**A novel method to quantify mobility in hospitalized individuals using a chest-worn accelerometer**

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**Abstract**

Purpose: Prolonged immobility of hospitalized individuals is a common cause of complications such as pressure injuries, pneumonia, and thromboembolism. Actigraphy-based techniques have shown to be accurate in monitoring mobility in hospitalized patients, but manual analysis of actigraphy data is time-consuming and prone to errors. We propose an automatic algorithm to calculate activity rates, which is a measurement that summarises frequency of activity of hospitalized patients from actigraphy data. Frequency of physical activity is relevant to evaluate risks of complications due to immobility.

Methods:

We calculated activity rates from activity counts, which is a popular actigraphy measurement used in clinical applications. The activity rates measurement describes distribution of activity counts over time based on two parameters: T1 and T2. T1 was used to define an active area after each sample of detected activity; T2 was used to average the contribution of active areas to provide a sample of activity rate per epoch. For validation, we made a comparison between results of the activity rate and physical impairment of hospitalized spinal cord injured (SCI) individuals.

Results: We calculate activity rate from 120 hours (five days and nights) of activity counts at 1 second epoch from 12 SCI patients. We chose T2 equal to 120 minutes to identify periods of immobility that last 2 hours or more. We found that T1 equal to 10 minutes facilitates differentiation of activity rate among individuals. From all the individuals, we observed that activity rate during the days is higher than during the nights, and that patients with severe physical impairment scores lower in activity rate than those with a higher capacity to move.

Conclusion: Results suggest that the proposed method is reliable to describe motor activity of hospitalized individuals. The method transforms activity counts to activity rates, which is a measurement of how much the patient moves during the previous two hours.

Significance: We proposed a novel measurement of mobility for hospitalized individuals who are mostly bedridden using a chest-worn accelerometer. The proposed measurement is intended to facilitate real-time monitoring of mobility and immobility of hospitalized patients who are at risk of complications due to immobility.

**Keywords**— Physical impairment, Spinal cord injury, Chest-worn accelerometer, Digital mobility assessment

**1 Introduction**

Hospitalized individuals spend most of their time in bed [(De Klein et al., 2021)](https://www.zotero.org/google-docs/?1AjOnG). Immobility is particularly harmful for bedridden patients with neurological impairments who are at risk of complications such as pressure injuries, thromboembolism, and pneumonia [(Li et al., 2019)](https://www.zotero.org/google-docs/?Ea7Sym). Frequent repositioning and/or changing body posture can help to minimize the risk of complications; even small posture changes can be protective [(Anders et al., 2010; Norton et al., 2017; Still et al., 2013)](https://www.zotero.org/google-docs/?VLB2ND). Individuals with limitations of independent voluntary movements such as patients with spinal cord injury (SCI), would require the help of caregivers for repositioning. Although the frequency of repositioning depends on the health conditions of each individual, general guidelines suggest avoiding immobility periods that exceed two hours [(MedlinePlus, 2023)](https://www.zotero.org/google-docs/?3WBINv).

Quantitative measurements of mobility and immobility can be supported by computerized tools such as pressure mapping [(Marzloff et al., 2022; Vos-Draper et al., 2023; Ziegler et al., 2023)](https://www.zotero.org/google-docs/?JtDYcD) or actigraphy [(Duclos et al., 2014; Osse et al., 2009; Verceles & Hager, 2015)](https://www.zotero.org/google-docs/?i8apM3). Using a pressure mat, pressure mapping quantifies interface pressures between the body and any supporting surface such as a bed or a chair; changes of interface pressures generally indicate changes in posture or repositioning. On the other hand, an actigraphy device measures changes in acceleration to identify periods of mobility/immobility. The increasing accessibility for the general population of wearable devices that include accelerometers led us to investigate the use of actigraphy to monitor mobility/immobility in hospitalized patients with SCI.

Actigraphy is a non-invasive technique that uses accelerometry to quantify periods of mobility and immobility. It has been used in clinical research to study relationships between physical activity and patients’ recovery [(Schwab et al., 2020)](https://www.zotero.org/google-docs/?ZqrpTu). Indeed, actigraphy has been used to estimate circadian rest-activity patterns of patients in the intensive care unit (ICU). They found that normalization of circadian rest-activity patterns has a positive correlation to patients’ recovery after a traumatic brain injury [(Duclos et al., 2014)](https://www.zotero.org/google-docs/?fyd6D9) or a cardiac surgery [(Osse et al., 2009)](https://www.zotero.org/google-docs/?fWyhZS). Those results suggest that actigraphy provides reliable data to monitor mobility/immobility of bedridden individuals.

