Assessment of daily physical activities with sensors attached to the upper limbs in healthy adults using a manual wheelchair

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Abstract This study examined the energy expenditure (EE) of healthy adults during typical use of a manual wheelchair by attaching sensors to the subjects’ upper limbs. The aim was to determine whether the measured EE values depend on the sensor attachment site and whether the addition of angular velocity information to the acceleration value was advantageous to the EE assessment. Subjects were 11 males and 10 females. Their wrists and mid-upper arms were fitted with sensors to monitor their daily physical activities. Triaxial acceleration, triaxial angular velocity, and EE were measured while performing activities with a manual wheelchair. Coefficients of determination for estimating EE at each sensor location ranged from 0.66 to 0.79 (based on gender, the calculated three axis value of acceleration and angular velocity) and from 0.65 to 0.78 (based on gender and the calculated three axis value of acceleration, without angular velocity). Furthermore, angular velocity was not selected as a significant explanatory variable for estimating EE at the wrist. The average percent error for estimating the EE of daily physical activity in healthy adults using a manual wheelchair and factoring in gender and the calculated three axis value of acceleration at each sensor location ranged from 5.2 to 7.2%. Angular velocity information added to the calculated three axis value of acceleration at the upper arms slightly improved the estimation of EE. In addition, it was found that there was no difference in the assessment at different sensor locations.

Keywords: energy expenditure, assessment, daily physical activity, acceleration, manual wheelchair user

Introduction

Individuals with spinal cord injury (SCI) are prone to experience disuse syndrome as their movement is restricted due to the injury. Compared to healthy people, these individuals are at a higher risk of suffering from lifestyle-related diseases and metabolic syndrome⁹. Thus, to improve and maintain their health, a plan for physical activity management is necessary⁹). A recent prospective cohort-study showed that increased physical activity is associated with improved physical fitness and a reduced risk of cardiovascular diseases⁹). Therefore, it is important to accurately assess physical activity levels, energy expenditure (EE) and the energy balance between EE and energy intake, and compare wheelchair-bound patients with healthy people⁹).

Previous studies⁵–⁷) have assessed the physical activity of manual wheelchair users by attaching an accelerometer to the wheelchair’s wheel. However, this is an indirect assessment of the physical activities of wheelchair users. If we want to assess the physical activity of wheelchair users, the acceleration of their upper limbs would be a more direct feasible measurement. We previously reported the assessment of driving a treadmill using a manual wheelchair. This assessment was performed using a triaxial accelerometer with a gyro sensor attached to the wrists and upper arms of subjects with paraplegia⁶). The study suggested that a combination of the calculated triaxial angular velocity and triaxial acceleration from the motion sensors may be used to estimate EE during wheelchair activity on a treadmill. However, we are yet to assess daily physical activity.

Fig. 1 illustrates the axial directions of the motion sensors attached to the subjects’ wrists and upper arms in this study. The dimension represented by the changes in the axes was dependent on the angle of the shoulder and
elbow joints. It is known that a wide range of motions and angular velocity and acceleration are involved in the movement of the shoulders, elbows, and wrists. Additional information of angular velocity to triaxial acceleration could be expected to improve estimating EE, especially concerning light intensity and intermittent physical activity such as household activities. We hypothesize that we can assess daily physical activities using the values of acceleration and angular velocity for the upper limbs of manual wheelchair users. In terms of wearability and stability, the upper arms and/or wrists are suitable for installing such a device.

It has been reported that energy metabolism in SCI patients is different compared to able-bodied people\(^9,10\). Most previous studies\(^{11}\) proposed equations of estimating EE for daily physical activity by people who had normal energy metabolism function. Therefore, the study must be conducted with able-bodied people before examining SCI patients. This study examined the relationship between the EE, acceleration, and angular velocity values along the three axes that correspond to the upper limbs (left and right wrists; left and right upper arms) during daily physical activities in healthy adults using a manual wheelchair. Furthermore, we determined whether the assessment varied for different sensor locations.

Methods

**Subjects.** This study was approved by Tokyo Metropolitan University and comprised 11 male and 10 female healthy subjects. Their mean age was 23.8 years (standard deviation (SD) = 4.7 years). Nineteen subjects were right-handed. All subjects lacked experience using a manual wheelchair. The purpose and procedures of the study were explained in detail to each subject before their participation, and all subjects provided informed consent. (Ethical Review Board of Tokyo Metropolitan University No.24-53).

