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# Methods for objective measure, quantification and analysis of sedentary behaviour and inactivity

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ABSTRACT

The purpose of this study was to develop and test a generic technique to robustly quantify the pattern of sedentary behaviour from objective records.

The technique was applied to four groups of subjects: a healthy group with an active occupation ($N = 54$), a healthy group with a sedentary occupation ($N = 53$), a group of subjects with chronic low back pain ($N = 5$) and a group of subjects with chronic fatigue syndrome ($N = 14$).

This study presents the first evidence that bouts of sedentary activity are power law distributed.

Results showed that there was no significant difference in total sedentary time between the groups, however, the patterns of accumulation of sedentary time were significantly different for the groups. Sedentary groups accumulated their total sedentary time from a small number of longer sedentary bouts. Active groups tended to break their sedentary time into a greater number of shorter bouts. This suggests that the power law exponent $\alpha$ and the GINI index $G$, used to describe the pattern of accumulation of sedentary time, could be used to evaluate and quantify sedentary behaviour.



## 1. Introduction

Sedentary behaviour is associated with a range of poor health outcomes, typically high levels of body fat/obesity, blood glucose levels and type 2 diabetes and cardiovascular problems [1]. Western lifestyle is becoming increasingly sedentary, at home, work and during leisure time [2]. This has driven global efforts to quantify physical. Consequently sedentary behaviour has generally been inferred from studies of physical activity where sedentary behaviour has been considered as the bottom end of a physical activity continuum. However, there is now mounting evidence, [1,3–7] that sedentary behaviour per se rather than just low level of physical activity, is an independent risk factor for chronic disease and poor health outcomes. This evidence has shown that there is a need to study and quantify sedentary behaviour.

Early studies of sedentary behaviour relied on self-reported methods, often using television viewing time as a proxy marker for sedentary time [8–13]. These subjective methods have the obvious caveats, with any self-report methods, that they tend to under report sedentary behaviour [14]. However, using these methods, associations between subjectively recorded total sedentary time and obesity [8], abnormal glucose metabolism [10] and the metabolic syndrome [11] have been reported, and it has been suggested that there is a need for more precise objective measures of sedentary behaviour [10].

Several studies [15–19] have used objective measures of energy expenditures, recorded by accelerometry. These studies have reported relationship between total sedentary time and abnormal glucose metabolism [16], metabolic risks [17] and obesity markers [18].

These findings do not provide insight into the drivers for adopting a sedentary lifestyle which are also poorly understood [20]. In order to investigate these, global measures of total sedentary time is not sufficient. Dietz [4] suggested that the study of “sedentarism” as a behaviour, rather than accounts of energy spent in sedentary pursuit might offer richer insight and assessment of factors that contribute to obesity and other diseases. Recent studies [5,6] highlight the fact that the pattern of inactivity has important physiological impact on muscles, cardiovascular health and metabolism.

Devices have been developed which enable long term recording of accelerometer signals. This technology offers the possibility to explore the temporal patterns sedentary behaviour. A recent study by Healy et al. [21] found a relationship between the number of breaks in sedentary periods and metabolic markers. This study illustrated the potential importance for studying patterns of sedentary periods.

The aim of this study was to develop a novel generic method for analysing and quantifying patterns of sedentary behaviour based on an objective monitoring technique and to test this to

