Moving standard deviation of trunk acceleration as a quantification index for physical activities: Validation study

Takuya Suzuki, Yuji Kono, Takayuki Ogasawara, Masahiko Mukaino, Yasushi Aoshima, Shotaro Furuzawa, Yurie Fujita, Hirotaka Matsuura, Masumi Yamaguchi, Shingo Tsukada, Yohei Otaka

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Abstract

Background: Step count is often used to quantify activity in individuals using accelerometers. However, slow and irregular gait patterns in the elderly or patients with motor impairments can hinder accurate step detection. Alternative device-specific measures of physical activity exist, but their specificity limits cross-applicability between different device sensors. Moving standard deviation of acceleration (MSDA), obtained from truncal acceleration measurements, is proposed as another alternative parameter to quantify physical activity in patients.

Objective: This study aims to evaluate the effectiveness of MSDA in quantifying physical activity in patients with stroke-induced hemiparesis compared to the traditional step count.

Methods: We enrolled 197 consecutive patients with stroke hemiparesis admitted to the recovery rehabilitation ward. Using the Hitoe system, a smart clothing-based truncal acceleration measurement system, we measured MSDA of trunk movement and step count. The correlation between MSDA and step count was examined across all participants. Based on their daily living mobility levels, measured using the mobility score of the Functional Independence Measure (FIM), participants were categorized into six subgroups: FIM1-4, FIM5 (wheelchair), FIM5 (walking), FIM6 (wheelchair), FIM6 (walking), and FIM7 (walking). Inter-subgroup differences in MSDA were analyzed.

Results: A strong correlation was observed between MSDA and step count ($r = 0.78$, $p < 0.001$), with a stronger correlation in the walking group ($r = 0.79$, $p < 0.001$) compared to the wheelchair group ($r = 0.55$, $p < 0.001$). The Shapiro-Wilk test, supported by an analysis of skewness and kurtosis, indicated that within the subgroups, the distribution of MSDA more closely resembled a normal distribution compared to that of the step count. MSDA corresponded with the independence level indicated by the FIM mobility score, while step count was more influenced by the mode of mobility (wheelchair vs walking).

Conclusions: The results suggest the validity of MSDA as a parameter for physical activity in patients with stroke. MSDA is potentially applicable to patients with motor impairments, irrespective of their mobility measures, supporting its wide use in rehabilitation clinical practice.

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Validation of the moving standard deviation of trunk acceleration as a quantification index for physical activities

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Conclusions: The results suggest the validity of MSDA as a parameter for physical activity in patients with stroke. MSDA is potentially applicable to patients with motor impairments, irrespective of their mobility measures, supporting its wide use in rehabilitation clinical practice.

Keywords: smart clothing, step count, MSDA, wheelchair, activity quantification

Introduction

Post-stroke rehabilitation is primarily undertaken to enhance patient independence in activities of daily living (ADL). To achieve this goal, it is important to improve movement ability as well as boost exercise tolerance, which is directly reflected in the daily amount of activity. Increases in physical activity and extended rehabilitation time are associated with improved physical function and shorter hospital stay [1, 2]. Higher levels of physical activity can decrease the mortality risk [3]. Therefore, physical activity requirement should be actively assessed in post-stroke patients.

To quantify physical activity, the number of steps, measured using an accelerometer, is widely used and is a valid, reliable parameter for assessing physical activity in clinical rehabilitation settings [4, 5]. Numerous studies have established a close association between the number of steps taken and health-related quality of life (HRQoL) [6], self-efficacy [7], and the risk of stroke recurrence [8]. Accelerometers are reliable, validated devices that can objectively measure physical activity in stroke patients [9]. Exercise therapy, when supplemented with accelerometer feedback and a goal-centred step-activity monitoring program, can enhance the physical activity of hospitalised patients recovering from ischaemic stroke [10, 11].