**Experimental protocol.** Before the experiment, we examined the types of daily physical activity in SCI patients using a physical activity record. As a result, the following activities were observed: sleeping, resting, talking, reading, writing, typing, drawing, observing, listening, desk work, eating, cycling, dressing oneself, laundry, cooking, cleaning the bath, moving at slow speed, stretching, and moving at normal speed. From these activities, we selected activities that would be relatively easy to control in the experiment.

Each subject performed eight activities with a manual wheelchair and using a face mask and Douglas bag while wearing a triaxial accelerometer. The eight activities were as follows: resting in a sitting position (for calculating the resting metabolic rate [RMR]), typing with both hands (typing), typing using a pen (typing with a pen), coloring some geometric figures (coloring book), folding shirts and towels (folding clothes), cooking fried vegetables (cooking), carrying a 1.5 L plastic bottle filled with water for 1.5 minutes (carrying a bag), and propelling oneself in a manual wheelchair for 45 seconds (wheelchair driving). An assistant walked at a set speed ahead of the subject during wheelchair driving with a metronome to help maintain a constant speed of the wheelchair. On the day of the experiment, subjects were first instructed to sit down quietly for 30 min. Then, the RMR was measured for 10 min, followed by the other activities being performed for 3-5 minutes. The expired air of the participant for each activity was collected from one minute after starting an activity. We defined the beginning of the steady state as a minute after starting an activity. Each subject completed the entire experimental protocol in approximately 3-4 h (hours), and sufficient rest was provided between activities to eliminate any carry-over effect.

**EE measurements.** The mask worn by subjects covered the mouth and nose and collected the expired gas to a Douglas bag. The collected gas was analyzed using a gas analyzer (AR-1; Arco System, Chiba, Japan). For each measurement of concentration and volume of expired O\(_2\) and CO\(_2\), the gas analyzer was initially calibrated using a certified gas mixture and atmospheric air. The values of O\(_2\) consumption and CO\(_2\) production, from which EE was estimated using Weir’s equation\(^{12}\), were determined under standard temperature, pressure, and dry air conditions.

**Measurement of acceleration and angular velocity.** Acceleration and angular velocity measurements were done using a motion sensor comprising a triaxial accelerometer with a gyro sensor (MicroStone Corporation, Nagano, Japan). The sensor, designed to be worn on the arm, was placed inside a plastic case (size = 45 × 45 × 23 mm\(^3\); weight = ~55 g). Anteroposterior (x-axis), vertical (y-axis), and mediolateral (z-axis) acceleration and gyro measurements were obtained at a frequency of 20 Hz. The sensor was attached at two locations on each side of the body: (1) the dorsal side of the distal end of the forearm (wrists) and
the midpoint between the acromion angle and the olecranon (upper arms).

Acceleration data were uploaded to a personal computer. The signals received from the motion sensor were processed as follows. All three signals from the triaxial accelerometer were passed through a high-pass filter with a cut-off frequency of 0.5 Hz to eliminate the gravitational acceleration component and sensor drift from the signal, and through a low-pass filter with a cut-off frequency of 5 Hz to eliminate the acceleration of the hand colliding with the hand rim during wheelchair operation. None of the three signals from the gyro sensor were filtered. We calculated the three axis value of acceleration and the three axis value of angular velocity (vector magnitude $\sqrt{x^2 + y^2 + z^2}$) using a filtered signal.

**Statistical analyses.** The EE values, the values of three axis accelerations and the values of three axis angular velocities are expressed as mean values and SD. The relationships between the measured EE and each motion-sensor value were evaluated using the coefficient of determination ($R^2$) with regression analysis. Multiple regression analyses were performed to develop equations for EE estimation. The relationships between the measured and estimated EE values were examined using Bland-Altman analysis. In this analysis, selected activities were categorized into three groups: typing, typing with a pen, and coloring in a book as activities with no wheelchair movement (group 1), folding clothes and cooking as activities with a little wheelchair movement (group 2) and carrying a bag and wheelchair driving as activities with wheelchair movement (group 3). Statistical analyses were performed using IBM SPSS Statistics v. 22 (IBM Japan Inc., Tokyo, Japan). The level of statistical significance was set at 5% for the two-tailed tests.