Descriptive statistics has been used to summarize the information of activity counts provided by actigraphy for the estimation of patients’ activity and rest during days and nights [(Duclos et al., 2014; Osse et al., 2009)](https://www.zotero.org/google-docs/?V2EXdR). Although the statistics summary provides information about the mobility/immobility for a specific period (day or night), it does not show how activity is distributed over time. We believe that the activity rate over time is relevant to evaluate the risk factors of immobility in bedridden individuals. However, to provide a real-time measurement of activity rate for bedridden individuals from actigraphy two limitations should be considered. First, there is a need to improve the quantification of short-duration activity values that otherwise could be neglected due to large amounts of zeros around it (non-activity). Second, there is also a need to score the overall distribution of detected activity over time, as regular and continuous movements over time minimizes the risk of complications.

We propose a method to quantify the frequency of activity of hospitalized patients with limited mobility. We called this measurement activity rates. The proposed method tackles the sparse nature of actigraphy signals–long periods of immobility–to provide values between zero and one that represent levels of mobility over time. Details of the proposed method are described as follows.

**2 Materials and Methods**

Mobility from hospitalized SCI patients was recorded during multiple days and nights using a non-invasive chest-worn accelerometer device (ActiGraph). From the collected data, we calculated activity rates, which quantify frequency of patients’ mobility over time. Finally, we evaluated the agreement between the calculated activity rates and clinical assessments of patients' physical impairment, which are related to patients’ mobility.

**2.1 Data collection**

From February 2023 to July 2024, we recruited spinal cord injured (SCI) patients during their acute hospitalization at the Hôpital du Sacré-Coeur-de-Montréal, a level I trauma center specialized in SCI care. Eligibility criteria included patients with traumatic and/or no-traumatic SCI, 18 years old or older, conscious, and the ability to communicate in English or French. The hospital ethical committee approved this study. Written informed consent was collected for every included participant.

We secured an ActiGraph GT9X Link (Pensacola, FL, USA) to the skin of the chest of each patient using an adhesive patch of medical grade (transparent film dressing, priMED Medical Products Inc, Edmonton, AB, Canada). The device was set to collect acceleration measurements from three spatial dimensions (X, Y, Z) with a minimum sample rate of 30 Hz (30 samples per second) for more than 120 consecutive hours. Once the data was collected, the ActiGraph was removed from the patient and the data was downloaded to a laptop using the ActiLife software (ActiLife 6 by ActiGraph, Pensacola, FL, USA).

Using the ActiLife software, the three-dimensional acceleration measurements were transformed into the activity counts signal (also called Vector Magnitude), which quantifies intensity and frequency of the accelerations by time-intervals or epochs [(Neishabouri et al., 2022)](https://www.zotero.org/google-docs/?Hz3YlP). For our application, we chose epochs of 1 second that was the shortest time-interval available. Although ActiLife is proprietary software, the algorithm that calculates activity counts is publicly available and has been already implemented in Python and R programming languages, which could facilitate integration of the algorithm with multiple accelerometer devices [(Neishabouri et al., 2022; Helsel et al., 2024)](https://www.zotero.org/google-docs/?zksWnS).

**2.2 Activity rates estimation**

Our objective was to quantify the frequency of activity from activity counts signals from subjects with physical limitations to evaluate their mobility during days and nights. In general, we have observed that those signals provide a scarce and irregular number of activity samples (samples greater than one), which hinders the frequency quantification over time. To tackle this problem, we proposed a method that calculates a signal of activity rates from the activity counts one applying a sequence of sliding window algorithms. The method’s details are described as follows.

