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Upper-limb activity in adults: Referent values using accelerometry

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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 h and provided information on modifying factors. Mean time of dominant UL activity was 9.1 \pm 1.9 h, and the ratio of activity between the nondominant and dominant ULs was 0.95 \pm 0.06 h. 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 preimpairment level of sedentary activity and to track progress during rehabilitation of the ULs.

Key words: accelerometry, arm activity, capacity, cognitive impairment, depression, function, real-world activity, referent data, sedentary activity, upper-limb activity.

INTRODUCTION

Upper-limb (UL) impairment from illness or injury results in significant financial and functional deficits, many of which have long-lasting consequences. Workers' compensation claims for UL injuries exceed \$500

million per year in the United States [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 to 4 yr postinjury [5,7]. Disability in ADLs because of hemiparesis following stroke persists beyond 6 mo in 54 percent 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.

Abbreviations: ADL = activity of daily living, MET = metabolic equivalent, NIH = National Institutes of Health, RA = rheumatoid arthritis, UL = upper limb.

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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 nonfunctional 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 have not yet been gathered. Some data on UL activity are available, but sample sizes have been small [17,22–23] and limited to nondisabled participants aged 65 to 78 yr [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 UL impairment is a consequence of many conditions that affect adults of all age. 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 account for the effect of modifying factors will provide clinicians with targeted values of UL activity for individual patients given their unique preimpairment 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.

METHODS

Participants

We recruited 74 community-dwelling adults from the St. Louis metropolitan area through a community-based recruitment organization. Participants were enrolled who were age 30 yr and older and 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.

Study Protocol

This cross-sectional study was conducted at the Neurorehabilitation Laboratory at Washington University School of Medicine, as well as in the homes of study participants. Participants attended a 1 h office visit during which they provided demographic information and 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., during writing).

Participants were asked to wear the accelerometers for the subsequent 25 h, including during 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 nonfunctional 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 if they were 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.

We chose 25 h because this time period 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 h period, separated by at least 1 wk, and demonstrated that UL activity values were reliable (intraclass correlation coefficient_(3,k) = 0.93, $p = 0.01$) and a good estimate of UL activity during an average day. At the conclusion of the 25 h period, participants were queried to ensure that the accelerometers were worn for the entire period. Additionally, accelerometry data were visually inspected to verify that participants wore the accelerometers for 25 h.

Measures

The primary outcome measure was hours of UL activity as determined by accelerometry data. Wireless accelerometers (GT3X+ Activity Monitor, ActiGraph; Pensacola, Florida) 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 ($4.6 \times 3.3 \times 1.5$ cm), waterproof, sensitive to -6 to $+6g$ -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 three 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 when the vector magnitude was ≥ 2 were categorized as "movement." Seconds when the vector magnitude was < 2 were categorized as "nonmovement." Seconds of movement were summed to determine hours of UL activity for the dominant and nondominant ULs. Percentage 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 nondominant 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 h weekday. Activities are grouped into nine 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 to 4 indicate normal cognition, 5 to 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 4-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.).

Data Analyses

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

Statistical analyses were performed using IBM SPSS Statistics 19 (Armonk, New York), 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 $p < 0.01$. Correlation coefficients of 0.60 and higher were considered to be strong, between 0.30 and 0.59 were moderate, and 0.29 and lower were weak [44]. Mann-Whitney U was 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.

RESULTS

Demographic information and categorical predictor variables are presented in **Table 1**. Because there was no difference in hours of dominant UL activity between participants not working (9.1 ± 2.0 h) and the participants who were working (9.0 ± 2.1 h, $p = 0.83$), all participants were grouped together for subsequent analyses. All participants wore the accelerometers for the entire recording period (mean 25.0 h, range: 24.3–26.0 h). No technical problems with the accelerometers were reported.