### Results

The mean and SD of the acceleration and triaxial acceleration for each activity as well as their relationships with measured EE are shown in Table 1. Table 2 shows the mean and SD of the calculated triaxial angular velocity and EE.

#### Table 1. Relationships between calculated three axis accelerations (in mg) and measured energy expenditures (EE) (in kcal min$^{-1}$ kg$^{-1}$) at each sensor location during daily physical activities.

| EE (10$^{-3}$) | Acceleration | Lw      | La      | Rw      | Ra      |
|----------------|--------------|---------|---------|---------|---------|
| resting        | 17.6±2.1     | 8.8±6.9 | 6.4±2.6 | 8.4±5.4 | 6.2±2.8 |
| typing         | 20.0±1.9     | 30.9±10.2| 13.4±4.4| 56.7±16.4| 21.0±6.0|
| typing with a pen| 20.3±1.8    | 26.5±41.5| 18.0±14.6| 110.9±38.9| 38.6±10.8|
| coloring book  | 20.5±2.6     | 30.7±34.7| 16.1±11.8| 102.4±41.8| 35.0±15.5|
| folding clothes| 27.5±4.2     | 337.1±58.5| 113.4±25.6| 359.0±65.5| 124.7±22.7|
| cooking        | 26.6±3.6     | 127.1±27.6| 47.9±10.1| 206.2±46.2| 75.5±17.6|
| carrying a bag | 37.0±8.1     | 330.8±77.7| 204.1±48.8| 404.5±78.6| 246.1±45.8|
| wheelchair diving | 43.5±10.8   | 398.1±102.9| 300.0±50.4| 540.3±122.2| 410.9±78.1|

EE, energy expenditure; Lw, Left wrist; La, Left arm; Rw, Right wrist; Ra, Right arm
Results are expressed by mean ± SD.

#### Table 2. Relationships between calculated three axis angular velocities (in deg s$^{-1}$) and measured energy expenditures (EE) (in kcal min$^{-1}$ kg$^{-1}$) at each sensor location during daily physical activities.

| EE (10$^{-3}$) | Gyro | Lw | La | Rw | Ra |
|----------------|------|----|----|----|----|
| resting        | 17.6±2.1 | 19.4±14.7 | 23.3±20.0 | 56.1±47.7 | 57.6±56.0 |
| typing         | 20.0±1.9 | 15.0±7.9 | 15.0±12.6 | 37.6±26.5 | 33.3±34.9 |
| typing with a pen| 20.3±1.8 | 14.4±12.6 | 16.6±13.8 | 45.6±23.4 | 40.2±34.6 |
| coloring book  | 20.5±2.6 | 15.8±11.7 | 17.0±14.0 | 46.8±25.0 | 38.4±36.9 |
| folding clothes| 27.5±4.2 | 98.3±14.5 | 49.4±10.0 | 108.4±15.1 | 63.0±19.6 |
| cooking        | 26.6±3.6 | 37.1±6.4 | 21.4±4.2 | 55.3±11.3 | 34.8±7.4 |
| carrying a bag | 37.0±8.1 | 94.9±16.1 | 95.2±12.2 | 135.3±23.3 | 136.6±35.8 |
| wheelchair diving | 43.5±10.8 | 103.6±18.4 | 120.7±18.3 | 154.1±32.8 | 182.1±37.7 |

EE, energy expenditure; Lw, Left wrist; La, Left arm; Rw, Right wrist; Ra, Right arm
Results are expressed by mean ± SD.
Multiple regression analysis was performed to examine the prediction equations shown in Table 3. The coefficient of determination of EE was 0.73-0.80 in Model 1, 0.66-0.79 in Model 2, 0.65-0.78 in Model 3, and 0.42-0.67 in Model 4.

Fig. 2 shows the relationships between measured EEs and estimated EEs during daily physical activities using a wheelchair in Model 3.