The Activity rates signal is calculated by a method of two consecutive stages (Figure **1**). Stage 1 enlarges the number of activity samples–values greater than zero–that are found in the activity counts signal; stage 2 calculates the rate of activity samples over time. Each stage includes a sliding window (SW) algorithm that uses a rectangular function with window size of T1 and T2 for stage 1 and stage 2, respectively. The window size defines the number of consecutive input samples that determine the value of an output sample. The SW algorithm of stage 1 translates its rectangular function one epoch at a time from the beginning until the end of the input signal, in order to calculate, at each position, the sum of values of the input samples that are in the same temporal range of the rectangular window. Thereafter, the resultant values of the SW are binarized being 1 (activity) for values greater than zero and 0 (no activity) otherwise. Those binary samples shape the discrete signal S’. The SW algorithm of stage 2 is applied from the beginning until the end of S’ in a similar way as in stage 1; namely, the SW calculates the sum at each step, but its outcomes are divided by T2 to provide values between 0 and 1 that quantify activity rates.

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| **Figure 1**: Diagram of our proposed method for activity rates calculation from the activity counts signal. T1 and T2 are window sizes of their respective sliding window algorithms. The uppercase letters (S, S’, S’’) represent discrete signals and the lowercase ones (s, s’, s’’) samples of those signals. |

Figure 2 shows a graphical representation of two examples to describe the algorithm’s operation. Comparing the two examples, values of activity rates are bigger when a number of activity samples are regularly separated than when they are in a cluster. That happens because the enlarged number of activity samples provided by stage 1 are overlapped in case of clustered samples. Therefore, activity rates provide measurements of the distribution of activity samples over time. Interpretation of values of activity rates, however, depends on the chosen values for the parameters T1 and T2.

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| **Figure 2**: Graphical representation of the proposed method outcomes given two inputs of activity counts with different distributions of activity samples over time. (a) Five activity samples in a cluster. (b) Five activity samples separated among them by a time greater than T1. Samples distribution in (a) produces an activity rate lower than that from the distribution in (b). |

The choice of values for T1 and T2 depends on the target population. In our case, it is relevant to know patients’ mobility during the last two hours (T2 = 120 min) for monitoring purposes. Additionally, we could consider a highly satisfactory outcome to find out that a patient moves at least once every 10 minutes (T1=10 min). Given T1 and T2, we could interpret the values of activity rates in function of number of movements with the following equation: number of movements = (activity rates)\* T2 / T1. A movement is one or a cluster of activity samples of short duration (T1/10). The equation estimates a number of movements regularly distributed in the respective interval T2. For example, being T1=10 min and T2=120 min, values of activity rates of 0.08, 0.17, 0.33, 0.67, and 1.00 could be interpreted as 1, 2, 4, 8, and 12 (or more) movements regularly distributed in a period of 2h, respectively.

**2.3 Neurological examination**

Two specialized physiatrists completed the sensory and motor assessment for each patient and reported the level and severity of the SCI using the ASIA (American Spinal Injury Association) Impairment Scale (AIS). Severity was graded as AIS grade A (complete injury defined as neither sensory nor motor preservation below the injury), grade B (sensory-incomplete and motor complete injury), grade C (sensory and motor incomplete injury, with less than half of key muscles with antigravity strength below the level of injury), and grade D (sensory and motor incomplete injury, with at least half of key muscles with antigravity strength below the level of injury) [(Kirshblum et al., 2020)](https://www.zotero.org/google-docs/?FM8HbB). The Neurological Level of Injury (NLI) was defined as the most caudal level for which the sensory and motor functions were preserved and were classified as cervical (C1-C8), thoracic (T1-T12), lumbar (L1-L5), or sacrum (S1-S5) region. Individuals with higher (cranial) NLI may sustain neurological impairments in all four limbs (tetraplegia), while lower NLI (thoracic and below) may sustain neurological impairments in the lower extremities (paraplegia). The NLI and severity of the injury was shown to represent major predictors of the mobility level following SCI [(Richard-Denis et al., 2018)](https://www.zotero.org/google-docs/?hhwupT).

**3 Results**

**3.1 Collected data**

Chest-worn accelerometer devices were set up to collect data continuously for up to 7 days from hospitalized patients. From the collected data, we chose 14 cases that showed a successful continuous data recording. We restricted our analysis to the five days and five nights (120 consecutive hours) after the first night of collected data. Data collected during the first day was not considered, since accommodating to wearing the accelerometer could potentially affect the activity patterns initially. The last day was not included because in some patients it did not include full 24-hour acquisitions. Figure 3 depicts the activity counts signals that were generated at one second epoch (one sample per second) from the acceleration data collected from each of the 14 patients during 5 days (7:00 am - 10:59 pm) and five nights (11:00 pm - 6:59 am).

