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ORIGINAL ARTICLE

Objective assessment of mobility of the spinal cord injured in a free-living environment

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Study design: An exploratory study of the practicality and feasibility of an instrument.
Objectives: To adapt an activity monitor for use on a wheelchair to assess long-term mobility in a free-living environment in the spinal cord injury (SCI) population, and to explore the utility of the data collected.
Setting: Glasgow, UK.
Methods: An activity monitor was adapted for use on a wheelchair wheel. The monitor was used to assess, for 1 week, the wheelchair mobility of seven participants with SCI who only used a wheelchair. In conjunction with a second monitor on the thigh the mobility of seven participants with SCI who used a wheelchair and upright mobility, and five healthy non-wheelchair users, were assessed for 1 day.
Results: The adapted monitor collected 1260 h of data and was suitable for use on both manual and electric wheelchairs. During 1 week, participants with SCI who only used a wheelchair spent between 4 and 13 h moving in the wheelchair, covering a distance of between 7 and 28 km. Distinct differences in mobility were shown between participants with an SCI and non-wheelchair users. The differences in time spent in mobility activities between the groups of participants with SCI were smaller.
Conclusions: The system was successfully used in this group of participants with SCI, and could provide useful information on the mobility of people with SCI in a free-living environment.
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Keywords: spinal cord injury; wheelchair; mobility; physical activity; assessment

Introduction

The effects of spinal cord injury (SCI) vary depending on the location and nature of the injury. The aim of rehabilitation is to optimise function, and to facilitate mobility and reintegration into the community.[1,2] Mobility, the ability to move around the physical environment, may be accomplished within the SCI population by use of a wheelchair, or upright mobility (standing or walking, with or without assistive devices), or both.

Subjective self-report via questionnaires,[3] general measures of disability[4] and functional assessment of wheelchair performance[1,2] have previously been used to assess wheelchair mobility in the SCI population. Options for the objective assessment of such outcomes in the free-living environment are currently limited. One objective measure consists of accelerometers assessing wheelchair propulsion from arm movement.[5] The use of subjective and objective assessments would provide complementary, but distinct, information allowing a more complete assessment of mobility.

The purpose of this study was to assess the feasibility of monitoring wheelchair and upright mobility in a free-living environment in the SCI population. To achieve this, an activity monitor that assesses upright mobility was adapted for use with a wheelchair. The study had two objectives: (1) to adapt an activity monitor for use on a wheelchair that is capable of assessing the long-term, free-living mobility of individuals with SCI; and (2) to explore the utility of data collected using the adapted monitor for assessment of mobility in the SCI population. Each objective was associated with a number of specific research questions:

(1a) Is the monitor accurate for recording angular acceleration of the wheel (allowing free-living assessment of distance travelled and overground speed)?
(1b) Does the adapted wheelchair monitor collect data when used in a free-living environment for a week?
(2a) Does the monitor adequately assess the basic outcome measures of mobility in an SCI population?

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(2b) Can the monitor (in conjunction with a conventional activity monitor) be used to distinguish between the mobility levels of groups of participants?
(2c) Can the monitor be used to assess temporal patterns of mobility in a SCI population?

Materials and methods

This study is an exploratory study of the practicality and feasibility of an activity monitor adapted for use on a wheelchair. After adaptation of the monitor, three investigations were conducted to answer the research questions. First, the accuracy of the monitor to measure angular velocity was tested (1a). Second, long-term use of the wheelchair monitor in a free-living environment was assessed over a week on seven individuals with SCI who used a wheelchair as their primary means of mobility (group 1). This allowed assessment of practical aspects of data collection (1b), and the basic outcome measures of mobility (2a). Third, the potential utility of the concurrent assessment of wheelchair and upright mobility was assessed over a single day in two further groups of participants; seven individuals with SCI who used a wheelchair in conjunction with upright mobility (group 2); and five non-wheelchair users (group 3). These data, with that collected for group 1, were used to investigate group differences (2b), and temporal patterns of mobility (2c).

Participants
The monitor system was tested on three groups of participants:

group 1: seven participants with SCI who only used a wheelchair for mobility;
group 2: seven participants with SCI who used both wheelchair and upright mobility; and
group 3: five healthy adults who were not wheelchair users.

A convenience sample of participants was recruited from inpatients ($n=13$), outpatients ($n=1$) (groups 1 and 2) and physiotherapists (group 3) of the Queen Elizabeth National Spinal Injuries Unit, Southern General Hospital, Glasgow, United Kingdom. Participants were excluded if they were not independently mobile. We certify that all applicable institutional and governmental regulations concerning the ethical use of human volunteers were followed during the course of this research.