Bland-Altman analysis is a statistical method for assessing the agreement between two clinical measurement methods. The Bland-Altman plot shows a systematic bias. Fig. 3 shows that the mean difference between

Table 3. Multiple regression analysis of models for estimating energy expenditure (in kcal min$^{-1}$ kg$^{-1}$).

| Sensor Location | Equation | R$^2$ | P-value | Variables in the equation | Standardized partial regression coefficient | P-value | VIF |
|-----------------|----------|------|---------|---------------------------|---------------------------------------------|---------|-----|
| Model1(stepwise) | Left wrist | EE=$0.0215-0.0029\times$gender+$0.000101\times$Ay-$0.00005\times$Gxy | 0.736 | $<0.001$ | gender | -0.147 | $<0.001$ | 1.004 |
|                  |          |      |         |                           | Ay | 0.982 | $<0.001$ | 3.994 |
|                  |          |      |         |                           | Gxy | -0.159 | 0.048 | 4.000 |
|                  | Left arm | EE=$0.0209-0.0031\times$gender+$0.000141\times$Axz-$0.00006\times$Gxz | 0.790 | $<0.001$ | gender | -0.151 | $<0.001$ | 1.023 |
|                  |          |      |         |                           | Axz | 1.076 | 0.015 | 6.253 |
|                  |          |      |         |                           | Gxz | -0.221 | $<0.001$ | 6.285 |
|                  | Right wrist | EE=$0.0206-0.0032\times$gender+$0.000070\times$Ay-$0.00003\times$Gx | 0.743 | $<0.001$ | gender | -0.159 | $<0.001$ | 1.015 |
|                  |          |      |         |                           | Ay | 0.901 | $<0.001$ | 1.381 |
|                  |          |      |         |                           | Gx | -0.102 | 0.030 | 1.396 |
|                  | Right arm | EE=$0.0205-0.0031\times$gender+$0.000112\times$Axz-$0.00007\times$Gz | 0.791 | $<0.001$ | gender | -0.150 | $<0.001$ | 1.055 |
|                  |          |      |         |                           | Axz | 1.023 | $<0.001$ | 2.241 |
|                  |          |      |         |                           | Gz | -0.211 | $<0.001$ | 2.311 |

Model2(force entry: gender, A(xyz), G(xyz))

| Sensor Location | Equation | R$^2$ | P-value | Variables in the equation | Standardized partial regression coefficient | P-value | VIF |
|-----------------|----------|------|---------|---------------------------|---------------------------------------------|---------|-----|
| Left wrist | EE=$0.0214-0.0029\times$gender+$0.000111\times$Axyz-$0.000011\times$Gxyz | 0.668 | $<0.001$ | gender | -0.143 | 0.002 | 1.003 |
|                  |          |      |         |                           | Axyz | 1.252 | $<0.001$ | 12.41 |
|                  |          |      |         |                           | Gxyz | -0.476 | 0.003 | 12.42 |
| Left arm | EE=$0.0214-0.0033\times$gender+$0.000106\times$Axyz-$0.000006\times$Gxyz | 0.784 | $<0.001$ | gender | -0.162 | $<0.001$ | 1.035 |
|                  |          |      |         |                           | Axyz | 1.100 | $<0.001$ | 9.586 |
|                  |          |      |         |                           | Gxyz | -0.242 | 0.033 | 9.624 |
| Right wrist | EE=$0.0186-0.0029\times$gender+$0.000044\times$Axyz-$0.000002\times$Gxyz | 0.694 | $<0.001$ | gender | -0.143 | 0.001 | 1.008 |
|                  |          |      |         |                           | Axyz | 0.883 | $<0.001$ | 2.809 |
|                  |          |      |         |                           | Gxyz | -0.076 | 0.294 | 2.821 |
| Right arm | EE=$0.0213-0.0030\times$gender+$0.000075\times$Axyz-$0.000003\times$Gxyz | 0.770 | $<0.001$ | gender | -0.150 | $<0.001$ | 1.039 |
|                  |          |      |         |                           | Axyz | 1.017 | $<0.001$ | 2.920 |
|                  |          |      |         |                           | Gxyz | -0.196 | 0.003 | 2.971 |
Equation 114), ranged from 3.9 × 10^{-3.3\%} to 20.5\% for the right-wrist, and −9.2\% to 11.4\% for the left-wrist. The mean differences ranged from −8.1\% to 30.3\% for activity with regular wheelchair movement.

