Assessment of Accelerometers for Measuring Upper-Extremity Physical Activity

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Objective: The overarching goal of this study was to examine the use of triaxial accelerometers in measuring upper-extremity motions to monitor upper-extremity-exercise compliance. There were multiple questions investigated, but the primary objective was to investigate the correlation between visually observed arm motions and triaxial accelerometer activity counts to establish fundamental activity counts for the upper extremity.

Study Design: Cross-sectional, basic research. Setting: Clinical laboratory. Participants: Thirty healthy individuals age 26 ± 6 y, body mass 24 ± 3 kg, and height 1.68 ± 0.09 m volunteered. Intervention: Participants performed 3 series of tasks: activities of daily living (ADLs), rehabilitation exercises, and passive shoulder range of motion at 5 specific velocities on an isokinetic dynamometer while wearing an accelerometer on each wrist. Participants performed exercises with their dominant arm to examine differences between sides. A researcher visually counted all arm motions to correlate counts with physical activity counts provided by the accelerometer. Main Outcome Measure: Physical activity counts derived from the accelerometer and visually observed activity counts recorded from a single investigator. Results: There was a strong positive correlation (r = .93, P < .01) between accelerometer physical activity counts and visual activity counts for all ADLs. Accelerometers activity counts demonstrated side-to-side difference for all ADLs (P < .001) and 5 of the 7 rehabilitation activities (P < .003). All velocities tested on the isokinetic dynamometer were shown to be significantly different from each other (P < .001). Conclusion: There is a linear relationship between arm motions counted visually and the physical activity counts generated by an accelerometer, indicating that arm motions could be potentially accounted for if monitoring arm usage. The accelerometers can detect differences in relatively slow arm-movement velocities, which is critical if attempting to evaluate exercise compliance during early phases of shoulder rehabilitation. These results provide fundamental information that indicates that triaxial accelerometers have the potential to objectively monitor and measure arm activities during rehabilitation and ADLs.

Keywords: rehabilitation, patient compliance, exercise compliance

Rehabilitation is a crucial component of recovery of full function after surgical interventions. A full recovery is, in part, based on the patient’s compliance to the required rehabilitation program. However, patients’ compliance can be inadequate. Progress and adherence to rehabilitative programs are typically determined from exercise logs, which are based on subjective information provided by the patient and can potentially be unreliable. Lack of compliance to a rehabilitative program can result in poor outcome, leading to patient dissatisfaction and increased cost to the health care system. Development of more objective methods to measure patient compliance would benefit the patient and health care provider to guide the rehabilitation process more accurately and may potentially result in a better rehabilitation outcome. There is a need to develop instrumentation to facilitate this type of assessment. The upper extremity poses some unique challenges, as it moves in multiple dimensions, the rate of motion can be very slow for some phases of rehabilitation, and the motions are asynchronous with various motions performed throughout a day.

A more objective measure of rehabilitation activity would allow the health care professional to observe the frequency, duration, and intensity of physical activity and exercises. An accelerometer is a small device that is attached to a patient externally. It measures acceleration of limb motion and has been used to track physical activity and exercises. Accelerometers measure rate of change during a movement and are capable of tracking 3-dimensional motions, which would be ideal for shoulder motions. Accelerometers have been found to provide accurate measures of physical activity in walking, with an overall accuracy of 92% in patients with previous hip and knee arthroplasties. Monitoring patients during rehabilitation
with objective accelerometers may demonstrate differences in patient outcomes. Patients with hip fractures were monitored with both self-reports and accelerometers during a longitudinal study of 6 months. The objective measures from the accelerometer positively correlated \((r = .3)\) with the treating therapists’ rating of patients’ level of participation. The patients with higher accelerometer activity counts were found to have significantly better functional outcome than patients with lower activity counts.\(^\text{13}\) This indicates that greater walking activity after knee and hip surgery could be tracked and was able to discriminate the activity that had a direct bearing on functional outcome. The use of accelerometers in the upper extremity has been limited primarily to patients after cerebral vascular accidents and found to demonstrate differences in upper-extremity activity on the involved versus the uninvolved side.\(^\text{14–16}\)

