Evaluation of a Body-Worn Sensor System to Measure Physical Activity in Older People With Impaired Function

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Background. There is limited information on reliable and valid measures of physical activity in older people with impaired function.

Objective. This study was conducted to compare the accuracy of single-axis accelerometers in recognizing postures and transitions and step counting with the accuracy of video recordings in people with stroke (n=14), older inpatients (n=14), people with hip fracture (n=8), and a reference group of 10 adults who were healthy.

Design. This was a cross-sectional study, evaluating the concurrent validity of small body-worn accelerometers against video observations as the criterion measure.

Methods. Activity data were collected from 3 sensors (activPAL) attached to the thighs and the sternum and from registration of the same activities from video recordings. Participants performed a test protocol of in-bed, transfer, and walking activities.

Results. The sensor system was highly accurate in classifying lying, sitting, and standing positions (100%) and in recognizing transitions from lying to sitting positions and from sitting to standing positions (100%). Placement of a sensor on the nonaffected leg resulted in less underestimation of step counts than placement on the affected leg. Still, the sensor system underestimated step counts during walking, especially at slow walking speeds (≤0.47 m/s) (limits of agreement=−2.01 to 16.54, absolute percent error=40.31).

Limitations. The study was performed in a controlled setting and not during the natural performance of activities.

Conclusions. The activPAL sensor system provides valid measures of postures and transitions in older people with impaired walking ability. Step counting needs to be improved for the sensor system to be acceptable for this population, especially at slow walking speeds.

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Physical activity seems to be one of the most important factors in effective treatment in stroke units[1] and in the rehabilitation or prevention of functional decline in older people.[2] Physical activity in older people with impaired function is mostly performed as part of daily activities, such as getting out of bed or up from a chair, standing, and walking. Thus, the measurement of physical activity in this population should include such activities.

Small, lightweight, body-worn accelerometers that are able to record activity over longer periods of time now are available commercially.[3] Outcomes are energy expenditure,[4] time or frequency of activities recognized by the sensors, and movement kinematics.[5,6] Detection of body positions and transitions and step counting are based on algorithms embedded in the sensor system's software. Algorithms used to predict such variables should be able to extract data from different movement patterns,[7] including data derived from older people with impaired function.

An activPAL Professional single-axis accelerometer* attached to the thigh can collect activity data at a frequency of 10 Hz for up to 7 days without recharging.[8] The activPAL was shown to have good accuracy for detecting positions and step counting during walking in people who were healthy[5,9,10] and community-dwelling older people without impaired function.[11] However, it is not known whether the software algorithms are accurate when used in older people with impaired function, who may have different movement patterns and who move slowly and shuffle while walking. In particular, the recognition of steps during walking may be challenging because slow gait has a small acceleration amplitude, which may hamper the recognition of steps.[12] Before the activPAL can be recommended for long-term monitoring in older people with wide variations in levels of functioning, it should be validated in people with impaired function.

The main purpose of this cross-sectional study was to evaluate the concurrent validity of the activPAL Professional single-axis accelerometer in recognizing postures (sitting or lying, standing, and walking) and transitions (from sitting to standing positions) and step counting in people with acute stroke, older inpatients, and people 3 months after surgery for hip fracture; video observations of the same activities were used as the criterion measure. A second aim was to assess whether step counts were affected by placement of a sensor on the affected limb versus the nonaffected limb in people with hip fracture and acute stroke. Finally, we also wanted to determine whether 2 sensors could be used to distinguish between sitting and lying positions.

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Method

Participants

Study participants included patients who had a diagnosis of acute stroke[13] and were admitted to the stroke unit at a university hospital (n=14), older inpatients at the department of geriatrics at a university hospital (n=14), and patients with hip fracture that had occurred 3 months earlier (n=8). Participants with hip fracture were home dwelling and were recruited at the end of participation in an observational study. These 3 groups of participants were convenience samples representing different groups of older people with impaired function; they served as the test group. All participants signed an informed consent statement. Participants were included if they were able to walk with or without a walking aid or with support from 1 or 2 people, if they were able to follow verbal instructions about movements, and if their medical conditions were stable.

For evaluating whether step counts were dependent upon gait speed, 10 adults who were healthy were recruited from employees at the Norwegian University of Science and Technology and the hospital staff at St. Olav's Hospital, Trondheim University Hospital. These participants served as a reference group.

