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A novel algorithm for detecting active propulsion in wheelchair users following spinal cord injury

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ABSTRACT

Physical activity in wheelchair-bound individuals can be assessed by monitoring their mobility as this is one of the most intense upper extremity activities they perform. Current accelerometer-based approaches for describing wheelchair mobility do not distinguish between self- and attendant-propulsion and hence may overestimate total physical activity. The aim of this study was to develop and validate an inertial measurement unit based algorithm to monitor wheel kinematics and the type of wheelchair propulsion (self- or attendant-) within a "real-world" situation. Different sensor set-ups were investigated, ranging from a high precision set-up including four sensor modules with a relatively short measurement duration of 24 h, to a less precise set-up with only one module attached at the wheel exceeding one week of measurement because the gyroscope of the sensor was turned off. The "high-precision" algorithm distinguished self- and attendant-propulsion with accuracy greater than 93% whilst the long-term measurement set-up showed an accuracy of 82%. The estimation accuracy of kinematic parameters was greater than 97% for both set-ups. The possibility of having different sensor set-ups allows the use of the inertial measurement units as high precision tools for researchers as well as unobtrusive and simple tools for manual wheelchair users.

1. Introduction

Regular physical activity is associated with positive health benefits following spinal cord injury (SCI) [1], but only 13–16% of affected individuals report being physically active [2]. Wheelchair propulsion is one of the most intense activities performed by wheelchair-bound individuals, and the measurement of wheelchair mobility has therefore been proposed as a means of estimating and tracking physical activity in these individuals. Such activity measurements could be powerful tools to monitor rehabilitation progress and motivate these individuals to maintain an active lifestyle. Wheelchair mobility can be quantified through direct observation, questionnaires, satellite navigation systems, specialized wheel modifications (e.g. SmartWheel, Three Rivers Holdings LLC) or through accelerometers mounted to the wheels. Direct observation is a valid approach but it is not practicable in long-term settings as it requires that the subject is followed with a video camera for the entire recording and involves intensive post processing to label the videos. Questionnaires require less effort but are rather subjective due to the individual (possibly biased) perception of subjects making it difficult to objectively quantify mobility. Furthermore, well-established questionnaires regarding wheelchair mobility used in clinical set-ups such as the SCIM III [3] do not reflect mobility in terms of physical activity but rather in terms of independence. A more objective way of describing mobility is to use a global positioning system (GPS) as described by Sindall et al. in a sport application [4]. However one major drawback is the dependence on the availability of GPS signals via satellites and therefore indoor applications that likely reflect the majority of daily activities are challenged.

Dedicated wheelchair activity measurement devices such as the SmartWheel are very powerful tools, allowing the collection of not only kinematic parameters, but also interaction forces with the wheelchair push-rims. The SmartWheel has already been used in

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several studies, for example to investigate start-up and steady state velocity in experienced wheelchair users [5], or to investigate push frequency and stroke length in manual wheelchair users with SCI [6]. Although the SmartWheel is a very promising and powerful tool to measure wheelchair mobility, it is a costly solution that requires a mechanical modification of the wheelchair that might affect the dynamic behaviour (e.g. through increased weight and a shift in the centre of mass). Furthermore it may not be applicable to subjects that need wheelchairs adapted to specific morphological characteristics (e.g. wheels with larger diameters), or that employ multiple wheelchairs (athletes).

A more simple approach to track mobility in manual wheelchair users is through the use of inertial sensors. In order to describe mobility in terms of distance travelled, velocity or number of wheel revolutions the angular velocity can be estimated through the use of accelerometers attached to the wheel [7,8]. This method has demonstrated a high accuracy of the estimated kinematic parameters such as distance travelled and has already been used for long-term monitoring [9]. Whilst describing mobility and thus physical activity in terms of e.g. distance travelled is a good approach it has one major drawback, namely that it overestimates the mobility produced by the wheelchair user because it does not distinguish between the user moving the wheelchair himself ("self-propulsion") and being pushed by someone else ("attendant-propulsion"). The alternative is to use accelerometers attached to the upper extremity of the user to detect manual wheelchair propulsion. For example, during standardized mobility-related activities, Postma et al. were able to detect hand-rim wheelchair propulsion with a high accuracy, sensitivity and specificity [10]. However, an estimation of wheelchair mobility based purely on activity measurements at the upper extremity might be misrepresented by upper limb activities unrelated to wheeling. Furthermore, complementary inertial sensors such as gyroscopes might provide a more accurate measure of wheel kinematics, as they directly measure angular velocity. In this direction, Hiremath et al. combined the two aforementioned approaches and showed that a multimodal system, consisting of a two-axis gyroscope fixed to the spoke of the wheel and multiple tri-axial accelerometers fixed to the upper extremity, were able to detect wheelchair activities (e.g. self-propulsion) with higher accuracy than with the individual components alone (e.g. only the accelerometers) [11]. Although the system has been tested in a structured laboratory, semi-structured organizational and unstructured home environments (real-world), for the cross validation the three datasets were mixed together which limited the generalization (approximated to the real world) of the study's results.