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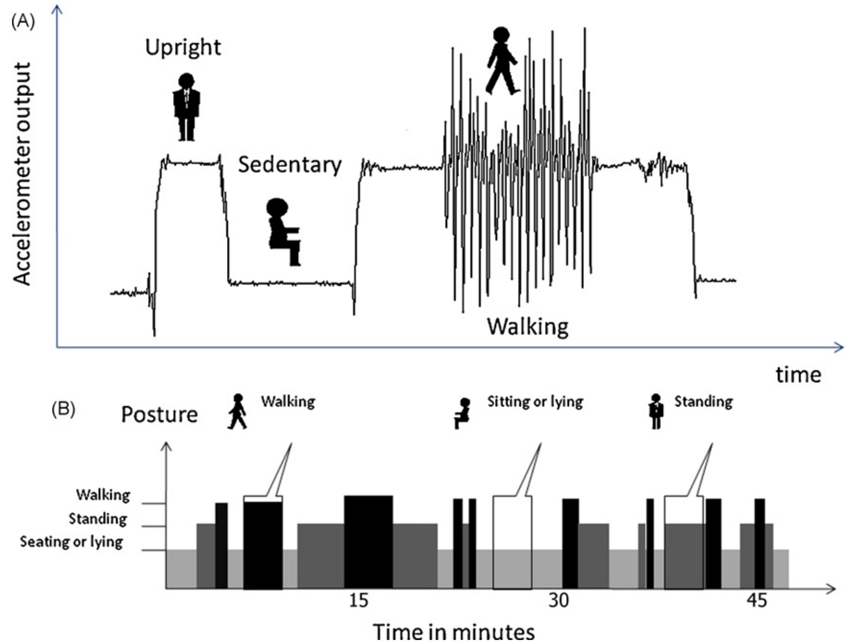


**Fig. 1.** (A) Typical signal from a thigh mounted activPAL depending on posture. (B) Pattern of activity derived from the accelerometer signal by the propreitory activPAL software (A).

explore how sedentary behaviour is modified by occupation and disease.

## 2. Objective measures of sedentary behaviour

### 2.1. Definition

A major difficulty in monitoring sedentary behaviour is finding a practical and accepted definition of sedentary activity [22]. A review by Bennett et al. [23] revealed that most studies of "sedentarism" define sedentary behaviour as a low level of physical activity. Owen et al. [20] proposed that sedentary behaviour is identified by an energy expenditure threshold. Using an energy threshold leads to large uncertainty about the sedentary data recorded, first of all because estimating energy expenditure from accelerometer data is not robust [24] and the length of sedentary period extracted will be very sensitive to the to the metabolic equivalent of task (MET) cut-off point chosen [2].

Secondly a MET threshold of 1.5 MET as defined by Owen et al. [20] can also include periods of quiet standing [25]. Hamilton et al. [6] showed that seating and quiet standing are fundamentally different physiologically and that it is important to makes a clear distinction between sedentary activity and low energy standing activity. This study introduces the concept that postural allocation is a direct reflection of sedentary behaviour.

Classifying sedentary behaviour as "non-upright" activities provides an unequivocal and robust definition supported by physiological and epidemiological studies. Matthews et al. [2] argue for a more direct measurement of sedentary behaviour by the recording of body posture.

### 2.2. Monitoring postural allocation

There have been various techniques for the classification of body posture from accelerometry data [26,27]. Various multi-sensor systems have been developed but accurate detection of seated and lying activity can be achieved using a single thigh mounted accelerometer [27]. In this position the accelerometer can act as inclinometers when the background acceleration is low. This creates a clear distinction between upright posture where the thigh is vertical and seated/lying activities where the thigh is near horizontal. This enables accurate detection of "non-upright" periods (Fig. 1).

## 3. Methodology

### 3.1. Design

This was a cross-sectional study of sedentary behaviour of four different groups. This study was approved by the ethic committee of the School of Health and Social care of Glasgow Caledonian University.

The demographics for these groups are presented in Table 1. The first group were healthy postal workers (Ha) whose occupation is by nature active involving mail delivery on foot. The second group were healthy office based postal workers (Hs), whose daily work activity was sedentary [35]. The third group were people diagnosed with chronic fatigue syndrome (CFS). The last group were people with chronic low back pain (LBP).

Posture recognition has been incorporated in the activPAL (PAL Technologies, Glasgow, UK) [28] activity monitor, which has been shown to accurately detect sedentary postures [29]. Participants wore an activPAL monitor continuously for 3–7 days. The monitors were then retrieved and data downloaded to a computer for further analysis.

