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Reliability of daily step activity monitoring in adults with incomplete spinal cord injury

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Abstract—We determined the number of days of step activity monitoring required to establish stable measures of walking activity in adults with incomplete spinal cord injury (iSCI). Eleven individuals with iSCI (mean age 49 +/– 14 years) wore a StepWatch Activity Monitor during waking hours for 7 consecutive days. We used generalizability theory to identify sources of variance in daily step counts and determine the minimum number of days necessary to obtain a reliability coefficient (G-coefficient) greater than or equal to 0.80. Average daily step activity (DSA) was 1,281 +/– 1,594 steps. Participants and days accounted for 70.9% and 1.3% of total variance in DSA, respectively, while unidentifiable error accounted for 27.8% of the total variance in DSA. A minimum of 2 days was required to achieve a G-coefficient greater than or equal to 0.80. An acceptably stable measure of walking activity in adults with iSCI can be obtained by averaging step count values from any 2-day period in a week. Results from this investigation should be useful in evaluating the effect of activity-based programs designed to enhance locomotor function in persons with iSCI.

Key words: daily step activity, exercise, generalizability theory, incomplete spinal cord injury, locomotor training, pedometer, physical activity, reliability, stable measure, step activity monitor.

INTRODUCTION

It is estimated that 12,000 new cases of spinal cord injury (SCI) occur each year in the United States, with ~262,000 persons having survived their initial injury [1]. SCI often results in loss of motor, sensory, and autonomic function depending on the level of the lesion and degree of impairment [2]. Because sedentary living in persons with SCI poses a greater risk of cardiovascular disease, type 2 diabetes mellitus, dyslipidemia, obesity, and urinary tract infection [3–5], individuals with SCI have been urged to engage in physical activity to improve ambulatory mobility and maintain a healthy lifestyle [6–11]. In this regard, improvements in walking ability, gait velocity, walking endurance, and lower-limb strength have been observed in adults with incomplete SCI (iSCI) following participation in targeted exercise programs [12–17].

Prior to quantifying changes in physical activity status in persons with iSCI resulting from therapeutic interventions, researchers must establish an accurate and reliable method of assessing locomotor activity. Along these lines, a current approach has been to employ step counting devices to document physical activity in persons with

Abbreviations: ASIA = American Spinal Injury Association, DSA = daily step activity, D-study = decision study, G-coefficient = reliability coefficient, G-study = generalizability study, G-theory = generalizability theory, iSCI = incomplete spinal cord injury, SAM = StepWatch Activity Monitor, SCI = spinal cord injury.

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neurological conditions [18–19]. Tudor-Locke et al. summarized typical step activity values reported in 60 studies of special populations encompassing persons with cardiovascular disease, diabetes, neuromuscular disease, arthritis, and mental retardation/intellectual disability and reported that the step activity monitoring period for individuals with neuromuscular diseases and disability ranged from 2 to 7 days [20]. Relatively little is known, though, concerning the ambulatory activity of persons with iSCI.

Using classical test theory (i.e., intraclass correlation coefficient), Tudor-Locke et al. confirmed that any 3-day combination within a week was sufficient to achieve an acceptable level of reliability ($r = 0.80$) with respect to predicting weekly physical activity in nondisabled adults [21]. However, the proportion of variation in a given measurement attributable to different variance sources cannot be readily identified using this traditional statistical approach [22–23]. In contrast, generalizability theory (G-theory) provides a statistical framework that is particularly useful for quantifying the relative contribution of multiple sources of variance to total measurement variation [22–24]. G-theory has been employed in recent studies of physical activity assessment featuring typically developing youth and nondisabled adults [25–27]. To the best of our knowledge, however, G-theory has not been used to document the reliability of step activity monitoring in adults with iSCI.

Against this backdrop, the purpose of our study was to use G-theory to establish the number of days necessary to obtain a stable and representative measure of daily step activity (DSA) in adults with iSCI and to identify sources of variation in step activity in this group. Given the challenges of initiating and maintaining locomotor activity posed by altered neurological and physiological function, we hypothesized that fewer days would be needed to establish a reliable step count profile in persons with iSCI than nondisabled adults.

METHODS

Participants

Eleven individuals with iSCI (mean ± standard deviation age = 49 ± 14 years; range = 23 to 65 years; 8 males, 3 females) participated in this study and provided written informed consent. Descriptive characteristics of the participants are shown in **Table 1**. The International Standards for Neurological and Functional Classification of SCI of the American Spinal Injury Association (ASIA) were used to classify study participants according to their level of neuromuscular function. All participants were medically stable and classified as ASIA Class C (incomplete: motor function is preserved below the neurological level, and more than half of key muscles below the neurological level have a muscle grade <3; $n = 9$) or Class D (incomplete: motor function is preserved below the neurological level, and at least half of key muscles below the neurological level have a muscle grade of ≥3; $n = 2$). Inclusion criteria for the study included the following: (1) older than 21 years, (2) able to complete a 10-meter walk with or without an assistive device, (3) at least 1 year postinjury to ensure the absence of spontaneous recovery from SCI, (4) free from comorbidity or degenerative disease, (5) physician's approval to engage in physical activity, and (6) availability of transportation to the testing site.