While widely used to quantify activity, counting steps is only applicable to ambulatory patients. Indeed, most of the previous studies have focused on stroke patients who could walk independently. However, in managing stroke patients, a substantial number face challenges with walking in their daily lives. Of note, at the time of discharge from acute hospitalization, approximately 30–50% of patients had a modified Rankin Scale score of 4 or higher [12], indicating significant mobility impairment. While step count, an acceleration threshold-based measure of activity, may partially capture movement in everyday activities, its validity in accurately measuring the activity of patients with walking difficulties remains questionable. These considerations highlight the need for acceleration-based measures that can be effectively used in patients with difficulty in walking.

To address this issue, we proposed an alternative metric: the moving standard deviation of acceleration (MSDA), which is derived from the standard deviation of the acceleration norm that is measured from the trunk using an accelerometer placed on the chest. The utility of the MSDA as an activity quantification measure has been validated previously, showing a strong correlation between the MSDA and % oxygen uptake reserve (%VO_2R) in healthy participants, and between MSDA and % heart rate reserve (%HRR) in patients suffering from cerebrovascular disease with motor dysfunction [13]. However, it remains to be clarified whether the MSDA, as compared to the traditional method of step counting, truly represents a superior measure for quantifying physical activity in patients with limited mobility.

Consequently, this study focused on exploring the relationship between the MSDA and step count and comparing their efficacy as measures of physical activity in patients with stroke. Specifically, our objectives were: (1) to examine the correlation between the MSDA and the number of steps taken, and (2) to compare their data characteristics, which includes an understanding of the features of data distribution and investigating their respective relationships with the level of ADL.

Materials and Methods

Participants

Between January 2018 and February 2020, we enrolled consecutive patients with stroke hemiparesis who were admitted to the recovery rehabilitation ward of Fujita Health University Hospital. Participants who did not provide informed consent were excluded. This study was reviewed and approved by the Ethics Committee of Fujita Health University (HM17-220). All participants provided written informed consent before participation in the study.

Study design and protocol

This single-centre cross-sectional study comprised participants who underwent physical activity assessment within 1 week of admission to the recovery rehabilitation ward.

Measurement

A *hitoe* system (NTT Cooperation, Toray Industry, Inc.) was used to measure the amount of physical activity [14]. The *hitoe* system is a clothing-based activity monitoring system that consists of a wearer, a transmitter equipped with an embedded accelerometer, a data receiver (which can be a smartphone or an Internet of Things [IoT] gateway), and a data server. The sampling rate was set to 25 Hz. Monitoring started before noon on the first assessment day and stopped after noon on the third assessment day. As clothing was used for monitoring, monitoring was paused during bathing; after bathing, the *hitoe* wear was changed, and the monitoring was continued. To mitigate the impact of daily fluctuations and compensate for deficiencies [15], we used 48-h data to calculate the 24-h ensemble average. Individuals with >5% deficit in the 24-h measurement data were excluded. In this study, 24-h average values of minute-by-minute data on the number of daily steps and the MSDA constitute the physical activity indices. The step detection capability of this system has been validated using data from various commercial pedometers [16]. The MSDA was derived from a 2-s window of 50 samples of the norm of truncal acceleration, as measured by the accelerometer. The acceleration norm was computed using the following equation:

$$Norm=\sqrt{¿¿}\,),$$

where, x, y, and z represent the vertical, lateral, and anterior/posterior axes, respectively.

Mobility levels of the patients were assessed using the Functional Independence Measure (FIM) scores. The FIM consists of 18, 13 motor, and 5 cognitive items. Each item is rated on a 7-scale from one (full assistance) to seven (independence). Other clinical characteristics including age, sex, height, weight, and disease were collected from the patients' medical records.