**Table 1**
Groups demographics data. F = number of female, M = number of male.

| Group | Number | Age range (years) | Mean age (years) |
|---|---|---|---|
| Healthy active (Ha) | 53 (F 5, M 48) | 23–59 | 39.2 |
| Healthy sedentary (Hs) | 54 (F 10, M 44) | 22–60 | 39.9 |
| Chronic fatigue syndrome (CFS) | 14 (F 11, M 3) | 34–63 | 48.3 |
| Chronic low back pain (LBP) | 5 (F 3, M 2) | 40–51 | 45 |

### 3.2. Data processing

Previous studies have concentrated on measuring sedentary behaviour during waking hours (e.g. [16]). This approach could be considered inconsistent as it disregards sleeping periods which are a main component of sedentary behaviour. This methodology requires the definition of waking hours using some a priori assumptions and introduces new variables in the analysis that can strongly influence the results and therefore increases uncertainties and reduces robustness. To deal with these potential problems sleep time is treated as a sedentary period and not removed from the dataset.

Periods spent in sedentary activities were identified via postural allocation. The length of periods spent seating and lying were both considered as sedentary bout.

### 3.3. Data analysis

We introduce generic techniques to analyse and describe statistically the pattern of objectively measured sedentary behaviour. The techniques were designed to minimise the amount of a priori assumptions required for analysis in order to provide robust estimates of the parameters.

#### 3.3.1. Global sedentary time

The time spent in sedentary postures were summed and normalised to the total recording time to obtain the relative contribution of sedentary behaviour to the subject's daily lifestyle.

#### 3.3.2. Distribution of the length of sedentary bouts

The density $p(x)$ of sedentary bouts in a time bin width $d(x)$ was plotted against the bout length $x$ on a logarithmic scale to check the shape of the distribution. From the shape of the histogram a power distribution:

$$p(x) = Cx^{-\alpha} \tag{1}$$

of the sedentary bouts, with respect to their length $\alpha$ was selected. This type of distribution is characterised by the exponent $\alpha$, which can quantify different sedentary behaviour strategies. A lower $\alpha$ would indicate that subjects tend to accumulate sedentary time with a larger proportion of long sedentary bouts. $\alpha$ was estimated using the robust maximum likelihood estimation technique [31] rather than via curve fitting of the histogram which lead to large uncertainties [30]. With this method, the exponent $\alpha$ can be calculated using equation (2) where $x_i$ are the observed sedentary bout lengths such that $x_i > x_{\min}$ with $x_i > x_{\min}$ being the shortest recordable sedentary bout:

$$\alpha = 1 + n\left[\sum_{i=1}^{n} \ln \frac{x_i}{x_{\min}}\right]^{-1} \tag{2}$$

The standard error $\sigma$ of the estimation can be computed using equation (3) below.

$$\sigma = \frac{\alpha - 1}{\sqrt{n}} \tag{3}$$

The power law scaling exponent $\alpha$ is a unit-less parameter and can be difficult to interpret. It would be useful to define a characteristic time scale that would describe a subject or population preferred sedentary bout length such as a mean sedentary bout length $\langle x \rangle$:

$$\langle x \rangle = \int_{x_{\min}}^{\infty} x\, p(x)\, dx = C\int_{x_{\min}}^{\infty} x^{-\alpha+1}\, dx = \frac{c}{2-\alpha}[x^{-\alpha+2}]_{x_{\min}}^{\infty} \tag{4}$$

This is, however, difficult for a power law distribution as the mean sedentary bout length, $\langle x \rangle$ is undefined for $\alpha \le 2$ because the integral in equation (4) diverges.

On the contrary the median $x_{1/2}$ is well defined for power law distributions characterised by exponent $\alpha > 1$. The median sedentary bout length $x_{1/2}$ gives some indication of the favoured length of sedentary behaviour.