Procedures

A StepWatch Activity Monitor (SAM, Orthocare Innovations; Oklahoma City, Oklahoma) was used to measure step activity counts. The SAM is a small, lightweight accelerometer that was developed in response to concerns regarding the accuracy and reliability of existing activity monitors when used by persons with gait dysfunction [28]. The SAM has been shown to demonstrate 95 percent accuracy and yield stable output during repeated testing (correlation range = 0.84 to 0.98) in persons with normal gait patterns [29]. In addition, Bowden and Behrman compared step counts obtained from the SAM to actual step counts registered during 10-meter and 6-minute walks and reported that the SAM displayed 97 percent accuracy among individuals with SCI [30]. The SAM, which is worn proximal to the malleolus on the lateral border of the ankle, is designed to detect and register step counts for a variety of walking styles, ranging from a slow shuffle to a fast run. Participants who wore an orthotic device on the right ankle were instructed to wear the SAM on the left ankle to increase the likelihood of registering valid step activity [31]. Step counts were recorded in 1-minute epochs during waking hours, and the SAM automatically reset at the end of each day.

Each participant wore a SAM that was randomly chosen from a set of three fully operational devices. Participants were instructed to wear the SAM during waking hours for 7 consecutive days (except when bathing) and maintain a typical physical activity regimen. If participants

Table 1.
Descriptive characteristics and mean step count activity of study participants (*n* = 11).

Subject	Sex	Age (yr)	Lesion Level	ASIA Class	Time Postinjury (yr)	Mechanism of Injury	Primary Mobility	Assistive Device	Physical Assistance	Step Counts* (Mean ± SD)
1	M	52	T5–6	C	3	Trauma	Wheelchair	Platform rolling walker	Moderate	191 ± 33
2	M	62	C4	D	2.5	Trauma	Ambulation	Bilateral forearm crutches	Independent	5,521 ± 2,057
3	M	63	L2	C	6	Tumor	Wheelchair	Bilateral forearm crutches	Minimal	60 ± 25
4	F	51	C3	C	3	Trauma	Ambulation	Platform rolling walker	Minimal	1,668 ± 365
5	M	43	T8	C	2	Surgical	Wheelchair	Platform rolling walker	Moderate	60 ± 37
6	M	29	L2	C	29	Birth	Wheelchair	Platform rolling walker	Minimal	31 ± 82
7	M	23	C6	C	1.5	Trauma	Wheelchair	Bilateral forearm crutches	Independent	1,846 ± 792
8	F	64	C4	C	1	Trauma	Ambulation	Platform rolling walker	Minimal	1,920 ± 2,151
9	M	50	C2	C	1	Trauma	Wheelchair	Bilateral forearm crutches	Minimal	633 ± 495
10	F	40	T6	D	3	Tumor	Wheelchair	Platform rolling walker	Independent	1,474 ± 925
11	F	65	L2	C	2	Surgical	Wheelchair	Platform rolling walker	Moderate	690 ± 348

*Step count value obtained by doubling single-leg step activity.
ASIA = American Spinal Injury Association, C = cervical, F = female, L = lumbar, M = male, SD = standard deviation, T = thoracic.

inadvertently wore the SAM for more than 7 days, only step count data for the first 7 days were used for statistical analysis. Calibration adjustments were made for expected cadence, sensitivity, threshold, and motion characteristics prior to affixing the SAM to either the right or left ankle of each participant with a Velcro wrap. An overground walking test was then performed. If step counts were missed during this initial walking trial or if nonstep activity was registered, further calibration adjustments were made to ensure that all valid step activity was captured. Participants were provided with verbal and written instructions on how to properly wear and position the SAM on the ankle and encouraged to contact the primary investigator if questions arose regarding the step activity monitoring protocol. Upon completion of data collection, the primary investigator contacted participants to record any special events, unexpected fatigue, and/or physical pain that occurred during the weeklong assessment period.

Step count data were downloaded from the SAM and initially screened for accuracy. Because step counts from the SAM reflect the step activity of only one leg, we obtained the overall step count of both legs by doubling single-leg step activity.

Data Analysis

Overview

For each participant, we calculated DSA for each day of the 7-day monitoring period and averaged the data to determine a mean step count for each participant. Based on G-theory, we performed a generalizability study (G-study) and a decision study (D-study) to quantify the relative contribution of different variance components to the total variance in step activity (G-study) and to compute a reliability coefficient (G-coefficient), which would enable the number of days required to obtain a stable measure of step activity to be determined (D-study).