Data analysis

Continuous variables were presented as means and standard deviations, and categorical variables were presented as percentages. The Shapiro–Wilk test was used to examine the normality of the number of steps and MSDA. To further investigate the characteristics of these distributions, their skewness and kurtosis were examined using the Fisher-Pearson coefficient of skewness (g1) and Fisher's coefficient of kurtosis (g2) [17]. Next, the relationship between MSDA and number of steps was examined using Spearman's rank correlation coefficient. This analysis was conducted for all participants and separately for the two groups: those in the walking group and those in the wheelchair group. Finally, we categorized all participants into six subgroups based on the mobility scores from the FIM and their mobility patterns as follows: FIM1-4, FIM5 wheelchair (WC), FIM5 Walking, FIM6 WC, FIM6

Walking, FIM7. The Kruskal–Wallis test was performed for the association between MSDA and the number of steps, and multiple comparisons were made using the Bonferroni method. All analyses were performed using SPSS version 26 (IBM Corp., Armonk, NY, USA). Statistical significance was set at $p < 0.05$.

Results

A total of 197 patients (129 males, 66.1 ± 12.5 years) were enrolled and included in the analysis (Table 1). Of these, 61 patients were ambulatory, and 136 patients used wheelchairs. The median period between onset and measurement was 41 days (11–390 days). The average MSDA and number of steps were 0.009 ± 0.003 and 1229 ± 1834, respectively.

Table 1. Participant characteristics in the study cohort

Variables	n = 197
Age, years [Mean (SD)]	66.1(12.5)
Sex (male/female)	129 / 68
Height, cm [Mean (SD)]	161.7 (15.5)
Weight, kg [Mean (SD)]	58.6 (13.7)
Aetiology, n	
Cerebral haemorrhage	71
Cerebral infarction	94
Subarachnoid haemorrhage	16
Others	16
Mobility, n	
Walk	61
Wheelchair	136
FIM-motor [Mean (SD)]	48.5 (26.0)
FIM-cognitive [Mean (SD)]	22.5 (10.2)
FIM-total [Mean (SD)]	70.7 (34.6)

The relationship between the MSDA and the number of steps is shown in Figure 1. Significant positive correlations were found for all participants (r=0.784, P<0.001), the walking group (r=0.787, P<0.001), and in the wheelchair group (r=0.546, P<0.001).

The detailed features of the MSDA distribution and the number of steps for all participants are shown in Figure 2. Neither the MSDA nor the number of steps exhibited a normal distribution. The distributions of MSDA and steps exhibited right-skewness, with skewness coefficients of 0.78 and 1.72, respectively (zero when normally distributed). The kurtosis coefficient for MSDA was 3.02, which is close to the typical value of 3 for a normal distribution. In contrast, the kurtosis coefficient for steps was 5.26, indicating a higher level of kurtosis. The normality of the distribution was further tested in each of the six subgroups (table 2). The distribution of MSDA data within subgroups exhibited smaller deviations from a normal distribution in terms of kurtosis and skewness coefficients, suggesting that it was closer to a normal distribution compared to the steps data. The Shapiro-Wilk test did not yield significant results for MSDA in all the subgroups, whereas the step data showed significance, especially within the wheelchair subgroups.

Table 2. Kurtosis, skewness values, and results of the Shapiro–Wilk test

	MSDA			Number of steps		
	Kurtosis (g2)	Skewness (g1)	Shapiro–Wilk, p-value	Kurtosis (g2)	Skewness (g1)	Shapiro–Wilk, p-value
WC 1-4 (n=94)	3.33	0.51	0.18	24.33	4.32	<0.001
WC 5(n=23)	3.15	0.94	0.05	2.22	0.75	0.005
WC 6 (n=19)	2.59	0.05	0.92	4.37	1.38	0.002
Walking 5 (n=15)	2.48	0.27	0.79	1.64	0.01	0.23
Walking 6 (n=18)	2.75	0.47	0.67	1.95	0.09	0.83
Walking 7 (n=28)	2.63	–0.38	0.62	2.57	0.10	0.42
WC (n=136)	3.91	0.93	<0.001	19.48	3.61	<0.001
Walking (n=61)	2.56	0.19	0.725	2.61	0.40	0.11
All participants (n=197)	3.02	0.78	<0.001	5.26	1.72	<0.001

WC, wheelchair; MSDA, moving standard deviation of acceleration.
For normal distribution: kurtosis (g2) = 3 and skewness (g1) = 0.