Of the 36 older people in the test group, 14 were men and 22 were women; their mean age was 79.7 years (SD=7.3, range=62.0–92.8). The 10 adults in the reference group were women. Seven of the 14 people with stroke, 10 of the 14 older inpatients, and 5 of the 8 people with hip fracture were women. The characteristics of the participants are shown in Table 1.

Instruments

For this study, activPAL Professional single-axis accelerometers (inclinometers) were used. The sensor (including the battery) weighs 20 g, and the outline dimensions are 7 mm (depth) × 53 mm (length) × 35 mm (width). The sensor collects data at 10 Hz, and the battery capacity allows continuous recording for up to 7 days. Data are transferred from

Table 1.
Characteristics of Participants[a]

Characteristic	Test Group								Reference Group (n=10)	
	Total (n=36)		People With Stroke (n=14)		Older Inpatients (n=14)		People With Hip Fracture (n=8)			
	$\overline{X}$	SD	$\overline{X}$	SD	$\overline{X}$	SD	$\overline{X}$	SD	$\overline{X}$	SD
Age (y)	79.7	7.3	75.2	6.2	84.0	5.8	80.1	7.6	46.3	9.0
Height (cm)	164.8	11.3	169.3	13.2	161.4	11.0	163.0	4.8	170.0	5.3
Weight (kg)	67.0	13.4	75.3	13.0	60.3	11.5	63.8	8.5	65.9	4.3
mRS score (0–6)	2.9	1.2	3.3	0.8	3.5	0.7	1.1	0.4	0	0.0
BI score (0–100)	79.2	18.7	77.5	16.6	70.0	18.2	98.1	5.3	100	0.0
Speed (m/s)	0.46	0.2	0.41	0.1	0.43	0.1	0.58	0.2	0.84	0.1

[a] mRS=modified Rankin Scale, BI=Barthel Index, speed=preferred gait speed (mean from tasks 11 and 12).

the sensor to a Windows[†]-compatible PC by use of a USB docking station. The software package (activPAL Professional Research Edition) processes the raw acceleration data signals by using proprietary algorithms not controlled by the user (Intelligent Activity Classification), summarizes activity as time in sedentary (sitting or lying) and upright (standing and walking) positions, registers the number of transitions from sitting to standing positions, and registers step counts during walking. Data in 1-second bytes can be converted into an Excel[†] spreadsheet issued by the activPAL manufacturer, allowing a more detailed analysis. The activPAL registers the number of steps taken by the lower extremity with the attached sensor only, and an algorithm doubles the total number of steps taken.

A 2D Sony mini digital video camera[‡,14] was used to capture the same activities as the sensors. The video camera has a 1.0-second timing system. Video camera time was manually synchronized with sensor time by using the PC time. In addition to steps being counted from the video, steps were counted and recorded in writing during the performance of each task.

Test Procedure

Before testing, all sensors were connected to the same PC for the synchronization of time. Three sensors were used in this study; all were attached with PALstickies* (dual-layer hydrogel adhesive pads): 1 sensor each on the right midthigh and the left midthigh[5] and 1 sensor on the chest at midsternum. Participants performed a test protocol of 23 tasks, including in-bed activities, transfers between positions, and upright activities selected from tests of mobility in older people[15–17] (Tab. 2). Instructions and the starting cue "Are you ready? 3, 2, 1, . . . start" were given before every task. Before starting and after finishing each task, the participants were asked to stand or lie still for 5 seconds. Standing and walking tasks were performed with shoes on. The six 5-m walking tasks were performed at slow, preferred, and fast instructed speeds. The protocol was performed in an open room measuring 15 m × 8 m. A stationary video camera operated by a person captured performance during the entire test sequence, which lasted from 20 to 60 minutes. The video camera was placed at the same 2 positions for all participants: in front of the bed for the in-bed tasks and in front of the participant for the walking tasks (capturing the whole body or at least the lower extremities from behind or in front when participants walked back and forth). The person operating the video camera ensured that the participants and activities being performed were captured on the video. The reference group performed the six 5-m walking tasks only (tasks 9–14) (Tab. 2).

Outcome Measures

The participants' age, height, weight, modified Rankin Scale[18] scores, and Barthel Index[19] scores were used to describe the sample. Outcomes from video observations and activPAL sensors included the type of activities performed (sedentary or upright and sitting or lying), the duration of activities (seconds), the number of transitions (from sitting to standing or standing to sitting positions and from sitting to lying or lying to sitting positions), and the number of steps during walking. Gait speed (m/s) was calculated from the time taken to perform the 5-m walking tasks. For the reference group, the number of steps and gait speed during walking were used as outcome variables.