| Sensor Location | Equation | R^2 | P-value |
|-----------------|----------|-----|---------|
| Model 3 (force entry: gender, A(\text{xyz})) | Left wrist \(EE=0.0200-0.0028\times\text{gender}+0.000048\times\text{Axyz}\) | 0.651 | <0.001 |
| | Left arm \(EE=0.0205-0.0030\times\text{gender}+0.000082\times\text{Axyz}\) | 0.779 | <0.001 |
| | Right wrist \(EE=0.0181-0.0028\times\text{gender}+0.000043\times\text{Axyz}\) | 0.694 | <0.001 |
| | Right arm \(EE=0.0202-0.0026\times\text{gender}+0.000062\times\text{Axyz}\) | 0.759 | <0.001 |
| Model 4 (force entry: gender, G(\text{xyz})) | Left wrist \(EE=0.0189-0.0026\times\text{gender}+0.000018\times\text{Gxyz}\) | 0.547 | <0.001 |
| | Left arm \(EE=0.0186-0.0020\times\text{gender}+0.000020\times\text{Gxyz}\) | 0.661 | <0.001 |
| | Right wrist \(EE=0.0175-0.0022\times\text{gender}+0.000013\times\text{Gxyz}\) | 0.422 | <0.001 |
| | Right arm \(EE=0.0197-0.0013\times\text{gender}+0.000010\times\text{Gxyz}\) | 0.420 | <0.001 |

The synthesized values of acceleration are potentially used to estimate the velocity at each sensor location using multiple regression. We correlated the EE with the acceleration and angular-velocity information to the acceleration value is advantageous to the EE assessment. Each subject wore sensors on the subjects’ upper limbs. Specifically, the aim is to examine whether the EE measurements depend on the sensor attachment site and whether the addition of angular-velocity information to the acceleration value is advantageous to the EE assessment.

Table 4 shows the error in the assessment of daily physical activities for each sensor location when using Model 3. The mean differences ranged from −8.1\% to 30.3\% for the left-wrist, −11.8\% to 12.8\% for the left upper arm, −3.3\% to 20.5\% for the right-wrist, and −9.2\% to 11.4\% for the right upper arm. The total error, calculated using Equation 114, ranged from 3.9 \times 10^{-4} to 6.2 \times 10^{-3}.

Total error = Σ (estimated EE − measured EE) / N ...

### Discussion

This study examines the EE of healthy adults performing daily activities with a manual wheelchair by attaching sensors on the subjects’ upper limbs. Specifically, the aim is to examine whether the EE measurements depend on the sensor attachment site and whether the addition of angular-velocity information to the acceleration value is advantageous to the EE assessment. Each subject wore sensors on both wrists and mid-upper arms and performed a range of daily physical activities in a wheelchair. Triaxial acceleration, triaxial angular velocity, and EE were measured while the subjects were performing the activities. We correlated the EE with the acceleration and angular velocity at each sensor location using multiple regression. The synthesized values of acceleration are potentially useful for determining EE during daily physical activities. Further, the estimated EE values did not depend on the...
sensor location.

Table 4 shows the difference between the measured and estimated EE from Model 3. In the analysis, we divided the selected activities into three categories: activities with no wheelchair movement (group 1), activities with a little wheelchair movement (group 2), and activities with wheelchair movement (group 3). The average percent error did not differ between group 2 and 3, though group 1 had smaller errors compared to the other groups. In the Bland-Altman analysis, some plots categorized in group 3 were outside the 95% confidence interval. That is, there was a wide range in variation of estimation errors in activities with wheelchair driving. We speculated that one of the reasons was all of the subjects were inexperienced at using a manual wheelchair. However, even if subjects were wheelchair users, a large variation of estimation errors could be showed in the future study. Activities with wheelchair driving are very important to spread daily EE among wheelchair users. Therefore, improvement in estimating EE during activities in group 3 must take precedence in issues to be resolved.