The relationships between the six subgroups according to the FIM scores of mobility items, mobility patterns, MSDA, and number of steps are shown in Figure 3. The median MSDA values in the six subgroups FIM1-4, FIM5(wheelchair), FIM5(walking), FIM6(wheelchair), FIM6(walking), and FIM7 were 0.006, 0.007, 0.010, 0.011, 0.011, and 0.014, respectively. Significant differences were found in MSDA between the following pairs; 1-4(WC) vs. 5(Walk)(P<0.001), 1-4(WC) vs 6(WC)(P<0.001), 1-4(WC) vs 6(Walk)(P<0.001), 1-4(WC) vs 7(Walk) (P<0.001), 5(WC) vs 5(Walk)(P<0.005), 5(WC) vs 6(Walk)(P<0.001), 5(WC) vs 7(Walk)(P<0.001), 5(Walk) vs 7(Walk)(P<0.001),and 6(WC) vs 7(Walk)(P<0.001). The median number of steps in the six subgroups were 68, 233, 1386, 367, 2835, and 4462, respectively. Significant differences were found in the steps between the following pairs 1-4(WC) vs. 5(Walk) and 5(WC) vs. 6(Walk) at *P*<0.005, and at *P*<0.001 for the remaining pairs: 1-4(WC) vs. 6(WC), 1-4(WC) vs. 6(Walk), 1-4(WC) vs. 7(Walk), 5(WC) vs. 7(Walk), 5(Walk) vs. 6(Walk), 5(Walk) vs. 7(Walk), 6(WC) vs. 6(Walk), 6(WC) vs. 7(Walk), and 6(Walk) vs. 7(Walk).

Discussion

This study compared the effectiveness of the MSDA and step count in measuring physical activity in patients with stroke-induced hemiparesis. The MSDA not only had a positive correlation with the number of steps but was also associated with the FIM-mobility score. Notably, the MSDA demonstrated superior characteristics over the traditional step count in several aspects of quantifying activity levels, particularly in patients with walking difficulties. First, in contrast to the step count, the distribution of the MSDA exhibited a closer alignment with a normal distribution, particularly within subgroups of patients using wheelchairs and those with similar ADL levels.

Second, the MSDA did not present a floor effect within the wheelchair group, which was observed with the step count. Finally, the Moving Standard Deviation of Acceleration (MSDA) was consistent with varying levels of mobility independence, showing no significant differences across types of mobility measures (walking or wheelchair use). In contrast, the step count was more susceptible to the mode of mobility; significant differences were observed in the step values between groups with the same level of independence but using different mobility measures.

The findings of this study demonstrated the superiority of the MSDA as a measure of physical activity in patients after stroke. This standard was particularly useful in those with limited gait functionality, such as slow walking speed, minimal steps, or an inability to walk. This was confirmed by analysing the activities of post-stroke rehabilitation inpatients, of whom approximately 70% relied on a wheelchair for mobility. Our results indicated that the MSDA was positively correlated with the number of steps, which is an established measure of physical activity. However, we observed different patterns between patients who walked independently and those who used wheelchairs. Specifically, step counts were strongly correlated with the MSDA in patients who could walk independently, whereas this correlation was weaker in patients who used wheelchairs. Moreover, compared to that with the MSDA, the data distribution exhibited a more pronounced deviation in the step count. Despite skewed distributions of both the number of steps and the MSDA, a deviation in kurtosis was observed only in the steps. Further stratified examination revealed that, in contrast to the number of steps, the MSDA was normally distributed within all levels of mobility independence.