Accelerometers have the potential to more accurately measure rehabilitation compliance in upper-extremity orthopedic pathologies. However, rehabilitation for orthopedic patients is quite different from rehabilitation after a cerebral vascular accident. In orthopedic rehabilitation, there are phases of rehabilitation that require immobilization and motions to regain mobility that slow and deliberate and then progress to more dynamic activities such as strengthening and functional activities of daily living (ADLs). It is well documented that accelerometers can collect data on typical arm movements during ADLs in a controlled setting\(^\text{14,15,17}\) but it is not known how accelerometer output correlates to specific arm movements. Previous researchers have compared differences between arms in healthy populations but have typically found no differences as individuals were allowed to perform usual ADLs for some period of time.\(^\text{17,18}\) The use of an accelerometer during rehabilitation would be to document whether patients are performing prescribed exercises, which has not been investigated in a controlled environment previously. Furthermore, it is unclear as to the accelerometer’s ability to accurately quantify slow upper-extremity movements. It is important to identify the slowest velocity that the accelerometer can accurately measure. There are commonly prescribed exercises such as passive external rotation that are performed in a slow and deliberate manner that would be appropriate to capture to evaluate patient compliance throughout multiple rehabilitation phases. To use accelerometers to objectively measure upper-extremity-exercise compliance, several fundamental questions needed to be answered first. Therefore the purpose of this study is threefold. The first is to determine the velocity threshold detectable by an accelerometer using 5 speeds on an isokinetic dynamometer, which would allow us to ensure that slow deliberate motions can be captured by an accelerometer. The second purpose is to determine if physical activity counts generated by the accelerometer can differentiate between the arm performing and not performing the activity in a controlled environment. This would simulate an injured condition of a patient performing specific exercise on 1 arm or not using the arm during the immobilization phase of rehabilitation. The final and most important purpose is to determine the correlation between physical activity counts generated by the accelerometer and visual activity counts recorded by the investigator to provide a context of what physical activity counts mean in relationship to number of arm movements.

### Methods

#### Participants

Participants for this study were 30 healthy individuals (21 female, 9 male) with the following demographic information: age 26 ± 6 years, body mass 24 ± 3 kg, and height 1.7 ± 0.10 m. All subjects volunteered to participate by signing a university-approved informed-consent form. Subjects were excluded if they reported having a current upper-extremity injury or previous surgical intervention to their upper extremity. Subjects were excluded if they did not have full range of motion in the shoulder, elbow, and wrist as determined by physical examination by a certified athletic trainer. Subjects’ hand dominance was determined using the Edinburgh Handedness Inventory.\(^\text{19}\) Hand dominance was used to emulate 1 injured and 1 noninjured extremity.

#### Apparatus and Measures

The 2 accelerometers used in this study were ActiGraph GT3X+ (ActiGraph, Pensacola, FL) activity monitors, which are triaxial accelerometers that have a mass 19 g and physical dimensions of 4.6 × 3.3 × 1.5 cm per device. The ActiGraph GT3X+ has the ability to record accelerations in 3 dimensions and combined the 3 orthogonal axes by using Pythagorean-theorem-termed vector-magnitude activity counts. This particular measure was used for this study, as multiple planes of motion occur during rehabilitation exercises and ADLs of the upper extremity. The accelerometers are battery operated and were initiated on a personal computer. The investigator’s watch was synchronized to the computer’s internal clock before initiation of each data-collection session to correctly record the start and end time of events during the multiple tests described in detail following. The accelerometer sampling rate was set at 30 Hz, recommended by the manufacturer, for all data collection and the device was attached to the wrist with wrist straps.