The aim of this study was to develop and validate an algorithm to continuously monitor the type of wheelchair propulsion (self- or attendant-propulsion) and wheel kinematics using an enhanced inertial measurement unit (IMU) [12] within a "real-world" situation. Similar to the methodology used by Hiremath et al. [11], the algorithm fuses two approaches, i.e. using accelerometers attached to the human body to detected manual wheelchair propulsion [10] and accelerometers attached to the wheel to estimate kinematic parameters such as wheel revolutions, angular velocity or distance travelled [7,8] and further allows the precise detection of wheeling phases and the distinction of self-propulsion from attendant-propulsion. The algorithm consists of two components, the first detects if the wheelchair was moved based on heuristic rules and the second component then determines whether the wheelchair was moved by the user itself based on a support vector machine (SVM) classifier. Six different sensor set-ups were investigated, ranging from a high precision measurement tool set-up involving multiple sensor modules and a relatively short measurement duration (around 1 day) where gyroscope data is included to a simple, less precise set-up with only one sensor module and an increased measurement duration exceeding one week (without gyroscope). In addition to kinematic parameters, the algorithm determines the percentage of wheelchair use which can be attributed to self-propulsion. The results obtained by this new approach provide a better insight into the effective mobility behaviour of wheelchair users, and the algorithm is especially suited for application both in acute in-patient rehabilitation through to discharge into the home environment (out-patient situation), and hence can provide information about mobility as patients progress from learning to use the wheelchair to eventually integrating the wheelchair into their activities of daily living.

2. Methods

2.1. Subjects

Seven paraplegic (age 61.85 ± 16.93 years, six male, one female, ASIA A, C and D) and 14 tetraplegic (age 38.71 ± 14.84 years, 12 male, two female, ASIA A–D) subjects in the chronic stage (at least 90 days post-injury) with traumatic SCI were recruited for this study. Inclusion criteria required that subjects were 18 years or older and were trained to use a manual wheelchair. Exclusion criteria were any neurological disorders, orthopaedic or rheumatological diseases affecting the upper limb (other than SCI) and pre-morbid or on-going major depression. Each participant provided written informed consent after having the experimental procedure explained to them. The measurements took place at the University Hospital Balgrist and the Swiss Paraplegic Center in Nottwil. The study was approved by the ethics committees of the cantons of Zurich (KEK-ZH 2013-0202) and Lucerne (EK 13018).

2.2. Measurement device

For this study an enhanced version of the ReSense module was used [12] (Fig. 1B). The new ReSense module is a miniature 10-degrees-of-freedom (DOF) IMU designed for long-term monitoring of human motor activities. It consists of a 3-axis accelerometer (ADXL345, Analog Devices), a 3-axis gyroscope (ITG-3050, InvenSense), a 3-axis magnetometer (MAG3110, Freescale) and a barometric pressure sensor (BMP 085, BOSCH). The electronics board is encased in a robust, water-resistant and biocompatible plastic housing. ReSense weighs 15 g (including the battery and housing), measures $36 \times 29 \times 13\,\text{mm}^3$ and can continuously record data for over 24 h at a 50 Hz sampling rate. An integrated power-management system can increase the operating time by a factor of 2–3. In addition, deactivation of the gyroscopes increases the operating time to 20 days. The collected data, which includes an absolute time stamp, is stored on an internal 2 GB microSD card. An advantage of the ReSense is the possibility to synchronize the on-board clock across different modules with a host PC via a custom-built USB base station.

2.3. Data collection

Participants were equipped with four ReSense modules (Fig. 1A) for up to 6 h. One module was worn on each wrist, attached with AlphaStrap Blue (North Coast) and Velcro Straps (Velcro). The chest module was attached with a custom-made chest strap (BalgristTec AG, Switzerland). The fourth sensor was fixed between the spokes of the wheelchair using a custom-designed fixation (Fig. 1C). The subjects, who were all in-patients, were asked to carry on with their daily clinical routine during the entire duration of the measurement. In order to validate the algorithm, a video camera (GoPro Hero HD 2, GoPro Inc.) was attached to the back of the wheelchair to film the right wheel only. The frame rate of the