One participant used an electric wheelchair, all other participants with SCI used manual wheelchairs (Table 1). No participant with SCI used a secondary wheelchair, and thus one wheelchair monitor was sufficient to record all the habitual wheelchair activities of each participant. Assistive devices used for upright mobility ranged from elbow crutches to an ankle-foot orthosis.

The activity monitor for assessing upright mobility
The *activ*PAL (PAL Technologies, Glasgow, UK) is a small ($50 \times 35 \times 7$ mm), lightweight (20 g) monitor, which attaches to any point on the anterior aspect of the thigh using adhesive pads. A single unit, consisting of uni-axial accelerometer, power source and data storage, allows continuous monitoring of upright mobility in a free-living environment for 10 days. After collection, data were downloaded onto a PC for analysis, and classified into postures of sitting/lying (which were indistinguishable using thigh inclination) or upright (subdivided into standing and walking). The activity monitor has been validated for use in the general population.[7–9]

Adaptation for measurement of wheelchair mobility
To assess wheelchair mobility, an *activ*PAL was mounted on the rear wheel of a wheelchair (Figure 1). The monitor was supported by a foam block and was placed in an enclosure for protection during field trials. The signal from the accelerometer when the wheelchair was moving (both

Table 1 Participant characteristics

Participant/ group		*Age*	*Sex*	*SCI classification*[a]		*Time since injury (months)*	*Wheelchair*	*Walking aids*
1	1	47	M	C7/4	I	11	Electric	—
2	1	21	F	L2	C	15	Manual	—
3	1	67	M	T10/6	I	15	Manual	—
4	1	71	M	T12/L1	C	4	Manual	—
5	1	67	M	C5/6	I	3	Manual	—
6	1	56	M	C5/6	I	15	Manual	—
7	1	27	M	C7	C	7	Manual	—
8	2	63	F	L2	I	4	Manual	Walker; elbow crutches
9	2	62	M	T10/12	I	—[b]	Manual	Elbow crutches
10	2	29	M	L1	I	2	Manual	Standing frame; walker
11	2	71	M	C5	I	17	Manual	Walker
12	2	31	M	C7	I	5	Manual	AFO; elbow crutches
13	2	43	M	C5	I	2	Manual	Walker
14	2	62	M	C4/5/6	I	69	Manual	Elbow crutches

Abbreviations: AFO, ankle-foot orthosis; F, female; M, male.
Information on participants with SCI in the study: age, sex, SCI classification, time since injury and assistive devices used for mobility.
[a]Spinal cord injury classification follows the ASIA system.[6] I: incomplete SCI (ASIA C and D); C: complete injury (ASIA A).
[b]Date of injury not available.

Figure 1 Demonstrating the attachment of an *activ*PAL activity monitor to the wheel of a manual wheelchair. Inset: close-up of the activPAL activity monitor.

forwards and backwards) consisted of a cyclical pattern of acceleration. Existing proprietary software was adapted by PAL Technologies to classify the monitor signal into periods of movement or non-movement, and to calculate the angular velocity of the wheel.

To investigate the accuracy of the wheelchair-mounted *activ*PAL to measure angular velocity, a wheelchair wheel with attached monitor was mounted vertically on a bench. Monitor accuracy was assessed at four angular velocities (representative of wheelchair motion 34, 68, 103 and 137 r.p.m.), and three radial distances (representative of wheel sizes of electric and manual wheelchairs 5, 12 and 25 cm). The wheel was driven by a motor at a pre-specified stable angular velocity for 1 min, and the output from a cycle computer was compared with the *activ*PAL.

Protocol
Each participant was assessed using *activ*PAL activity monitors, placed on the rear wheelchair wheel (groups 1 and 2), and/or on the thigh (groups 2 and 3). The wheelchair monitor was secured to one rear wheel of the wheelchair using electrical tape (Figure 1). The diameter of the wheel was recorded. The thigh monitor was placed on the anterior aspect of the thigh using a hypoallergenic adhesive pad. The wheelchair and thigh monitors were synchronised using a PC prior to monitor placement.

Participants in group 1 were monitored for 7 consecutive calendar days. The monitor was placed on the wheelchair by the researcher, and removed after data collection. Participants in groups 2 and 3 were each assessed for a single weekday. The monitors were attached by the researcher in the morning of the day for data collection. The thigh monitor was removed by the participant that evening, and the wheelchair monitor was removed by the researcher the following day. During the periods of monitoring, all participants were instructed to participate as normal in their habitual daily activities.