#### Procedures

The participants’ age, gender, height, and body mass were recorded. The order of tests was counterbalanced using Latin square with 2 levels to minimize fatigue and order bias. The first level of counterbalancing was between 3 categories (isokinetic, ADLs, and rehabilitation). The second level of counterbalancing was the specific activity within each category. The counterbalance was performed before enrollment for the 30 participants using an Excel (Microsoft, Redmond, WA) spreadsheet.
Accelerometers were placed on both wrists using a wrist band to prevent displacement during testing and to keep orientation consistent throughout testing. A single test administrator instructed the subjects how to perform each activity with their specific arm, detailed herein. This investigator provided all instructions and recorded all repetitions of dominant-arm motions for all subjects to minimize errors. The participants were allotted 2 minutes to perform each activity while the investigator visually monitored the trial to record the beginning and end of each activity. This time recording was critical as it allowed the continually collected data from the accelerometers to be delineated for each specific activity. Later in data processing, this allowed the specific time of an activity and the respective accelerometer physical activity counts output to be counted for each particular task. All motions were counted by the investigator with use of a video camera and recorded on a data sheet for each individual activity, regardless of the direction. For the purpose of this study these were called visual activity counts. Visual activity counts were defined as the investigator’s record of the number of arm motions performed by the subject. These data were used for later statistical analysis to provide context to the accelerometer’s vector-magnitude physical activity counts. The 3 tests are speed testing, ADL testing, and rehabilitation testing and are detailed below.

**Speed Testing**

Isokinetic testing was performed with the participant in supine position with the shoulder flexed to 90°. The subject was instructed to grasp the handle of an isokinetic dynamometer (Cybex Norm, Stoughton, MA). The dynamometer moved the arm passively at 5 different velocities (0.5°/s, 15°/s, 30°/s, 45°/s, 60°/s), with each angular velocity serving as a trial. The subject performed 2 minutes of passive shoulder flexion at each angular velocity through shoulder-flexion range of motion of 0° to 90°. The investigator video recorded and then visually counted and recorded the number of dominant-arm motions during the trial on the data sheet. The subject was instructed to allow the nondominant arm to rest by his or her side during testing. There was a recovery period of 1 minute between trials to set the next velocity on the isokinetic dynamometer. Testing was repeated until all 5 velocities were recorded.

**ADL Testing**

The test administrator explained the 4 ADLs to the subjects before each task. The ADLs were selected based on their use in previous publications.20,21 Subjects moved 9 dinner bowls from a countertop to the second shelf of an overhead cabinet with the dominant arm only. They washed a countertop by spraying a 0.9-by-0.65-m area with a standard surface-cleaning product with the nondominant arm and wiping clean until dry with the dominant arm. The specific manner in which to carry out the tasks was up to the individual to simulate real life. The only control was the time limit and the arm used to perform the task.

**Rehabilitation Testing**

The rehabilitation exercises were selected based on the standard rehabilitation program for a rotator-cuff repair prescribed by the investigators and from the literature.22–24 The test administrator explained and demonstrated each exercise before having the subject perform the 7 rehabilitation exercises with the dominant arm. The exercises performed were passive pendulum exercises, standing passive external rotation, passive internal-rotation towel stretches, passive forward bows, active assistive table slides, resistive internal rotation, and resistive rows with an elastic band.22–24 All subjects were instructed to perform 20 repetitions of each exercise. The number of actual repetitions performed with the subject’s dominant arm was counted by a single investigator from the video record.

**Data Reduction**

All visual recording of dominant-arm motion was transferred from data sheet to Excel file. ADLs were watched a minimum of 3 times using a video camera to correctly record visual activity counts, which allowed participants the most freedom in arm movements. The vector-magnitude physical activity counts from each accelerometer were calculated with ActiLife software (ActiGraph, Pensacola, FL). The ActiLife vector-magnitude physical activity counts were exported to an Excel spreadsheet using 1-second epochs for every second during the entire data collection. This value could range from zero to several hundred counts depending on the magnitude of the acceleration. Each row of data represented 1 second of physical activity counts. The start and end time of each activity recorded on the data sheet were identified by a single investigator. A blinded investigator summed the total vector-magnitude physical activity counts for both arms individually for each of the 3 tests. These data were used for the statistical analysis along with the visual activity counts recorded.