Generally the proportion of bouts of length $x > X$ is given by equation (5) below:

$$P(x > X) = \int_{x}^{\infty} p(x')\, dx' = \left(\frac{x}{x_{\min}}\right)^{-\alpha+1} \tag{5}$$

Using equation (5) $x_{1/2}$ can be directly related to the distribution exponent $\alpha$ using equation (6):

$$x_{1/2} = 2^{1/(\alpha-1)x_{\min}} \tag{6}$$

#### 3.3.3. Measure of pattern of sedentary time accumulation

In order to further characterise the pattern of accumulation of sedentary time, it is interesting to know the fraction of the total sedentary time that is accumulated in bouts longer than $x_{1/2}$. This can be estimated using equation (7):

$$W_{1/2} = \frac{\text{Total time of bouts} > x_{1/2}}{\text{Total sedentary time}} = \frac{\sum_{x_{1/2}}^{x_{\max}} x\, p(x)}{\sum_{x_{\min}}^{x_{\max}} x\, p(x)} \quad (\text{with } x_{\max} \text{ the largest bout}) \tag{7}$$

Equation (7) can be generalised to equation (8) to give the fraction $W_x$ of the total sedentary time that is accumulated in bouts longer than any sedentary period of length $x$:

$$W_x = \frac{\int_x^{\infty} x'\, p(x')\, dx'}{\int_{x_{\min}}^{\infty} x'\, p(x')\, dx'} \tag{8}$$

Plotting $W_x$ against $P(x > X)$ (Fig. 3) it is possible to link the contribution $W_x$ to the total sedentary time to the proportion of bouts above a certain length $P(x > X)$ from equation (6). These curves are known as Lorenz curves. They provide a graphical representation of the sedentary time accumulation strategy.

These curves can be reduced to a single parameter by calculating the Gini index ($G$). $G$ is a standardised statistics for comparing patterns of accumulation [32]. This coefficient ranges from 0 to 1. A $G$ index of 1 would indicate that all of the sedentary time is due to a very small proportion of the longest sedentary bouts. Conversely a $G = 0$ would indicate that all sedentary bouts length contribute equally to the total sedentary time.

The index can be computed by integration of the Lorentz curve as in equation (9):

$$G = 1 - 2\int_0^1 W(P)\, dP \tag{9}$$

## 4. Results

### 4.1. Global sedentary time

Overall subjects spent an average of around 75% of their time in sedentary behaviour. Individual values ranged from 41% to 92%. Comparison between these groups based on an ANOVA analysis reveals that there was no significant difference ($p = 0.167$) in the total daily sedentary time between groups.

### 4.2. Distribution of the length of sedentary bouts

The sedentary bout histogram represented on a loglog scale (Fig. 2) seems to follow a straight line. This means that the sedentary bouts, with respect to their length $x$, appear to be distributed as a power law (1). Table 2 presents the estimated

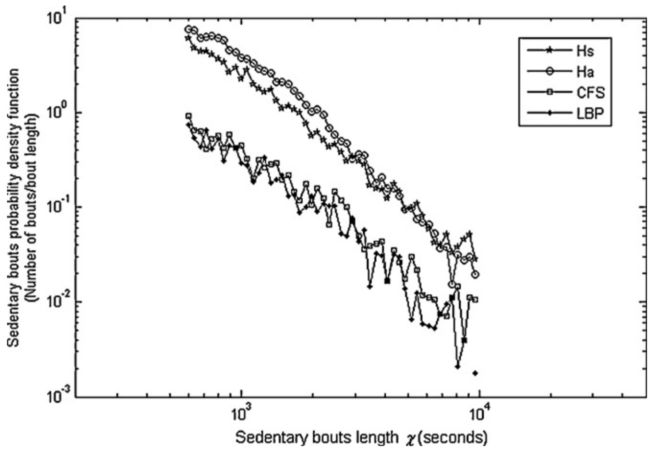


**Fig. 2.** Distributions of sedentary bouts per bout length: *, healthy sedentary workers Hs; ○, healthy active workers; □, chronic fatigue syndrome subjects; ●, chronic low back pain subjects.