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| **Figure 3**: Signals of activity counts of 5 days (7:00 am to 10:59 pm) and 5 nights (11:00 pm to 6:59 am) from 14 hospitalized spinal cord injured patients (P01 - P14). |

**3.2 Parameters’ selection**

Experimentally, we calculate activity rates for all the patients using window sizes of 1/60, 0.5, 1, 4, 7, 10, 13, 16, 19, 22, and 25 min for T1, being T2 equal to 120 min. We observed that 10 min provided a centered data distribution of activity rates from all the patients during the five day periods (Figure 4). A centered data distribution facilitates comparison between cases; therefore, we chose T1 equal to 10 min. On the other hand, T2 was set at 120 min to quantify mobility, but mainly to identify periods of immobility that last 2 hours or more. For patients with limited mobility it is recommended to change body posture at least once every two hours.

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| Figure 4. Activity rates distribution for different values of T1. Each box plot represents data distribution of activity rates calculated with a particular T1 value for all the 14 patients during the five days (7h00 - 22h59). T2 was set at 120 min. |

**3.3 Results of activity rates and neurological examinations**

Table 1 presents results of both activity rates and neurological examinations for all the 14 patients. Data in Table 1 were ordered by the Neurological Level of Injury (NLI), and inside each group of patients with the same NLI, they were ordered by their AIS. As a general remark, every patient scored higher on mean activity rates during the days than during the nights. Inside every group of patients with the same NLI, the greatest values of activity rates (day and night) were obtained by patients with AIS D. Inside the group of patients with NLI C4 (first group), mean activity rates were similar among patients with AIS B, whose scores were higher than those for a patient with AIS C. The former two patients with AIS B were younger than the later one with AIS C, with at least 20 years of difference. Inside the group of patients with NLI C5 (second group), mean activity rates were higher for the patient with AIS C than for patients with AIS A or B. In this second group, the patient with AIS C was younger than those with AIS A or B.

| **Table 1**. Activity rates (median and interquartile range [iqr]) from 14 SCI patients during their hospitalization for five consecutive days (7:00 am - 10:59 pm) and nights (11:00 pm - 6:59 am). Patients’ ASIA Impairment Scale (AIS) score and Neurological Level of Injury (NLI) were evaluated during their participation in the study. |
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| | **patient** | **sex** | **age (years)** | **AIS** | **NLI** | **activity rates** | | | | | --- | --- | --- | --- | --- | --- | --- | --- | --- | | **5 days** | | **5 nights** | | | **mean** | **std** | **mean** | **std** | | P01 | M | 25 | B | C4 | 0.19 | 0.15 | 0.13 | 0.13 | | P02 | M | 33 | B | C4 | 0.24 | 0.17 | 0.12 | 0.09 | | P08 | M | 53 | C | C4 | 0.13 | 0.12 | 0.09 | 0.08 | | P03 | M | 20 | D | C4 | 0.83 | 0.19 | 0.41 | 0.27 | | P05 | M | 67 | A | C5 | 0.21 | 0.16 | 0.14 | 0.15 | | P07 | F | 41 | A | C5 | 0.29 | 0.21 | 0.08 | 0.08 | | P04 | M | 54 | B | C5 | 0.31 | 0.19 | 0.11 | 0.13 | | P13 | M | 37 | C | C5 | 0.45 | 0.25 | 0.17 | 0.15 | | P06 | M | 68 | D | C5 | 0.57 | 0.26 | 0.30 | 0.18 | | P09 | M | 31 | A | C6 | 0.73 | 0.23 | 0.18 | 0.18 | | P10 | M | 28 | A | C6 | 0.58 | 0.21 | 0.24 | 0.19 | | P14 | F | 88 | D | T4 | 0.71 | 0.20 | 0.38 | 0.27 | | P11 | F | 75 | A | T7 | 0.79 | 0.15 | 0.73 | 0.22 | | P12 | F | 40 | C | T10 | 0.97 | 0.08 | 0.56 | 0.24 | |

In order to compare scores of mean activity rates in function of NLI, we calculated the median of those scores for each NLI group. Median values of mean activity rates (daytime, nighttime) for each NLI group are as follows: (0.22, 0.13), (0.31, 0.14), (0.66, 0.21), (0.71, 0.38), (0.79, 0.73), and (0.97, 0.56) for NLI C4, C5, C6, T4, T7, and T10, respectively. From these results, we observed that activity rates from both daytime and nighttime increase when the NLI goes from C4 to T10, with only one exception: nighttime activity for the group NLI T10 (0.56), which is only lower than the result of the previous group (T7 with a score of 0.73).