Descriptive statistics of outcome variables and remaining continuous predictor variables are reported in **Table 2**. Hours of dominant UL activity were greater than hours of nondominant UL activity ($p < 0.001$), though the absolute difference between limbs was only 30 min. Because Pearson correlations were excellent between dominant and nondominant UL activity, between dominant and nondominant 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

Table 1.
Demographic information and categorical predictor variables.

Variable	Value
Age (yr)	
Mean \pm Standard Deviation	54 \pm 11
Range	30–83
Sex	
Male	35 (47%)
Female	39 (53%)
Race	
White	30 (40%)
African American	44 (60%)
Hand Dominance	
Right	62 (84%)
Left	12 (16%)
Work Status	
Not Working	62 (84%)
<20 h/wk	7 (10%)
Part-Time	4 (5%)
Full-Time	1 (1%)
Cohabitation Status	
Lives Alone	27 (36%)
Lives with Others	47 (64%)

Table 2.

Mean, standard deviation (SD), and range of outcome variable and other predictor variables.

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

*Determined by self-report.

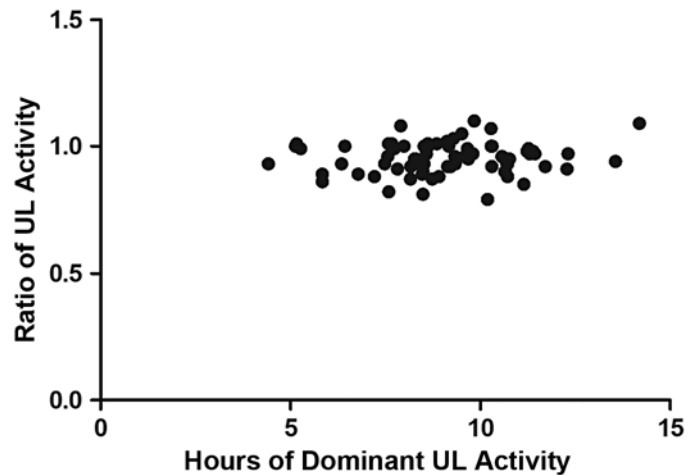
UL = upper limb.

hours of UL activity (**Table 2**). **Figure 1** illustrates the absence of a relationship between hours of dominant UL activity and the ratio of UL activity ($r = 0.08$, $p = 0.51$).

Hours of dominant UL activity were moderately correlated with time spent in sedentary activity (**Figure 2(a)**, $r = -0.36$, $p < 0.01$). Correlations for hours of dominant UL activity versus cognitive impairment ($\rho = 0.20$, $p = 0.09$), depressive symptomatology (**Figure 2(b)**, $r = 0.11$, $p = 0.37$), number of comorbidities ($\rho = -0.12$, $p = 0.32$), and age (**Figure 2(c)**, $r = -0.002$, $p = 0.99$) 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 $\rho < 0.13$, $p > 0.27$).

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 \pm 1.9 h and 8.6 \pm 2.0 h for dominant and nondominant ULs, respectively. The ratio of UL activity (0.95 \pm 0.06) indicates that the duration of UL activity between limbs was roughly equal, though quality of movements likely differed between limbs (e.g., stabilizing a bowl with one hand while stirring with the other hand). Potential modifiers of UL activity

**Figure 1.**

Scatterplot of ratio of upper-limb (UL) activity vs hours of dominant UL activity. Despite variability in hours of dominant UL activity, duration of activity between limbs is roughly equal, as indicated by narrow range in ratio 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 nondisabled, 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, which 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 to 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 limbs [13]. General physical activity (e.g., walking) is accounted for because it likely affects both limbs equally [12]. A lower ratio of UL activity indicates increased asymmetry in duration of activity