Data analysis
Data were downloaded from the monitor(s) to a PC, and outcome measures were calculated. For the wheelchair monitor, the primary outcome measure was the time spent moving in the wheelchair. Secondary outcome measures of distance travelled and overground speed were calculated using time spent moving, angular velocity and wheel diameter. For the thigh monitor, outcome measures were time spent standing and time spent walking.

For all participants in group 1, outcome measures were calculated for 7 consecutive days. For participants in groups 2 and 3, who were monitored for a day, outcome measures were calculated for the period between 0900 and 2100 hours, which is here defined as the 'waking day'. For participants in group 1, 'waking day' data for comparison with other groups were taken from the first complete day of data recording. To assess the pattern of mobility, the 'waking day' was divided into daytime (before 1600 hours) and evening (after 1600 hours) activities. The mean and standard deviation of the outcome measures were calculated for each group of participants.

Results

Accuracy of measuring angular velocity (1a)
The accuracy of the *activ*PAL monitor to measure angular velocity, in comparison with the cycle computer, ranged between 92 and 95% across all test angular velocities and radial placements.

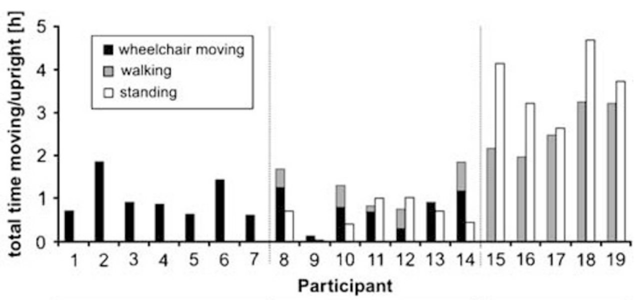
Practical use of the wheelchair activity monitor (1b)
The adapted wheelchair monitor was used on the wheelchair of 14 participants with SCI (groups 1 and 2). The monitor was attached to eight different wheelchair models (from three manufacturers), including one electric wheelchair. Participants moved in their usual environment, predominantly the hospital unit, but the wheelchair was used by some participants in the hospital grounds ($n=2$), at home ($n=2$), and at indoor ($n=4$) and outdoor ($n=2$) external locations. A total of 1260 h of data from the wheelchair-mounted monitors were analysed.

Weekly wheelchair mobility (2a)
The seven participants of group 1 moved in the wheelchair for between 4 and 13 h over the course of a week (Table 2). This represents between 3 and 8% of the week, and approximately 7–19% of the 'waking day'. During the week, participants travelled between 7 and 35 km, with average speeds of 0.43–0.88 m s^{-1}. Participant 1 used an electric wheelchair and had an average speed during the week that was faster than those of the manual wheelchair users.

Table 2 Weekly wheelchair use (group 1)

Participant	*Time moving (h)*	*Distance (km)*	*Speed* ($m\,s^{-1}$)	*Daily covariance (%)*
1	8.8	27.9	0.88	23
2	13.2	34.9	0.73	34
3	4.5	8.4	0.52	55
4	6.2	12.5	0.56	14
5	9.4	17.0	0.50	57
6	10.0	15.6	0.43	20
7	4.1	7.4	0.50	29

Weekly totals of the outcome measures of total time spent moving in a wheelchair, total distance travelled and average speed, and the coefficient of variance in total time spent moving in a wheelchair over the 7 days of data collection, for participants with an SCI whose sole method of mobility was a wheelchair (group 1).



	Group 1	Group 2	Group 3
all mobility mean [± st. dev.]	1.0 [± 0.5]	1.7 [± 0.7]	6.3 [± 1.3]
locomotion (without standing)	1.0 [± 0.5]	1.1 [± 0.6]	2.6 [± 0.6]

Figure 2 Total time spent in the mobility activities of wheelchair movement, standing and stepping during a 'waking day' (0900–2100 hours) for all subjects. Mean (± s. d.) for the three groups of participants: for all mobility activities (including standing); and for locomotion-based activities (moving in the wheelchair and walking, excluding standing).