G-Study

We performed a two-way participant × day repeated-measures analysis of variance to calculate the amount of variance in step counts associated with the participant and day terms as well as the interaction between these terms. The interaction between the participant and day terms also encompassed unidentifiable sources of variation. We calculated the percentage of total variation in DSA attributable to each term and the interaction between terms by dividing the individual variance component estimate by the total variance and multiplying the quotient by 100.

D-Study

We conducted a D-study using a fully crossed design (participant × day) to provide reliability estimates (G-coefficients) for various combinations of days of step activity monitoring. By conducting a D-study, we were able to determine the number of days necessary to obtain a mean G-coefficient value >0.80 for step count measurement [22,24]. As noted by Welk et al., a G-coefficient of 0.80 is an acceptable level of reliability and is interpreted in a similar fashion as an intraclass correlation coefficient of 0.80 [26]. All statistical analyses were performed using Generalized Analysis of Variance software (American College Testing Program; Iowa City, Iowa) [32].

RESULTS

Mean ± standard deviation step counts per day for each participant are shown in **Table 1**. As depicted in **Table 2**, participants averaged 1,281 ± 1,594 steps per day over the 7-day monitoring period, with a range of 718 steps on Sunday to 1,642 steps on Thursday.

Findings from the G-study revealed that the participant term accounted for the largest source of variance (70.9%) in DSA, while the day term contributed to 1.3 percent of the total variance in DSA. The participant and day interaction term, which reflected nonspecific sources of variation, accounted for 27.8 percent of the total variance in DSA. Variance component estimates and the relative magnitude of error for each component term are shown in **Table 3**.

As presented in the **Figure**, findings from the D-study revealed that various combinations of days of step activity monitoring resulted in G-coefficients ranging from 0.72 to 0.95 and that a minimum of any 2 days of the week yielded a G-coefficient ≥0.80.

Table 2.
Daily and mean step counts for each day of the week (n = 11).

Day	Mean ± Standard Deviation
Saturday	1,476 ± 2,531
Sunday	718 ± 1,154
Monday	1,127 ± 1,567
Tuesday	919 ± 1,230
Wednesday	1,523 ± 1,649
Thursday	1,642 ± 1,925
Friday	1,563 ± 2,303
Overall Mean	1,281 ± 1,594

Table 3.
Variance component estimates and relative magnitude of error for each term.

Term	Variance Component Estimates	Relative Magnitude of Error* (%)
P	2,405,046.00	70.9
D	44,005.28	1.3
P × D	942,204.07	27.8
Total	3,391,255.40	100

*Relative magnitude of error for each term was calculated by dividing variance component estimates by total variance estimate and multiplying quotient by 100.
D = day term, P = participant term, P × D = participant × day interaction term.

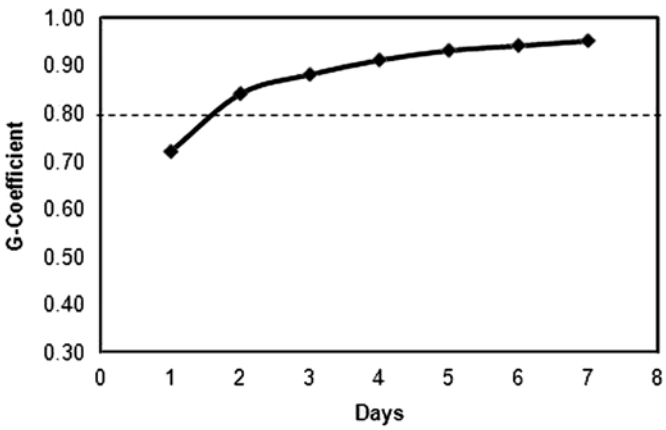

Figure.
Relationship between various combinations of days of step activity monitoring and mean reliability coefficient (G-coefficient) values.

DISCUSSION

In the current study, G-theory was used to quantify sources of variance in daily step counts and to determine the number of days needed to obtain a reliable measure of walking activity in adults with iSCI. In contrast with classical reliability testing models, G-theory allows for the total variance in a particular variable to be apportioned into known and unknown sources of measurement variance.

Results from our study demonstrated that ~70 percent of the total variance in DSA was attributable to the participant term, which is the true score variance [25]. More specifically, this finding indicates that the majority of variance in DSA was related to individual differences in daily step counts. Relative to this point, mean DSA varied markedly across participants (31 steps to 5,521 steps). Although speculative, it is possible that this disparity in average step count values may reflect individual differences in both ASIA scale classification and the absence or presence of physical fatigue and pain during the weeklong assessment period. Individuals classified as ASIA Class D, for instance, displayed a higher average step count value (mean = 3,498 steps) compared with individuals classified as ASIA Class C (mean = 789 steps). However, because only two participants were classified as ASIA Class D, caution should be applied in interpreting these findings.