**Statistical Analysis**

To determine if the accelerometer physical activity counts can differentiate between speeds during isokinetic testing, the dominant-arm accelerometer physical activity counts were analyzed with a repeated-measures ANOVA with 1 within variable of speed with 5 levels. The nondominant-arm data were not used in this analysis, as the question was between velocities not differences between arms. To
determine if the accelerometer physical activity counts can differentiate between the dominant- and nondominant-arm movements during ADLs and rehabilitation exercises, 2 separate repeated-measures ANOVAs were used. The repeated-measures ANOVA for ADLs had 2 within variables: activity (4 levels) and arm (2 levels). The repeated-measures ANOVA for rehabilitation exercises had 2 within variables: exercise (7 levels) and arm (2 levels). For all measures alpha was set a priori at $P \leq .05$. For significant differences, Bonferroni post hoc analyses were performed to determine where specific differences occurred, with a $P$ value corrected for multiple comparisons.

To investigate the context of what physical activity counts mean in relationship to number of arm movements, a bivariate correlation was performed between the visual activity counts and the vector magnitude for ADLs to determine the relationship between the accelerometer physical activity counts and visual activity counts.

**Results**

A Mauchly sphericity test was significant for all repeated-measures ANOVAs. Greenhouse-Geisser correction was used as the epsilon was <0.75 to correct for the lack of homogeneity of variance for all the results. The first purpose of this study determined which speeds could be detected by the accelerometer. There was a significant difference between all velocities ($P < .001$). Post hoc analysis with a Bonferroni correction revealed that at each velocity the physical activity counts were different for the dominant arm (Figure 1).

The second purpose of this study was to determine if the physical activity counts generated by the accelerometers could identify differences between the arm performing and not performing the specific activity in a controlled environment. There was a significant interaction for activity by arm for ADLs ($P < .001$) and a significant interaction of exercise and arm for rehabilitation exercises ($P < .001$). A Bonferroni post hoc analysis demonstrated that the dominant arm was always more active for all ADLs (Table 1). A Bonferroni post hoc analysis demonstrated that the dominant arm was more active in 5 of the 7 rehabilitation exercises (Table 2). The external-rotation activity revealed no difference between the 2 arms ($P = .18$). The towel internal-rotation stretch activity resulted in greater nondominant-arm activity (8401 ± 634 counts) than dominant-arm activity (7116 ± 463 counts) ($P = .016$).

Our third purpose was to determine the correlation between physical activity counts generated by the accelerometer and visual activity counts recorded by the investigator to provide a context of what physical activity counts mean in relationship to number of arm movements. A bivariate correlation was performed between the visual activity counts and the vector magnitude for ADLs to determine the relationship between the accelerometer physical activity counts and visual activity counts.

**Cybex Data**

![Figure 1](image-url) — Illustration of the difference between the dominant arm’s physical activity counts at the 5 different passive speeds on the isokinetic dynamometer. Bonferroni post hoc analysis revealed a significant difference at each increasing speed for the dominant arm ($P < .001$).
counts mean in relation to arm movements. The bivariate correlation of the dominant-arm accelerometer with 3 of the 4 ADLs (vacuuming, mirror washing, and countertop activities combined) resulted in a significant correlation of ($r = .93$, $P < .001$) (Figure 2). The bowl-shelving activity, rehabilitation exercises, and isokinetic testing data were not considered, as each of these activities had been given purposeful constant counts or time that would invalidate a correlation calculation.