From our study results, the use of angular velocity as a single explanatory variable may not be appropriate for the assessment of daily physical activities performed with a manual wheelchair. In Model 1 and 2, the values of angular velocity were not selected as significant explanatory variables for estimating EE at the wrists. On the other hand, angular velocity information at the upper arms was

Fig. 2 Relationships between measured EEs and estimated EEs during daily physical activities using a wheelchair. a: left upper arm ($R^2 = 0.779$, $p < 0.001$); b: right upper arm ($R^2 = 0.759$, $p < 0.001$); c: left wrist ($R^2 = 0.651$, $p < 0.001$); d: right wrist ($R^2 = 0.694$, $p < 0.001$). A, resting; B, typing; C, typing with a pen; D, coloring book; E, folding clothes; F, cooking; G, carrying a bag; H, wheelchair driving. EE, energy expenditure.
assessed the EE of manual wheelchair users performing physical activities using GT3X+ and GENEActiv accelerometers. The sensors were attached to the right upper arm and right wrist of subjects. They reported that the absolute estimation errors in EE were 19–66% for GT3X+ on the right upper arm, 17–122% for GT3X+ on the right wrist, 15–26% for GENEActiv on the right upper arm, and 17–32% for GENEActiv on the right wrist17). Furthermore, Hiremath et al. assessed the physical activity of manual wheelchair users with a gyroscope-based wheel rotation monitor and an arm accelerometer or a wrist accelerometer. In their study, the average estimation errors were −9.8 ± 37.0% for the arm and −5.7 ± 32.6% for the wrist18).

In our study, the absolute estimation errors ranged from 1.5 to 20.5% and from 0.6 to 11.4% for the right wrist and right upper arm, respectively. Our estimation model showed lower error values, but the devices and activities selected differed from the abovementioned studies. Even if results were expressed by three categories (group 1, 2 and 3), apparent differences in estimated error was not seen between sensor locations. Therefore, sensor location doesn’t seem to be a factor and can be determined by wearability and stability.

This study has several limitations. First, all the subjects in this study were healthy, and not actual wheelchair-users. Previous studies with SCI patients reported that the coefficient of determination of assessing the EE equation using the values of angular velocity and acceleration were higher than assessing the EE equation only using the acceleration value19). Thus, angular velocity data has potential for improving the assessment of EE for all daily physical activities in manual wheelchair users. However, one must take note that the resulting equation may not be used in the assessment of manual wheelchair users with paraplegia, since the assessment was conducted only on healthy subjects. Thus, we cannot conclude that angular velocity is necessary for the assessment of daily physical activities of manual wheelchair patients with SCI. From a different perspective, the calculated triaxial angular velocity can possibly be used for classifying physical activities. A classification study classifies physical activities with decreasing error in EE estimation using angular velocity. Such studies used some feature values for classification, e.g., the acceleration value. In this study, angular velocity had some influence on the estimation of EE using acceleration. Therefore, it is possible that the value of angular velocity includes a feature value for classification.

We found no statistically significant differences in the results for the assessed sensor locations. Nightingale et al. assessed the EE of manual wheelchair users performing physical activities using GT3X+ and GENEActiv accelerometers. The sensors were attached to the right upper arm and right wrist of subjects. They reported that the absolute estimation errors in EE were 19-66% for GT3X+ on the right upper arm, 17-122% for GT3X+ on the right wrist, 15-26% for GENEActiv on the right upper arm, and 17-32% for GENEActiv on the right wrist17). Furthermore, Hiremath et al. assessed the physical activity of manual wheelchair users with a gyroscope-based wheel rotation monitor and an arm accelerometer or a wrist accelerometer. In their study, the average estimation errors were −9.8 ± 37.0% for the arm and −5.7 ± 32.6% for the wrist18).
Table 4. Absolute and percentage differences between measured and estimated by model 3 energy expenditure (EE).