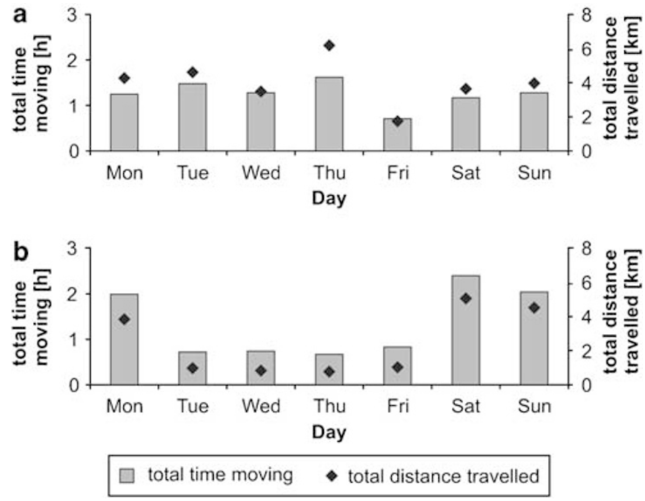


Figure 3 Daily totals of the time spent moving in the wheelchair and the distance travelled over the course of a week-long recording period: (**a**) for participant 1 using an electric wheelchair; (**b**) for participant 5 using a manual wheelchair.

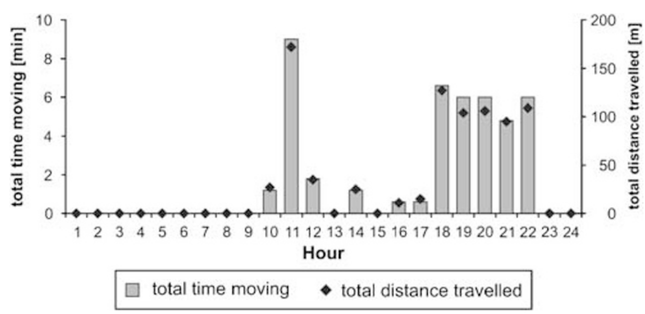


Figure 4 Hourly summary of the time spent moving in the wheelchair and the distance travelled for a single day for participant 5, who used a manual wheelchair as their sole method of mobility.

Comparison of daily mobility between participant groups (2b)

Data for the 'waking day' for all participants are shown in Figure 2. Physiotherapists (group 3) clearly engaged in all mobility activities for longer periods of time compared with participants with SCI (groups 1 and 2). The physiotherapists spent the majority of that time standing, however even when excluding standing, physiotherapists engaged in mobility activities for considerably longer times than participants with SCI. Comparing groups of participants with SCI, average total mobility was 70% higher for participants in group 2 than in group 1. However, the differences between groups were smaller when comparing locomotion-based activities (wheelchair motion and walking only, excluding standing).

Temporal patterns of mobility (2c)

The daily variation of the time spent moving in a wheelchair of participants in group 1 was considerable, with the coefficient of variance ranging between 14 and 57% (Table 2). Patterns of mobility from two participants are shown in more detail. The variability in time spent moving and distance travelled ranged from less than 1 to over 2 h per day, and from less than 1 to over 6 km per day (Figure 3).

From within the entire week, data for a single 24 h period for participant 5 are displayed as time spent moving and distance travelled in the wheelchair in each hour (Figure 4). Waking and sleeping periods can be clearly distinguished as there was no use of the wheelchair before 1000, or after 2300 hours. There were peaks of mobility at 1100 hours, and between 1800 and 2200 hours. However, the wheelchair was not used for more than 10 min, or over 200 m, in any hour.

In general, the groups of participants used in this study could be clearly distinguished based on the relative time per hour spent in mobility activities during the daytime and the evening (Figure 5). Most participants in groups 1 and 3 spent similar amounts of time per hour engaged in mobility activities during the daytime and during the evening, whereas most of the participants in group 2 spent considerably longer per hour engaged in mobility activities during the daytime than during the evening. Six participants in group 2 did not stand or walk at all after 1600 hours.

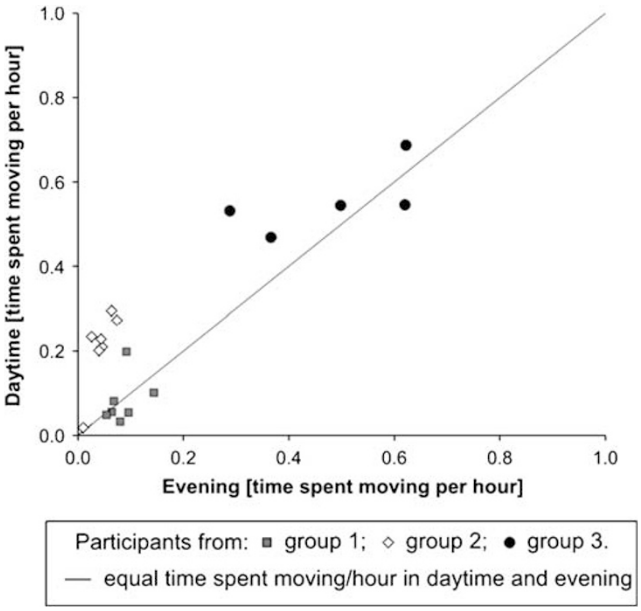


Figure 5 Total time per hour spent in mobility activities (wheelchair movement, standing and stepping) during the daytime (0900–1600 hours) and the evening (1600–2100 hours) for all participants.