**Discussion**

This study provides fundamental information regarding the use of accelerometers for objectively capturing upper-extremity movements. The results suggest that accelerometers can differentiate activity between relatively slow motions. This confirms the previous finding that accelerometers can differentiate between arms in a controlled setting\(^{14,15}\) and provides new information regarding the context of accelerometers’ physical activity counts in the upper extremity.

Acceleration is the rate of change of velocity over time. Therefore, an isokinetic measure that moves at nearly a constant rate would be a good instrument to determine the speeds at which the ActiGraph GT3X+ could differentiate quantified motions. The current study results indicate that arm movements can be detected by the ActiGraph GT3X+. This is important, as many shoulder rehabilitation exercises are performed in a relatively slow and deliberate manner. All movements were shown to be significantly different from each other; therefore, the ActiGraph GT3X+ is able to capture differences in velocity during arm movement. A secondary analysis was done comparing dominant-arm and nondominant-arm motion at each velocity. There was significantly more activity in the dominant arm than in the nondominant arm at speeds $\geq 30°/s$ ($P < .001$). At $15°/s$ there was no difference between the arms ($P = .54$). The movements at $0.5°/s$ were found to be so slow that they were actually less than the nondominant arm ($P = .011$), which moved minimally during the testing. Subjects were instructed to relax their arm, but their nondominant was not strapped down to prevent any motion, which may account for the increase of nondominant-arm motion. The nondominant-arm-motion physical activity counts were not different through all testing speeds ($P > .28$).

Accelerometers measure rate of change, not the amount of motion occurring. As several rehabilitation exercises after shoulder surgery are performed in a slow and deliberate manner, it is important to know if the accelerometers can detect relatively slow movements. One of the most basic and commonly prescribed postoperative shoulder rehabilitation exercises is the pendulum exercise. The accelerometer was able to clearly

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<th>Nondominant Mean</th>
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1. Lawinger et al. 2015
2. JSR Vol. 24, No. 3, 2015
differentiate between arms performing this exercise in a healthy population. This cannot be directly extrapolated to an injured population, as their rate of motion may be slower. However, the relatively slow speeds able to be detected produce promising initial results in the use of accelerometers to track exercise compliance. The typical velocity of ADLs certainly varies by task and individual, but Lacquaniti26 found that reaching velocities ranged from 80° to 200°/s. The current study demonstrated that much slower velocities can be detected by the ActiGraph GT3X+ accelerometers.

Accelerometers were shown to be able to detect differences between the dominant and nondominant arm when the dominant arm is the prime mover during the activity. These results were found with all ADLs and 5 out of the 7 rehabilitation exercises. The study was set up to facilitate this result due to instructions given to the subjects. The intention was to simulate a condition with 1 injured and 1 noninjured extremity to determine if utilization of arms could be detected. The ability to differentiate between arms agrees with previous research in a hemiparetic population, when the affected arm was shown to be used less than the nonaffected limb.14 Hemiparetic patients have been shown to use their affected and unaffected arms less than a healthy population. In addition, their affected arm is used only 3.3 h/d compared with their unaffected arm at 6.0 h/d.14 Supporting the idea that arm activity can be discriminated, however, in unrestricted activity of a healthy population, there was no difference between the physical activity counts between arms.14,17

Future research is needed to determine if the difference between injured and noninjured arms is similar to the difference found in hemiparetic patients.

Two rehabilitation exercises did not have more activity in the dominant arm. This can be explained by the way the exercises were performed. The towel stretch requires both arms to perform the exercise simultaneously, but the dominant arm was behind the subject’s back, which may have impaired motion of the accelerometer. The direct contact between the subject’s body and the dominant accelerometer may have reduced some of the motion occurring, resulting in lower physical activity counts. The external-rotation stretch requires subjects to hold their dominant arm on a door frame and rotate the body around the arm. This would require movement of the nondominant arm as it moves with the body, which likely explains why there was no difference in the physical activity counts between arms during this exercise. The rate of arm motion was not controlled, but this exercise was among the slowest movement performed and produced one of the lowest physical activity counts (Table 2). The lower velocity of motion may also account for the lack of difference between the arms.