[†] Microsoft Corp, One Microsoft Way, Redmond, WA 98052-6399.
[‡] Sony Corporation, 1-7-1 Konan, Minato-ku, Tokyo 108-0075, Japan.

Table 2.
Test Protocol[a]

Order	Task	Classification (Body Position)
1	Transition from sitting position to lying position	Sedentary (sitting and lying)
2	Turning right in bed	Sedentary (lying)
3	Turning left in bed	Sedentary (lying)
4	Transition from lying position to sitting position	Sedentary (sitting and lying)
5	Sitting on the edge of the bed for 20 s	Sedentary (sitting)
6	Moving from sitting on the edge of the bed to a chair	Sedentary (sitting) and upright (standing and walking)
7	Transition from sitting position to standing position	Sedentary (sitting) and upright (standing)
8	Transition from standing position to sitting position	Upright (standing) and sedentary (sitting)
9 and 10	Back-and-forth 5-m walking at slow speed	Upright (walking)
11 and 12	Back-and-forth 5-m walking at preferred speed	Upright (walking)
13 and 14	Back-and-forth 5-m walking at fast speed	Upright (walking)
15	Turning 180°	Upright
16	Turning 360°	Upright
17	Timed "Up & Go" Test	Sedentary (sitting) and upright (standing and walking)
18, 19, and 20	Three 4-step walking sequences	Upright (walking)
21, 22, and 23	Three 8-step walking sequences	Upright (walking)

[a] Tasks were performed in a fixed order and are classified according to categories derived from activity monitoring. Participants were asked to stand or lie still for 5 seconds before starting and after finishing each task so that the beginning and the end of each task could be identified during data analysis.

Data Analysis

An activity was defined as the lying position when both the thigh sensor and the chest sensor for the same sequence registered the activity as sedentary. When the chest sensor registered the activity as upright and the thigh sensor registered the activity as sedentary, the activity was defined as the sitting position. When both sensors registered the activity as upright, the activity was defined as the upright position.

Video data were analyzed before activPAL data were analyzed. Observations from the video recordings were replayed on the camera, and 1 researcher classified start and stop times (time intervals) and counted steps for each of the tasks in the test protocol. The number of steps counted from the video observations were compared with the number of steps counted and recorded in writing during the performance. If the numbers of steps counted by these 2 methods differed, the video recordings were reanalyzed. If disagreement persisted, the results from the video observations were used. Time intervals were plotted and stored as Excel files.

An Excel spreadsheet provided by PAL Technologies was used to read processed activPAL data and display collected data as second-by-second cumulative output. For synchronizing start and stop times from activPAL data with those from video data, a custom-made MATLAB[§] program was used.

Twenty of the 23 tasks from the test protocol were used in the data analysis. Task 6, moving from sitting on the edge of a bed to a chair, was not included because participants used different movement strategies (moving while keeping a seated position or moving by rising to an upright position). The 2 standing and turning tasks (tasks 15 and 16) were excluded because the steps during turning were difficult to count from the video recordings.[20]

Time in sedentary (sitting or lying) and upright (standing and walking) positions was calculated from tasks 1 to 5, 9 to 14, and 18 to 23. Transitions from sitting to standing positions and from standing to sitting positions were counted from tasks 7, 8, and 17. Analyses of time in sitting and lying positions were based on tasks 2, 3 and 5. When evaluating whether transitions from sitting to lying positions and from lying to sitting positions could be classified by the thigh and chest sensors, a transition was counted when the position changed in tasks 1, 4, 7, 8, and 17. Tasks 9 to 14 and 18 to 23 were used for evaluating asymmetric gait, and the most accurate lower sensor was then used for the step count accuracy analysis for a single monitor. Tasks 9 to 14 also were used in the

[§] The MathWorks Inc, 3 Apple Hill Dr, Natick, MA 01760-2098.

step count accuracy analyses for the test group and the reference group.

To ensure that the entire movement and position sequence was included in the analysis, we included 2 seconds before and after every transition and step count time interval in the analysis.

Step count accuracy was assessed from all walking tasks performed at slow, preferred, and fast speeds. For the test group, we divided gait speed into slow and fast speeds. *Slow speed* was defined as a gait speed equal to or lower than the mean gait speed for the sample, whereas *fast speed* was defined as a gait speed higher than the mean gait speed.