The very limited amount of variance in DSA attributable to the day term (1.3%) was similar to that noted by Wickel and Welk [25], who reported a day term of 2.7 percent for establishing the number of days needed to reliably estimate physical activity levels in youth. In the present study, the small error variation linked to the day term is consistent with the relative stability in mean daily step counts observed across the 7 days of step activity monitoring and suggests that increasing the number of days of step count assessment would have only had a minimal effect on reducing total variance in walking activity. We should note that the monitoring period used by Wickel and Welk spanned three seasons (September to May), and the season term accounted for nearly two and a half times the variance associated with their day term [25]. According to Wickel and Welk, seasonal changes linked to weather factors may influence the time available for children to spend outdoors and contribute to a greater proportion of the variance in step activity in youth who are monitored on a long-term basis [25].

The interaction term (participant × day), which represented unidentified error sources, accounted for nearly 28 percent of the total variance in DSA. In considering possible factors that may have contributed to this source of variation, we minimized the potential influence of activity monitor malfunction by following an established calibration protocol and providing a detailed set of instructions to participants regarding how to properly wear and position the SAM on the ankle. Other factors that may have contributed to the variance in the interaction term include motivation, availability of physical activity resources, ease of navigating the local environment, challenges related to self-care, and physical and mental health status, all of which have been identified as barriers or facilitators of daily physical activity among persons with SCI [33–34]. Recognition of these variables in future studies may help shape our understanding of the myriad internal and external factors that individually or collectively affect physical activity levels in persons who are physically challenged.

As shown in **Table 2**, a relatively large between-subject variability in daily step count values was observed compared with the smaller between-day variability in DSA displayed in **Table 1**. Consequently, a high reliability in walking behavior was recorded for our participant group, leading to the finding that within a week any 2-day combination of step count values can be averaged to obtain a stable value of step activity in adults with iSCI. This result confirms our original hypothesis, which stated that fewer days would be required to derive a stable measure of walking activity compared with data published by Tudor-Locke et al. [21], who demonstrated that at least 3 days of monitoring were required to establish reliable step count values in nondisabled adults. In Tudor-Locke et al.'s study [21], an intraclass reliability model was employed, which is similar in approach to G-theory, insofar as a correlation coefficient of ≥0.80 is deemed an acceptable level of reliability [35]. From a practical standpoint, the need to collect step count data for only 2 days is advantageous, as participant and investigator burdens are reduced and data processing and analysis are simplified. However, as suggested by Kang et al., activity monitoring for relatively short periods may not necessarily yield an accurate picture of physical activity patterns followed for extended time blocks [36]. In addition, although any 2-day combination of step activity monitoring is sufficient to produce a reliable estimate of DSA in adults with iSCI, researchers and clinicians may wish to adopt a more conservative approach by assessing walking activity over a slightly longer time period (e.g., 3 or 4 days) to assure even more generalizable results [24].

As with all studies, some limitations were present in our investigation. Step activity data, for example, were collected on a relatively small sample size with limited variability in ASIA classification. In acknowledging these concerns, we should note that our sample size of 11 participants was comparable to that found in previous studies of persons with iSCI [30,37]. Another limitation of the current study was the lack of diary usage to track the occurrence of sickness, physical pain, fatigue, and special occasions that may have influenced the number of steps taken by participants. In an attempt to address this issue, the primary investigator contacted each participant regarding pain, fatigue, sickness, and/or special events experienced during the 7-day monitoring period to confirm the internal validity of the step activity measure. The use of assistive devices can also influence step activity levels. However, because all participants required assistive devices to walk, it is unlikely that this factor biased our findings [12]. Lastly, the extent to which a 2-day period of step activity assessment accurately reflects valid monthly, seasonal, or yearly ambulatory behavior remains unexplored. Based on this collective set of study limitations, additional research should be conducted to more thoroughly quantify variability in locomotor activity in a larger, more functionally diverse sample of individuals with iSCI and to determine whether a brief period of step activity monitoring reflects longer-term ambulatory activity in this group.

CONCLUSIONS

Results from our study demonstrate that while DSA differs widely among adults with iSCI, a reliable measure of locomotor activity in this population can be obtained by monitoring daily step counts over any combination of 2 days within a week. From a clinical perspective, these findings provide a basis for evaluating the effect of activity-related therapies to enhance walking ability in persons with SCI.

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Study concept and design: M. Kang, D. W. Morgan, S. Ishikawa.
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Analysis and interpretation of data: M. Kang.
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Statistical analysis: S. Ishikawa, M. Kang.
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