A graphical representation to compare activity rates among patients with AIS A is presented in Figure 5. From those patients, we observed that the ones with NLI C5 (P05, P07) showed mainly low values of both daytime and nighttime activity rates. Patients with NLI C6 (P09, P10) presented mainly moderate values of activity rates during the days and low values during the nights. Finally, patient P11 (AIS A, NLI T7) showed mainly moderate to high values of activity rates during the days and nights. Plots in Figure 5 suggest that patterns of activity rates agree with the severity of the SCI, namely lower values of activity rates for patients with a more severe SCI.

Interpretation values of mean activity rates: what does it mean 0.0, 0.5, and 1.0?

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| **Figure 5**: Graphical representation of activity rates from patients P05, P10, and P11. Inferior and superior borders of the shading regions represent the minimum and maximum values of activity rates per epoch from five consecutive days (from 7h00 to 22h59) and nights (from 23h00 to 6h59). Black lines inside shaded regions represent median values of activity rates. The three patients presented the same ASIA Impairment Scale (AIS) but with a different Neurological Level of Injury (NLI). |

**4. Discussion**

We proposed a novel algorithm of two stages to quantify activity rates of hospitalized patients using a chest-worn accelerometer device. The first stage is to extend the duration of any activity detected by the device (activity samples) to tackle the sparse nature of mobility of patients with physical limitations. The second stage is to quantify the new set of activity samples in periods of two hours, in order to provide values of activity rates every second. The proposed algorithm facilitated comparison of activity rates among 14 hospitalized SCI patients who wore an accelerometer device for more than 120 consecutive hours. Results suggest that the proposed activity rates measurement agrees with expected physical impairment levels, namely lower activity rates for patients with more severe SCI.

Experimental tests were conducted to determine a proper value for T1, which controls the extension size of activity samples over time (stage 1 of the proposed algorithm, being T2 equal to 120 min in the second stage). Firstly, we observed that with a minimum extension of activity samples (T1=1 s), we obtained very small values of activity rates, close to zero, for a large part of daytime activity data from the 14 patients. Those small values hinders data analysis and results’ comparison among patients. As T1 gradually increases, the distribution of activity rates grows. When T1 equaled 10 min, we observed a centered data distribution of activity rates (in the range between zero and one), which facilitates data analysis. Interpretation of activity rates when T1 is equal to 10 min is as follows. When activity rates is zero, it means that

We considered that 10 min Greater values for T1 tend to saturated the outcomes to one which was the selected value. Interpreting values of activity rates being T1 equal to 10 min, values of activity rates are interpreted as follows.

Values greater than 10 min for T1 could not be necessary, and those could saturate output.

We tested a set of values for T1, from 1 s to 25 min, being T2 equal to 120 min, to calculate activity rates for all the 14 patients.

10 min for T1 provides a centered data distribution of daytime activity rates from all the patients

are close to zero

for daytime activity samples from all the 14 patients

This value A centered distribution facilitates comparison of activity rates among patients

one second (1/60 min), no extension to activity samples is made, therefore many values of activity rates would be close to zero, which would hinder outcomes comparison intra- and inter-individuos. On the other hand, a value of T1 greater than 20 min would saturate the outcomes to one, which could also limit outcomes comparison. Therefore, we evaluated the algorithm's outcomes testing different values for T1 using all our dataset; we chose the value for T1 equal to 10 min that provided a centered distribution of activity rates, which facilitates comparison between cases. The parameter T2 was set at 120 min to identify periods of immobility that last 2 h or more. Two hours was chosen because it is a common parameter recommended in clinical practice to monitor activity in patients with limited mobility [(MedlinePlus, 2023; Saeed, 2023)](https://www.zotero.org/google-docs/?CSNBsd).

Each sample of activity rates provides a score in the range between zero and one, where zero represents a period of immobility and one a period of high activity.