Statistical Analysis

Statistical analysis was performed with SPSS version 17.0 software.[‖] The significance level was set to $P<.05$. Agreement between activPAL sensor registrations and video observations was assessed by the method of Bland and Altman,[21] as follows: The differences between sensor registrations and video observations were plotted against the average measures obtained by the 2 methods. Horizontal lines were drawn at the mean difference, and the limits of agreement (LOA) were defined as the mean difference plus or minus 1.96 times the standard deviation of the difference. The absolute percent error (APE) was calculated with the following formula: (sensor data − video data)/video data × 100.

Role of the Funding Source

The health authorities of Mid Norway funded this study. No financial support was received from any commercial agency.

[‖] SPSS Inc, 233 S Wacker Dr, Chicago, IL 60606.

Results

There were significant differences in age between people with stroke and older inpatients ($P=.001$), in weight between people with stroke and older inpatients ($P=.002$) and between people with stroke and people with hip fracture ($P=.035$), and in modified Rankin Scale and Barthel Index scores between people with stroke and people with hip fracture ($P<.001$) and between older inpatients and people with hip fracture ($P<.001$).

If needed, participants in the test group used their own walking aids during the walking tests; 12 walked without a walking aid or support from another person, 5 used a cane or a crutch, 17 used a roller, and 2 used their walking aids only during fast walking. Twelve participants in the test group were not able to perform the entire test protocol.

Classification of Posture

Classification of sedentary and upright positions was based on a total of 555 tasks performed by 34 participants in the test group. The sensors showed no misclassifications of time in a sedentary position versus time in an upright position, and the maximum time difference between video observations and the single-sensor registrations was 1 second. When 1 thigh sensor was used, tasks 2, 3, and 5 were classified as sedentary positions; when 2 sensors (thigh and chest) (2-sensor unit) were used, tasks 2 and 3 were classified as lying positions and task 5 was classified as a sitting position.

Recognition of Transitions

Analyses of recognition of transitions from sitting to standing positions and from standing to sitting positions were based on 101 tasks involving 132 transitions performed by 35 participants in the test group. Analyses of recognition by the 2-sensor unit of transitions from sitting to lying positions and from lying to sitting positions were based on 70 tasks. The numbers of transitions from lying to sitting positions and from sitting to standing positions were identical for activPAL registrations and video observations.

Placement of a Sensor on the Affected Lower Limb Versus the Nonaffected Lower Limb

Data were obtained from both right and left thigh sensors for 11 of the 14 participants with stroke and all 8 participants with hip fracture; in 9 of these participants, the right lower limb was affected, and in 10 participants, the left lower limb was affected. Three participants with stroke were excluded from these analyses because of technical problems with 1 of the sensors. Four participants were not able to complete all 12 walking tasks, leaving a total of 211 tasks for the analysis.

Figure 1 shows the level of agreement between video observations and activPAL registrations for total step counts. The mean step counts during all 211 tasks were 10.66 (SD=4.70) for the video camera, 6.30 (SD=3.94) for the sensor on the nonaffected limb, and 4.97 (SD=3.85) for the sensor on the affected limb. The 95% LOA, derived from Bland-Altman analyses, were ±4.36 steps for the sensor on the nonaffected limb and ±5.69 steps for the sensor on the affected limb. The APEs for the sensor on the nonaffected limb and the sensor on the affected limb were 26.91 and 53.40, respectively.

Step Counts

A total of 188 tasks were performed by participants in the test group during the back-and-forth 5-m walking tasks at slow, preferred, and fast speeds. The overall mean gait speed during these tasks was 0.47 m/s (SD=0.21 m/s). The mean gait speed for slow walking was 0.32 m/s (SD=