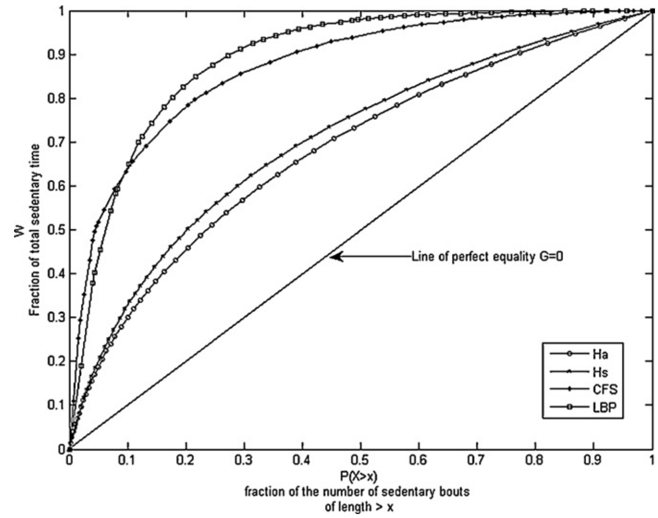


**Fig. 3.** Lorenz curves: *, healthy sedentary workers Hs; ○, healthy active workers; □, chronic fatigue syndrome subjects; ●, chronic low back pain subjects. The GINI index corresponds to the area between the curve and the line of perfect equality is marked by a solid line.

value of power law characteristic exponent $\alpha$ for the four different groups. ANOVA analysis reveals that these exponents are significantly different ($p < 0.01$) between groups. For the Ha group the mean sedentary bout length is 45 min but since $\alpha < 2$ for the Hs, LBP and CFS groups, a mean sedentary bout cannot be defined for these groups.

Values of the median, $x_{1/2}$, and fraction $W_{1/2}$ for the different groups studied are also presented in Table 2. An ANOVA test reveals that there is a statistically significant difference ($p < 0.01$) between the groups. These values show that there is a strong imbalance between the number of sedentary bouts and their contribution to accumulation of sedentary time. For Ha the majority of bouts are shorter than 20 min but bouts longer than this contribute the majority (71.5%) of the total sedentary time. This tendency is exacerbated in the case of Hs group (76.1%) with the LPB and CFS groups the proportion is greater than 90%.

### 4.3. Measure of pattern of sedentary time accumulation

The Lorentz curve obtained for the four groups are plotted in Fig. 3. The Gini indexes $G$ derived from these curves for each group are shown in Table 2. ANOVA analysis of these results shows that there is a significant difference in $G$ index between the groups ($p < 0.01$). $G$ is low for the healthy groups with $G_{Ha} = 0.35$ and $G_{Hs} = 0.40$ and almost double for the chronic condition groups with $G_{LBP} = 0.74$ and $G_{CFS} = 0.77$.

## 5. Discussion

Subjects spent on average around 75% of their daily time in sedentary behaviour irrespectively of their health status and occupation. This value is larger than that reported elsewhere in the literature [2,16–18,21]. The difference arises from the fact that sleep was included as sedentary time in this study.

The total sedentary time was not a sensitive outcome measure or diagnostic since it was not possible to differentiate between those a priori active and sedentary groups.

This study revealed that while occupation and/or disease do not seem to affect notably total sedentary time, they have a significant effect on the pattern of sedentary behaviour. Sedentary bouts appear distributed as power law with respect to their length. The exponent of this power law varied significantly with health status and occupation.

Groups with different occupation and health status, seen to adopt different strategies for accumulating sedentary time. The distribution exponent $\alpha$ decreased from $\alpha = 2.27$ for an active healthy group to $\alpha = 1.95$ for a healthy group with sedentary occupation. The exponent was even lower for groups affected by chronic diseases, with $\alpha = 1.8$ for subjects with chronic low back pain and $\alpha = 1.76$ for subjects with chronic fatigue syndrome. This indicates that the sedentary time of subjects with chronic diseases and sedentary occupation is made up of a larger proportion of long sedentary periods compared to healthy subject with active occupation. This was confirmed by the fact that the median bout length was also higher for groups with sedentary occupation and chronic diseases.