| Group  | Activity                  | Lw (absolute $10^{-3}$ kcal/kg/min) | Lw (%)  | La (absolute $10^{-3}$ kcal/kg/min) | La (%)  | Rw (absolute $10^{-3}$ kcal/kg/min) | Rw (%)  | Ra (absolute $10^{-3}$ kcal/kg/min) | Ra (%)  |
|--------|---------------------------|--------------------------------------|---------|--------------------------------------|---------|--------------------------------------|---------|--------------------------------------|---------|
|        |                           |                                      |         |                                      |         |                                      |         |                                      |         |
|        | Resting                   | 15.1±20.9                            | 10.0±14.4| 20.0±21.3                            | 12.8±14.9| -4.9±21.0                           | -1.6±13.1| 17.5±20.5                            | 11.4±14.5|
| Group 1 | Typing                    | 1.8±19.3                             | 1.5±9.6  | 1.7±19.3                             | 1.4±9.6  | -7.7±20.5                           | -3.3±10.0| 2.8±18.8                             | 2.0±9.5  |
|        | Typing with a pen         | -3.5±30.4                            | -1.1±14.4| 2.4±26.4                             | 1.8±12.7 | 13.1±28.8                           | 7.1±14.2 | 10.9±23.1                            | 6.0±11.6 |
|        | Coloring book             | -1.5±25.8                            | 0.0±11.8 | 0.6±23.4                             | 1.1±10.7 | 8.9±26.6                            | 5.1±12.7 | 7.9±21.7                             | 4.7±10.4 |
|        | Average                   | 0.1±11.9                             | 1.4±11.0 |                                      |         | 3.0±12.3                            | 4.2±10.5 |
| Group 2 | Folding clothes           | 77.1±45.5                            | 30.3±20.4| 10.5±37.3                            | 5.3±14.0 | 50.8±43.3                           | 20.5±18.9| -5.8±34.7                            | -0.6±12.8|
|        | Cooking                   | -16.3±36.4                           | -4.7±12.7| -34.7±34.0                           | -11.8±11.1| -7.0±29.9                           | -1.5±11.6| -27.8±31.7                           | -9.2±11.0|
|        | Average                   | 12.8±16.6                            | -3.3±12.6|                                      |         | 9.5±15.8                            | -4.9±11.9|
| Group 3 | Carrying a bag            | -20.6±61.5                           | -2.1±20.5| -8.4±60.8                            | 1.3±21.1 | -23.8±81.0                           | -1.8±24.9| -23.1±77.4                           | -1.8±24.2|
|        | Wheelchair driving        | -53.0±98.6                           | -8.1±21.2| 6.3±92.4                            | 6.3±22.1 | -29.3±97.7                           | -2.2±24.6| 16.6±90.8                            | 8.8±24.8 |
|        | Average                   | -5.1±20.9                            | 3.8±21.6 |                                      |         | -2.0±24.8                           | 3.5±24.5 |
| All    |                          | 7.2±15.6                             | 5.2±14.5 |                                      |         | 5.4±16.2                            | 5.6±14.8 |
| Total Error |                    | 9.4±10.9                             | 8.4±8.5  | 9.5±9.7                             | 8.8±8.8  |

Results are expressed by mean ± SD.
Lw, Left wrist; La, Left arm; Rw, Right wrist; Ra, Right arm
a Group 1 activity is an activity with no wheelchair move.
b Group 2 activity is an activity with a little wheelchair move.
c Group 3 activity is an activity with wheelchair move.
bound patients. Second, the sample size of this study was small; therefore, we did not check for cross-validation. Third, some activities were measured over short time intervals. For example, wheelchair driving was only measured for 3 min. Thus, we could not measure activities in the steady state condition. Further study is needed to assess the daily physical activities of manual wheelchair users with SCI.

**Conclusion**

Coefficients of determination for estimating EE ranged from 0.65 to 0.78 (forced-entry regression variables: gender and the calculated three axis value of acceleration) for each sensor location. Average of percent error for estimating EE of the daily physical activity in healthy adults - using a manual wheelchair, gender and the calculated three axis value of acceleration on each sensor location - ranged from 5.2 to 7.2 (%). Moreover, coefficients of determination for estimating EE ranged from 0.66 to 0.79 (forced-entry regression variables: gender, the calculated three axis value of acceleration, and the calculated three axis value of angular velocity) for each sensor location. Average of percent error for estimating EE of the daily physical activity in healthy adults - using a manual wheelchair, gender, the calculated three axis value of acceleration and the calculated three axis value of angular velocity for each sensor location. Average of percent error for estimating EE of the daily physical activity in healthy adults - using a manual wheelchair, gender, the calculated three axis value of acceleration and the calculated three axis value of angular velocity on the upper limbs slightly improved estimating the EE of daily physical activity in healthy adults using a manual wheelchair. In addition, it was found that there was no difference in the assessment at different sensor locations.

**Conflict of Interests**

The authors declare that there is no conflict of interests regarding the publication of this article.

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