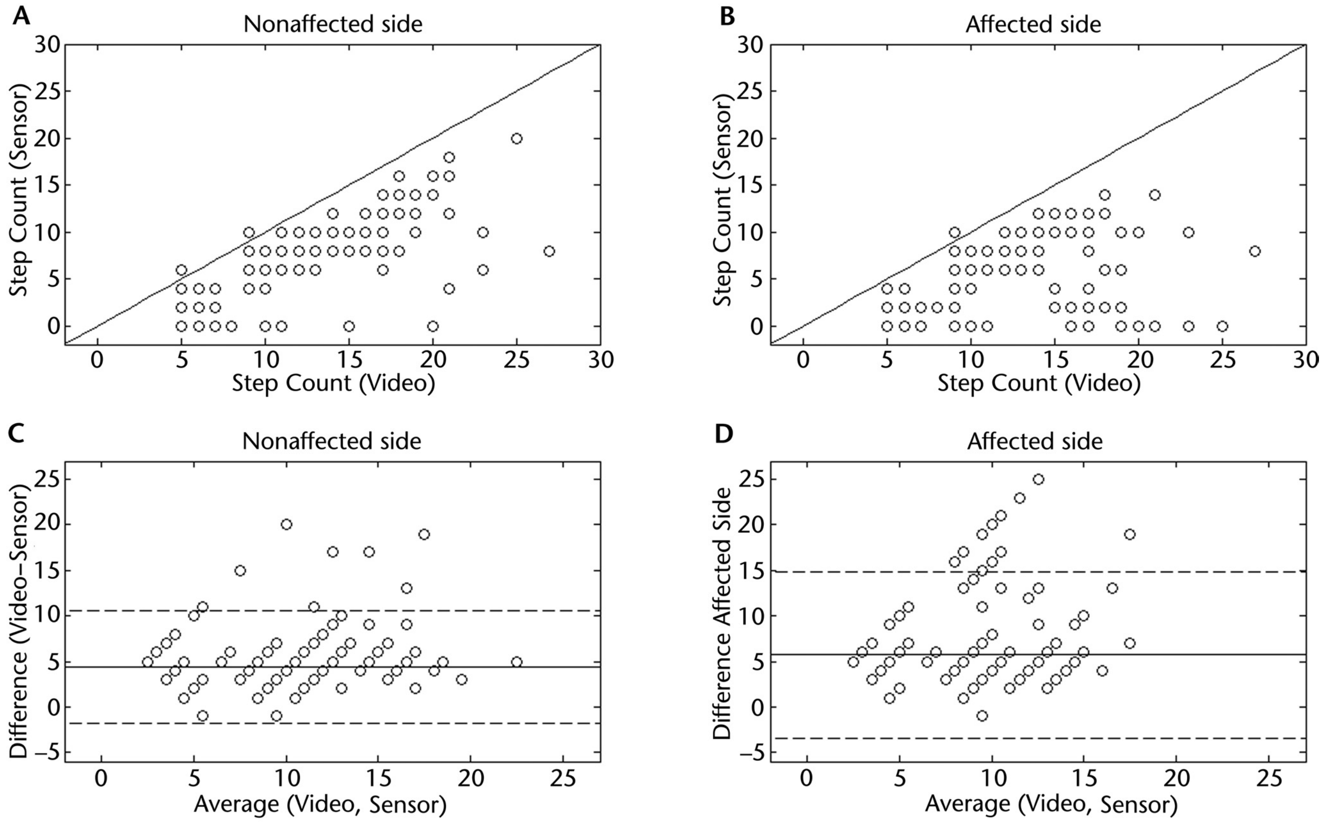

Figure 1.
Scatterplots of total step counts obtained from activPAL sensor registrations and video observations for the nonaffected limb (A) and the affected limb (B) and Bland-Altman plots of agreement between activPAL sensor registrations and video observations for the nonaffected side (C) and the affected side (D) in 19 participants with 1 affected lower limb (participants with stroke or hip fracture).

0.11 m/s), that for walking at the preferred speed was 0.45 m/s (SD=0.16 m/s), and that for fast walking was 0.62 m/s (SD=0.22 m/s).

A total of 60 walking tasks were performed by participants in the reference group. The overall mean gait speed was 0.86 m/s (SD=0.36 m/s). The mean gait speeds for slow walking, walking at the preferred speed, and fast walking were 0.47 m/s (SD=0.08 m/s), 0.84 m/s (SD=0.09 m/s), and 1.26 m/s (SD=0.20 m/s), respectively.

For 3 walking tasks in the reference group and 1 walking task in the test group, the step counts obtained from activPAL registrations were higher than those obtained from video observations. Inspection of the raw activPAL data revealed double registrations of steps for these data sequences.

Figures 2 and 3 show the level of agreement between video observations and sensor registrations for step counts for the reference group and the test group, respectively. The 95% LOAs for participants in the test group were ±7.27 steps (lower limit of agreement [LLOA]=−2.01; upper limit of agreement [ULOA]=16.54) for slow speed and ±3.34 steps (LLOA=0.31; ULOA=6.39) for fast speed. For participants in the reference group, the 95% LOAs were ±3.88 steps (LLOA=−0.22; ULOA=7.91) for slow speed and ±1.62 steps (LLOA=−1.82; ULOA=5.05) for fast speed. The accuracy was poorest and the APE was highest for step counts at or slower than 0.47 m/s for walking tasks performed by participants in the test group. Walking at slow speed by participants in the test group was performed with more steps than walking at other speeds. The APEs for slow speed and fast speed by participants in the test group were 40.31 and 29.13, respectively; the APEs for slow speed and fast speed by participants in the reference group were 33.06 and 19.32, respectively.