The healthy active subjects had a distribution exponent $\alpha > 2$ which implies that there is some form of underlying organisation of their sedentary behaviour with sedentary periods fluctuating around a mean value ~45 min. The sedentary workers (Hs) had $\alpha < 2$ which reflects a loss of this characteristic mean. This might be interpreted as a loss of ability for the Hs subjects to control their sedentary behaviour. Sedentary workers have imposed periods of sedentary behaviour by their occupation but healthy active workers do not have such a strong regulation and they are freer to choose favoured rest periods. Similarly pain for LBP subjects and metabolism for CFS subjects might regulate sedentary behaviour rather than the individual freewill.

The GINI index ($G$) describes how the total sedentary time is accumulated using different sedentary bout lengths. This index was significantly different for all groups. The very high $G$ index for CFS and

**Table 2**
Estimates of the characteristic exponent $\alpha$ of sedentary bout distribution and its standard error $\sigma$, median of the distribution $x_{1/2}$, percentage contribution to the total sedentary time by bouts of length greater than the median $W_{1/2}$ and GINI index $G$ for the group studied.

| Group | Exponent $\alpha$ | Standard error $\sigma$ on $\alpha$ | Median $x_{1/2}$ (min) | (%) | $G$ |
|---|---|---|---|---|---|
| Healthy active (Ha) | 2.27 | 0.021 | 17.3 | 71.5 | 0.35 |
| Healthy sedentary (Hs) | 1.95 | 0.022 | 20.7 | 76.1 | 0.40 |
| Chronic low back pain (LBP) | 1.80 | 0.030 | 23.8 | 92.7 | 0.74 |
| Chronic fatigue syndrome (CFS) | 1.76 | 0.034 | 24.9 | 95.4 | 0.77 |

LBP groups suggest that these subjects seem to adopt a boom-bust behaviour with sedentary time mostly made of very long rest periods. On the other hand healthy active subjects seem to break sedentary time into a larger number of periods of different length.

Our results seem in agreement with Healy et al. [21] who found more numerous breaks in sedentary periods in subjects with better health status.

Finding that sedentary bouts are distributed as a power law was not entirely surprising as this type of distribution are common in many physiological signals [33] such as hear rate variability and gait stride length and time variability. This is generally interpreted as a sign of complexity and of some underlying fractal or self-organising dynamics [34]. However, there are many possible ways that power law distributions can emerge [31]. Understanding the mechanism that lead to these power law distributions for sedentary periods might be important to explain the mechanism leading to different sedentary behaviours.

The simplest possible explanation is that it emerges from an inverse relationship. Indeed if we consider the probability $P(x > X)$ to fit a sedentary bout of length $x$ into a remaining available time window $t$, it will be inversely proportional to $t$. Hence, $P(x \le t) \sim t^{-1}$. This would lead to a probability density function of the form $p(x) \sim C\,x^{-\alpha}$, with $\alpha = 2$ which is close to what is found for healthy active subjects.

This study suggests that the exponent of the distribution of sedentary bout length $\alpha$ and the $G$ index that quantify the pattern of sedentary time accumulation could be very valuable outcome measures of change in sedentary behaviour. Detailed study of the distribution of sedentary bouts and its accumulation might help understand sedentary behaviour as argued by Hamilton et al. [6] and its link to health risks as suggested by Healy et al. [21].

## 6. Conclusion

This paper develops a novel generic technique for analysis objectively measured sedentary behaviour that minimise a priori assumption. This technique enabled the quantification of the pattern of accumulation of sedentary time using statistically robust parameters. This study found evidence that sedentary bouts are power law distributed and that this pattern is modified by occupation and disease with total sedentary time being insensitive to these differences. This study suggests that the sedentary bout distribution parameters and quantification of pattern of accumulation of sedentary time using $G$ could be used as powerful outcome measures for studying sedentary behaviour and its association with health.

## Conflict of interest

Professor Malcolm Granat is a coinventor of the activPAL physical activity monitor and a director of PAL Technologies Ltd.

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