The superiority of the MSDA over step count in the current population can be attributed to the distinct characteristics of the parameters. The number of steps, which is a frequently used parameter for activity monitoring, is a threshold-based parameter that measures the number of movements with greater acceleration beyond a specific threshold [16]. However, this approach may induce challenges when applied to patients with neurological disorders who often manifest irregular step patterns and slower gait speeds. Indeed, accelerometer use to count steps can produce misleading results in such cases [18]. In contrast, the MSDA quantifies truncal oscillations; as the trunk is the body's heaviest segment, this can, without imposing a specific threshold, be captured as a continuous value [13]. Thus, the MSDA could be more sensitive to variations in non-walking activities. Consequently, the MSDA distribution encompasses both walking and non-walking activities; this characteristic of the MSDA underscores its potential application as a comprehensive metric for evaluating activity levels irrespective of individual mobility methods, whether walking or using wheelchairs.

Furthermore, our results illustrate that the MSDA effectively reflects the level of independence in daily life. Previous studies have demonstrated a strong correlation between physical activity and independence levels; for instance, the Life-Space Assessment, a physical activity parameter, shows a positive correlation with Lawton's instrumental ADL scores [19, 20]. A similar positive correlation has been noted between accelerometer-measured physical activity and FIM-motor scores in stroke patients [21].

The study’s results further support previous observations and reveal significant differences in both the MSDA and step count between patients with and without independent mobility. Furthermore, in contrast to the step count, the MSDA appears to be less influenced by the mode of mobility. In the case of mobility levels FIM5 and FIM6, no significant differences were observed between patients using wheelchairs and those walking, while significant disparities in step counts were observed across different mobility measures at both levels, leading to reduced coherence with respect to levels of independence: it tends to be higher for patients capable of walking with a level of FIM 5, as opposed to those who are using wheelchair with a FIM score of 6.

These findings suggest that the MSDA can serve as a universal measure of physical activity, regardless of an individual's gait capabilities. This objective measure could be beneficial for providing feedback and setting goals for rehabilitation, to encourage daily activities. Many community-dwelling patients with a stroke fail to achieve the recommended activity level [22]. Thus, utilizing the MSDA to track daily activities could offer a valuable strategy for promoting more active daily living in the realm of rehabilitation.

Limitations

This study has some limitations. Firstly, its applicability to non-hospitalized patients warrants further exploration. The study was conducted in a rehabilitation ward with a flat floor, which differs from the environment outside the hospital. With barriers such as steps or uneven surfaces, the MSDA values may be higher than those in hospital wards. The impact of environmental variables on MSDA merits investigation in future studies. Despite these considerations, the current study remains meaningful by demonstrating the superiority of the MSDA over traditional step count in patients with stroke-induced slow walking speeds and unusual gait patterns.

Second, as the MSDA reflects truncal movement oscillations without identifying the specific movements involved, certain neurological symptoms may influence the measurements. For instance, patients with Parkinson's disease experience tremors that can affect the MSDA values, which reflect movement variability. Further research is needed to clarify the movements or symptoms that may distort MSDA values. Finally, to enhance understanding, the clinical significance of MSDA values should be further investigated, specifically in terms of interpreting different values as corresponding levels of physical activity. While the step count serves as an easily understandable and intuitive metric for clinical feedback, the MSDA value lacks this straightforwardness, posing challenges for patients in correlating it with specific activities. Therefore, it is imperative to foster a deeper comprehension and interpretation of this parameter within clinical contexts. Efforts should be directed towards contextualizing the MSDA values and making them more intuitive and meaningful for patients.

Conclusion

This study indicates that the MSDA is a valid parameter for measurement of physical activity, applicable to stroke patients irrespective of their mobility measures. Future research is warranted to examine the factors influencing MSDA values and to establish the clinical utility of this parameter.