Discussion

The aim of the present study was to assess the accuracy of activPAL sensor registrations of positions during physical activity or inactivity, numbers of transitions, and numbers of steps during walking in older people

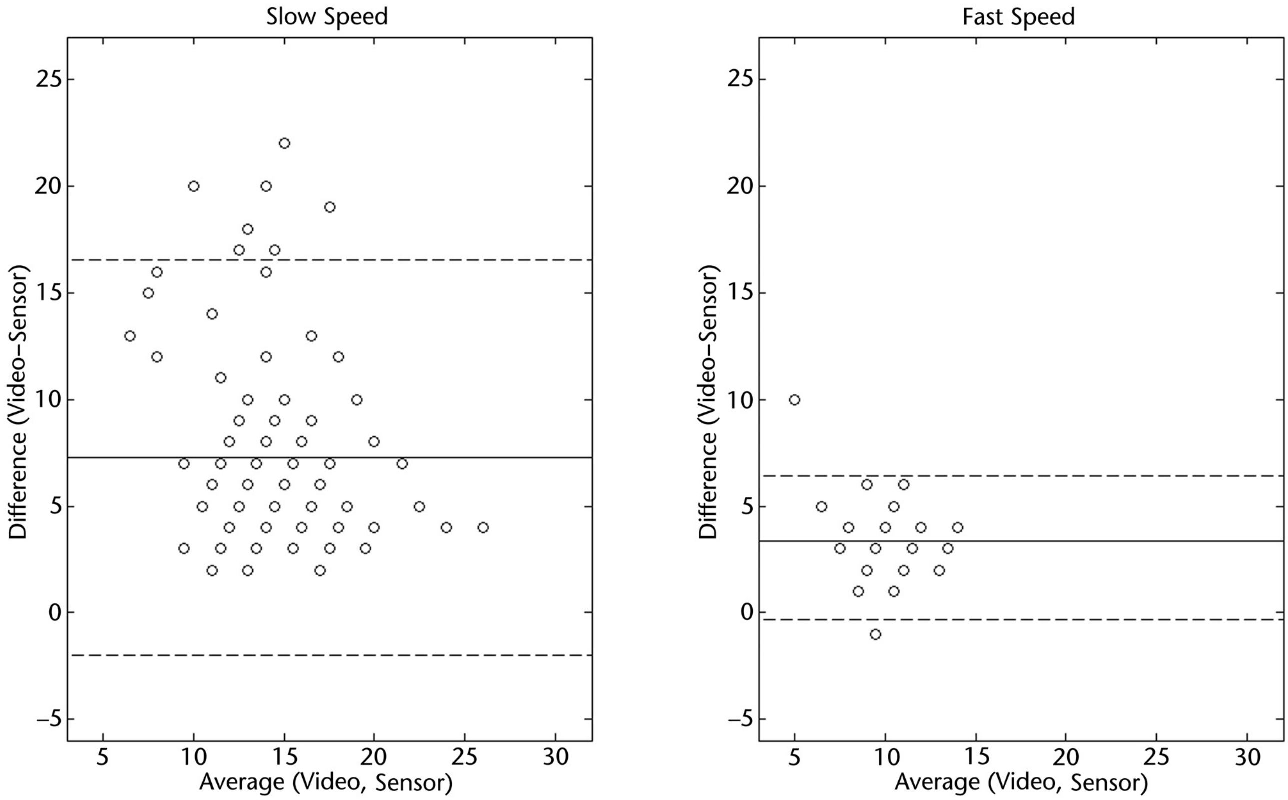

Figure 2.
Bland-Altman plots demonstrating step count agreement between activPAL sensor registrations and video observations for participants who had impaired function and walked at slow speeds (≤0.47 m/s) (n=105) (left) and fast speeds (>0.47 m/s) (n=83) (right).

with impaired function. The results demonstrated high accuracy of the activPAL sensor in classifying activities as sedentary or upright and in recognizing transitions from sitting to standing positions and from lying to sitting positions in older people who were frail, people with hip fracture, and people with acute stroke. Placement of a sensor on the affected limb resulted in a greater underestimation of step counts than placement on the nonaffected limb. Still, the sensor underestimated step counts during walking, especially at slow gait speeds, in these groups of people.