The accelerometers could discriminate 9 of 11 (81%) activities performed in this study, but it cannot discriminate between all activities. The prescript laboratory environment is far from postoperative shoulder patients functioning independently at home with precautions and specified rehabilitation exercises. The discriminating nature of these results suggests that accelerometers may
provide a useful tool to objectively measure exercise activity in the future. These results are encouraging and support further investigation, in patients with shoulder injury, to determine if they are resting or not resting their injured arm as prescribed by their treating physician.

The physical activity counts of a uniaxial accelerometer have been correlated to the number of steps a person takes over the course of a day. There are even recommended step counts for a healthy lifestyle.27,28 In the upper extremity, the use of accelerometers is far behind that in the lower extremity. There is limited research that has primarily focused on differences between arms and energy expenditures. One intention of this study was to provide contextual information as to what a physical activity count means for the upper extremity. Therefore, a correlation between physical activity counts and accelerometer counts was undertaken. The results show a strong positive nearly linear correlation of \( r = .93 (P < .01) \), \( R^2 = .87 \). This indicates that there is a relatively linear relationship between upper-extremity ADL visual counts and accelerometer physical activity counts. This is an initial step toward understanding categories of arm movements, similar to how many steps per day should be taken for an active lifestyle. The linearity of this relationship allows for context to be given to the vector-magnitude physical activity counts of the GT3X+ accelerometer. The context derived in this controlled laboratory study indicated that every 100 vector-magnitude physical activity counts equals 5 arm motions. This is just a first step in a series of studies that needs to occur before we can categorize arm motions similar to lower-extremity steps per day into categories of activities based on counts.27,29,30

This study had limitations that we fully acknowledge. The test sessions were conducted in a laboratory setting with a healthy population. These results may not be extrapolated to be indicative of a person’s normal day-to-day activities or how injured individuals may use their upper extremity. Activities measured in this study were performed in a healthy population, so the rate of motion cannot be extrapolated to an injured population as they may perform activities at a very different rate, which would directly affect the physical activity counts. The context of physical activity counts cannot be extrapolated to an injured population until further research is performed. In addition, when assessing the ADLs and rehabilitation activities, we used physical activity counts. Physical activity counts have been shown to have a relationship with lower-extremity activity, but this is the first study to show this relationship in the upper extremity.

**Conclusions**

This study’s findings suggest that ActiGraph GT3X+ accelerometers have good potential to be a valid tool for measuring exercise compliance based on this fundamental study that was performed in a controlled laboratory setting. This study addressed 3 primary purposes that provide fundamental information for use of accelerometers in measuring upper-extremity activity to evaluate exercise compliance. ActiGraph GT3X+ accelerometers can detect differences in varying arm-movement velocities on an isokinetic dynamometer. The accelerometers can detect differences in relatively slow arm-movement velocities, which is critical if attempting to evaluate exercise compliance during the early phase of shoulder rehabilitation. The accelerometer’s vector-magnitude physical activity counts can be used to discriminate between arms for most specific arm activities in a controlled laboratory environment. This is important to confirm that patients were compliant; if they are given instruction to perform varying amounts of unilateral and bilateral exercises we would expect to see a difference between the 2 accelerometer counts, indicating compliance to the exercises prescribed. There is a nearly linear relationship between vector-magnitude physical activity counts generated by the accelerometer and visually observed arm motions. These results suggest that a link between arm motions could be determined by having patients wear an accelerometer during rehabilitation to objectively measure arm use over the course of days or weeks. These results support the need for further research in supervised and unsupervised environments on patients with upper-extremity pathologies to further determine if accelerometers can provide an objective measure of arm use during ADLs and rehabilitation, to more objectively track exercise compliance.

**References**