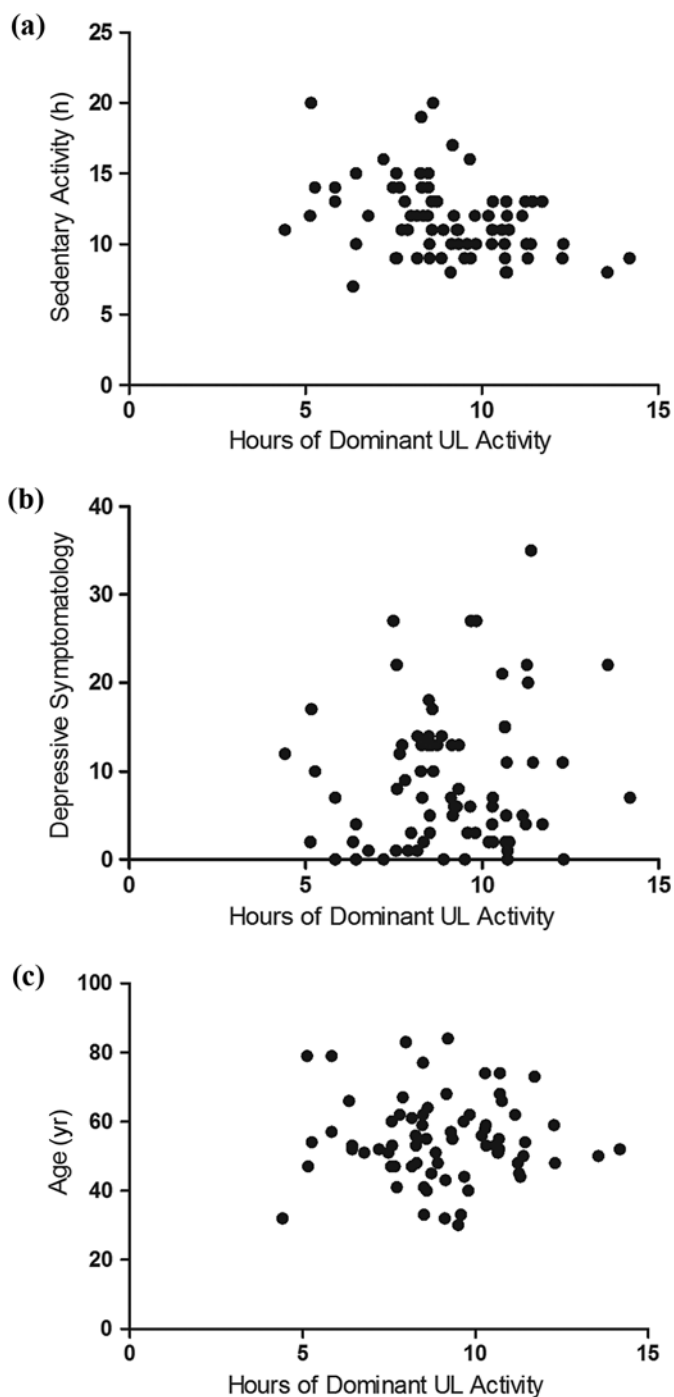


Figure 2. Scatterplots of hours of dominant upper-limb (UL) activity vs (a) time spent in sedentary activity, (b) depressive symptomatology measured using Center for Epidemiological Studies-Depression Scale, and (c) age. Time spent in sedentary activity, but not depressive symptomatology or age, was associated with hours of UL activity.

between the limbs, 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 postrehabilitation hours of UL activity could be adjusted to be consistent with preimpairment 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 percent 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 were low (**Table 2**). The range of scores for depressive symptomatology was larger but still not associated with hours of UL activity (**Figure 2(b)**). 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 postimpairment 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 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 widespread, 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 to 1.1. These data can help clinicians modify expectations of hours of UL activity based on preimpairment, 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 h 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 percent 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.

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 subject 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.

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.

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Author Contributions:

Study concept and design: R. R. Bailey, C. E. Lang.

Acquisition of data: R. R. Bailey.

Analysis and interpretation of data: R. R. Bailey, C. E. Lang.

Drafting of manuscript: R. R. Bailey, C. E. Lang.

Statistical analysis: R. R. Bailey.

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