Step Detection in Older Adults Who Were Frail

Gait speed obviously affected step count accuracy. Participants in our study walked at slower gait speeds than participants in earlier validation studies with activPAL sensors,[9,11] a fact that may explain the poorer results in our study.

Our study revealed that activPAL underestimated step counts; the greatest underestimation was noted for people walking at gait speeds slower than 0.47 m/s. Inspection of the raw data demonstrated that all steps had been registered by the accelerometers. However, the activPAL step count is calculated from raw acceleration data signals by an automatic software procedure. The findings, therefore, indicate that the algorithms are not effective at detecting slow stepping. Older adults who are frail may walk slowly, and development of a more appropriate algorithm for recognizing gait acceleration patterns is needed to provide acceptable step count accuracy for use in people who walk slowly. Because the activPAL underestimated step counts, the calculation of energy expenditure (in metabolic equivalents) also was inaccurate. The findings from our study support earlier results[22] and suggest that the sensor should be attached to the nonaffected lower limb to enhance accuracy.

Classification of Sedentary Versus Upright Positions

The sensors showed no misclassifications of activities in sedentary versus upright positions. These activities, therefore, are accurately registered in older people who are frail. Older people with impaired function spend most active periods performing indoor activities of daily living. Time in an upright position during the day may be a relevant measure of activity