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Disclosure statement

The authors utilised leased wearable clothing and hardware devices from Toray Industries and NTT Corporation, respectively, which are the manufacturers of the tracking devices. Takayuki Ogasawara, Masumi Yamaguchi, and Shingo Tsukada are employees of NTT Corporation. The other authors declare no conflicts of interest associated with this manuscript.

Data availability statement

The data collected and analysed during the current study are available from the corresponding author on reasonable request.

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Figure legends

Figure 1

Scatter plot showing the correlations between MSDA and number of steps in: (A) all cases, (B) wheelchair group, and (C) walking group.

Open squares and open circles represent the walking and wheelchair groups, respectively.

MSDA, moving standard deviation of acceleration. We compared the MSDA and the number of steps per day.

Figure 2

Distribution of the MSDA and number of steps (n=197): Histograms of the (A) MSDA and (B) number of steps are shown. Wheelchair group (red) and walking group (blue).

MSDA, moving standard deviation of acceleration

Figure 3

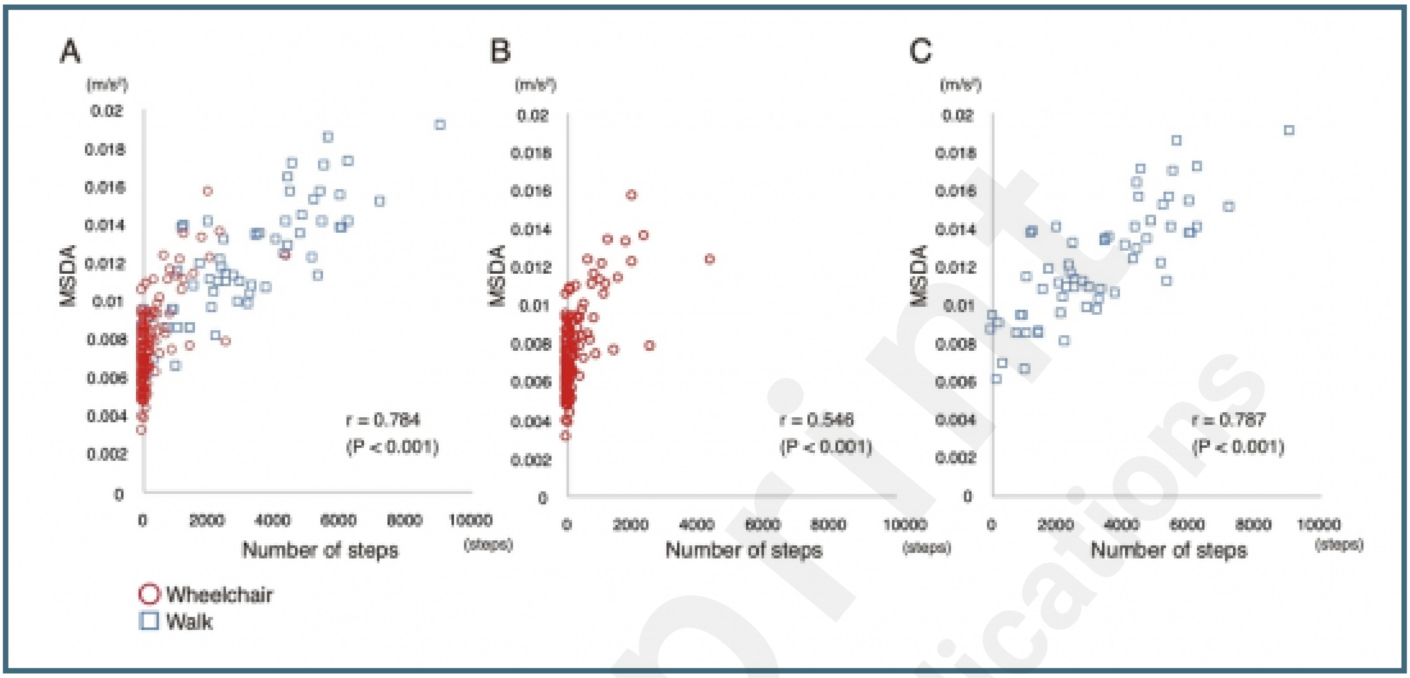
Relationship between FIM-motor scores and the MSDA for 6 groups divided by mobility type: Physical activity was compared among the six subgroups according to the FIM scores of the mobility items and mobility patterns. (A) MSDA and (B) number of steps.

