)