Discussion

The monitor was functionally suitable for monitoring wheelchair and upright mobility in a free-living environment of the SCI population. The *activ*PAL was used to record wheelchair mobility in the usual free-living environment (including outdoor use), for seven participants over the course of a week, and was used in conjunction with a range of wheelchair makes and designs (both manual and electric). As a system for assessing overall mobility in a free-living environment within the SCI population, data from two synchronised but physically unconnected *activ*PAL activity monitors were used on the wheelchair and on the thigh.

Average wheelchair rolling speed for the SCI participants in this study was between 0.32 and 0.77 $m\,s^{-1}$. Other studies have reported higher mean wheelchair rolling speeds for SCI participants (1.2 ± 0.3,[10] 1.2 ± 0.04,[11] and $1.3 \pm 0.4\,m\,s^{-1}$ (ref. 12)). The difference could be due to measurement in this study of habitual wheelchair mobility over an extended period, compared to the measurement in the other studies of performance in a test of much shorter duration. Monitoring habitual wheelchair mobility in a free-living environment for the SCI population could provide information on actual use, to complement that provided by performance-based tests on potential ability.

The study illustrated differences in mobility activities between the three groups of participants. The physiotherapists spent longer engaged in mobility activities than any participant with an SCI. The participants with SCI were placed in the groups based on their mobility status, without regard to injury, medical or rehabilitation status. There were large inter-individual differences between participants with SCI in both groups, however on average, participants in group 2 spent 70% longer engaged in all mobility activities than participants in group 1. This suggests that the technique could be used to assess differences between subgroups of the SCI population for population or intervention studies.

The data collected were continuous and could be analysed for any time period (for example hourly), allowing an investigation of the pattern of mobility. Such analysis could be used to investigate differences in, for example, changes in routine, health status or environment, on the mobility of an individual; information which could be used to inform decision-making in rehabilitation.

Participants in group 2 tended to spend longer in mobility activities during the daytime than during the evening, and six participants spent no time standing or walking in the evening. The lack of time spent upright could have been due to the need for supervision, physiotherapist support or equipment provided by the spinal injuries unit for upright mobility in this group of participants, which was not available during the evening. The purpose of this study was not to investigate physiotherapy or orthotic provision among this community, however, these data have illustrated the potential utility of the device to monitor aspects of mobility, such as participation and social inclusion, within the spinal cord injured population.

Postma *et al*.[5] validated an activity monitor system to assess upright and wheelchair mobility in the SCI population. The monitor system, six small accelerometers connected to a data logger, monitors free-living wheelchair use for 2 days by classifying the pattern of arm movement as a manual wheelchair is propelled. It does not classify wheelchair movement from other propulsive methods (for example an electric wheelchair or when being pushed). In contrast, the monitor system developed here, two physically unconnected monitors, records the movement of the wheelchair wheel in a free-living environment for 10 days. The two systems measure related but distinct aspects of the wheelchair mobility of an individual with SCI; the Postma system monitors the time spent physically propelling a wheelchair (but not necessarily capturing all movement), while the system described in this study monitors the time spent moving in the wheelchair (not necessarily self-propelled movement). The choice of a system to use in a research or clinical context should be governed by the particular aspect of wheelchair mobility under investigation.

This study was designed to be exploratory, data were collected from a small number of participants who were recruited as a convenience sample. Any differences found in the data should be interpreted in this light, and the information drawn from the wheelchair mobility of these participants cannot be generalised to the SCI population as a whole. Ideally, more than one electric wheelchair user would have been recruited to the study, to confirm if the monitor was appropriate for use with electric wheelchairs. While not the case for the participants in this study, individuals with SCI often use more than one wheelchair. This is a practical consideration for future study design, which could be overcome by the use of multiple monitors. A formal validation of the wheelchair monitor would need to be undertaken, prior to use as a tool evaluating mobility in the SCI population.

This study has shown that the proposed monitoring system can be used to measure overall mobility across a broad spectrum of the SCI population. Information has been presented on time spent moving in a wheelchair, and the additional outcome measures of distance travelled and overground speed. Detailed information can be obtained regarding the type and pattern of mobility. This information could be used to evaluate interventions, or to inform decision-making in rehabilitation.

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