MSDA, moving standard deviation of acceleration. $^{*}p<0.05$, $^{**}p<0.01$

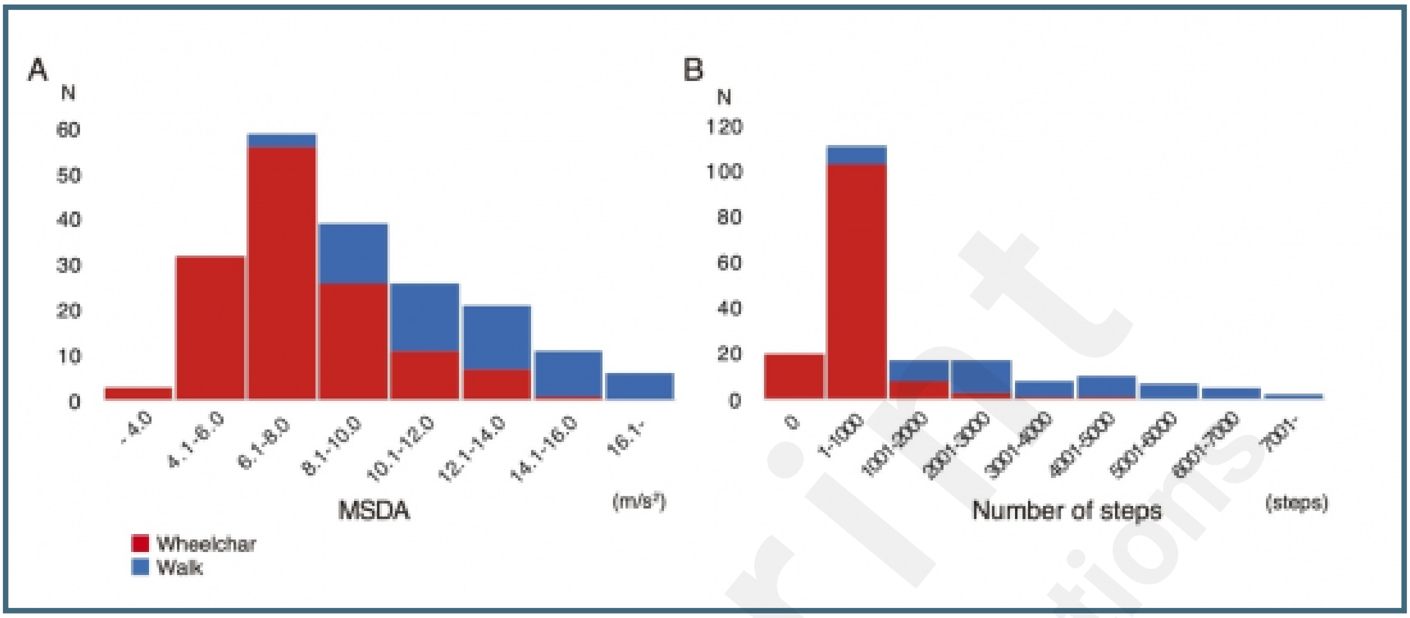
Supplementary Files

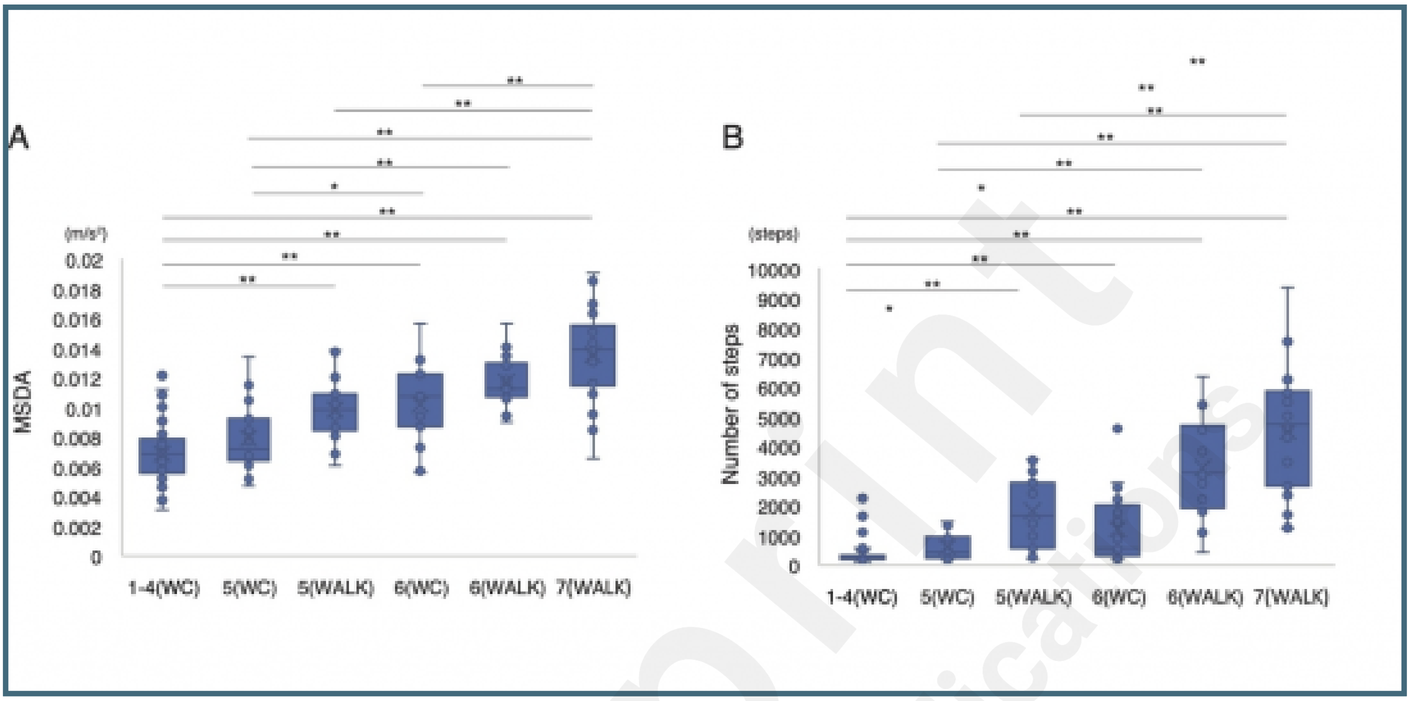
Figures

Scatter plot showing the correlations between MSDA and number of steps in: (A) all cases, (B) wheelchair group, and (C) walking group. Open squares and open circles represent the walking and wheelchair groups, respectively. MSDA, moving standard deviation of acceleration. We compared the MSDA and the number of steps per day.



Distribution of the MSDA and number of steps (n=197): Histograms of the (A) MSDA and (B) number of steps are shown. Wheelchair group (red) and walking group (blue). MSDA, moving standard deviation of acceleration.




A
(m/s²)
MSDA
0.02
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
1-4(WC) 5(WC) 5(WALK) 6(WC) 6(WALK) 7(WALK)
B
(steps)
Number of steps
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
1-4(WC) 5(WC) 5(WALK) 6(WC) 6(WALK) 7(WALK)