\*A value of activity rates equal to zero indicates immobility during the previous two hours. A value of one indicates periods of immobility no greater than T1 during a T2-interval.

Monitoring immobility is relevant to evaluate individuals’ activity and to provide them assistance in a timely manner that could minimize risk of complications.

Regular activity of hospitalized patients minimizes risk of complications due to immobility.

In the results, we observed that median activity rates during the days are bigger than those during the nights, with small or big differences. Markedly, some patients had low activity rates at night despite a high activity rate during the day (P09, P10), suggesting that there are individual specificities in terms of mobility patterns. This could partly explain the difficulty to predict the occurrence of pressure injuries after SCI, considering that risk assessment for pressure injuries in this population has been assessed only from the mobility level during daytime, without much emphasis on nighttime mobility. Physiotherapy and medical exams that promote patients’ mobility usually happen during daytime rather than during the night; additionally, activity rates during the night may reveal levels of independent mobility. Therefore, it is logical to think that for the same level of mobility observed during the day, those with decreased nighttime mobility will be at increased risk of pressure injuries.

Age -> we noted a difference, sex -> few women, we did not observe significative differences

The ActiLife software (ActiGraph) calculates activity counts (Vector Magnitude [VM]) after a filtering process to eliminate acceleration components that are far from those related to physical activity of the human body [(Neishabouri et al., 2022)](https://www.zotero.org/google-docs/?BsDEt5). The filtering goal is to make sure that accelerations associated with physiological functions (such as respiratory movements) or with external actions (such as being transported to another department while in hospital bed) do not affect the outcomes of activity counts. However, filtering could also eliminate components related to very slow movements that may be relevant to evaluate mobility of hospitalized individuals. Therefore, it would be interesting to investigate the effect of those filters on the estimation of activity counts.

Body posture could complement the analysis of activity rate to evaluate risk factors due to immobility [(Lehmkuhl et al., 2023)](https://www.zotero.org/google-docs/?BzUiRe). Namely, low activity rates captured from individuals at a standing position (walking) may be more beneficial to reduce complications than the same quantity of activity rates from individuals at a lying or a sitting position. Posture changing is also relevant in the analysis because even small pressure-reducing movements are protective against complications due to immobility [(Anders et al., 2010)](https://www.zotero.org/google-docs/?xC92i8). Additionally, body posture and posture changing are variables that can be estimated from the same accelerometer data that are used to calculate activity rates; obtaining multiple measurements using the same device is advantageous for instrumentation purposes.

We secured an accelerometer device to the patient’s chest–using a patch of medical grade–to obtain direct measurements of the torso’s mobility. Keeping the device for multiple days attached to the body could potentially be uncomfortable for some individuals and could interfere with their body cleaning, but it was not an issue in the current study. Alternatively, elastic bands or adapted clothes could be used to easily install and remove an accelerometer device [(Mukaino et al., 2022; Ryser et al., 2022)](https://www.zotero.org/google-docs/?3jM5ru) which could improve the flexibility of the proposed technology.

On the other hand, wearing the device in a different part location such as the wrist could facilitate

thigh, or ankle could be of interest to evaluate device’s placement that best describes patients’ mobility.

two actigraphs: chest and thigh, facilitates posture identification: sitting, standing. Standing relieves any pressure and indicates a greater patient’s mobility.

**4.1 Limitations**

Mobility in SCI individuals can result from the individual’s muscular activity or from external assistance from caregivers. Although, activity rates could not be enough to distinguish between the two sources of mobility [(Verceles & Hager, 2015)](https://www.zotero.org/google-docs/?8ZztID), additional data such as respiratory movements, which could be inferred from the chest-worn accelerometer [(Ryser et al., 2022)](https://www.zotero.org/google-docs/?b69Z0i), muscular (electromyography) or cardiac (electrocardiography) activity could complement the analysis in the future to solve that problem.

**5. Conclusion**

We have proposed a novel algorithm to quantify mobility of hospitalized individuals using a chest-worn accelerometer. The algorithm transforms activity counts into a measurement of mobility that evaluates activity rates. The proposed method has the potential to monitor around-the-clock mobility of hospitalized individuals, and to help in the assessment of patients at high risk of complications associated with immobility such as SCI individuals.

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