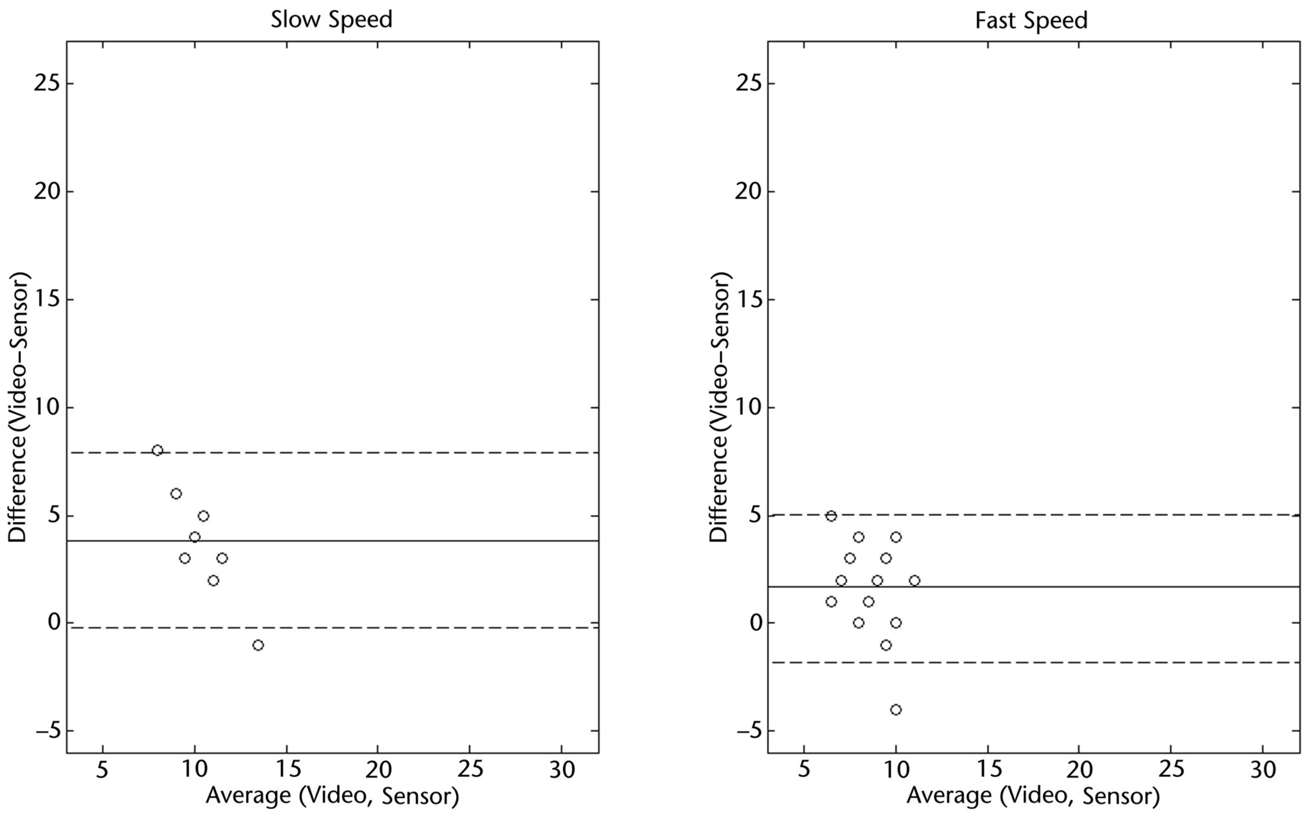

Figure 3.
Bland-Altman plots demonstrating step count agreement between activPAL sensor registrations and video observations for adults who were healthy and walked at slow speeds (≤0.47 m/s) (n=13) (left) and fast speeds (>0.47 m/s) (n=47) (right).

and a focus of interventions to increase or maintain activity levels.

The accurate results for transitions and time in sedentary and upright positions in our study are comparable to the results of previous studies of participants who were healthy and used activPAL sensors,[5] confirming that use of the activPAL is an accurate method for activity monitoring in older adults who are frail. Transition counts could provide valuable information about changes in activity and could serve as supplementary measures of activity during the day. Other outcomes, such as number and duration of periods in an upright (standing or walking) position during the day, also might serve as interesting measures of changes in activity and length of active periods and should be explored in future studies.

Expanding the Range of Use With an Additional Chest Sensor

The strengths of a single-axis acceleration sensor system are simplicity and ease of use. The limitation is the number of activities that the system can distinguish. By using a second sensor, we were able to distinguish between lying and sitting positions by synchronizing the outputs from the 2 sensors through a MATLAB-based procedure. This finding confirms that 2 sensors can be used as a 2-sensor unit when necessary and is comparable to findings from other studies with similar methods.[23] This important finding expands the applicability of activPAL to monitoring, recording, and registering early mobilization out of bed, which has been documented to be the most significant factor for a good functional outcome for people after stroke[1] and probably also for other groups of people who are frail and bedridden.

Limitations

The present study raises several methodological considerations. We used only a short walking distance (5 m), and it is likely that this short distance partly explains the extent of measurement error. The activPAL sensor was attached to 1 thigh, and every second step was doubled to capture both right and left steps during the walking sequences. This process resulted in a 25% chance of calculating 1 step fewer than was actually performed, depending upon which leg took the first step and which leg took the last step. Longer walking distances could have decreased the measurement error by reducing the percentage of steps used during gait initiation and stopping compared with the percentage of steps used during steady-state walking. However, longer walking distances were neither an option nor a relevant approach for our study population. Walking shorter distances at slow speeds is the main daily activity of our study population, and this activity needs to be calculated with high accuracy if it is to be used as an outcome for people with decreased levels of functioning. We did not consider information about the medical conditions of the participants in our study; such information could be useful for comparing our study population with other groups of older people.

We evaluated accuracy during a controlled test protocol and not during the natural performance of activities. This protocol may have yielded lower measurement errors than natural conditions. On the other hand, the testing period in our study was short compared with typical activity monitoring periods of up to 1 week for describing activity patterns and levels. Thus, it is likely that relative errors decrease with increasing monitoring time.

Conclusion

The activPAL system can be used as a single sensor or as a 2-sensor unit to provide a valid measure of activity or inactivity for the long-term monitoring of older people with impaired function. The step count algorithm is not acceptable for slow walking speeds and needs to be improved before the activPAL system can be recommended for use in people who are frail. Future studies should investigate the validity of outcomes from activity monitoring for changes over time and for the detection of people at risk of functional decline.

Dr Askim, Dr Sletvold, Dr Indredavik, and Dr Helbostad provided concept/idea/research design. Mrs Taraldsen and Dr Helbostad provided writing and data analysis. Mrs Taraldsen, Mrs Einarsen, and Mrs Grüner Bjåstad provided data collection. Dr Askim and Dr Helbostad provided project management. Dr Sletvold and Dr Helbostad provided fund procurement and facilities/equipment. Mrs Taraldsen, Dr Askim, Dr Sletvold, Mrs Einarsen, and Dr Indredavik provided participants. Dr Helbostad provided institutional liaisons. Mrs Taraldsen provided clerical/secretarial support. Mrs Taraldsen, Dr Askim, Dr Sletvold, Mrs Einarsen, Dr Indredavik, and Dr Helbostad provided consultation (including review of manuscript before submission).

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The Regional Committee for Ethics in Medical Research in Mid Norway and the Norwegian Social Science Data Services approved the study protocol.

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