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Quantifying sit-to-stand and stand-to-sit transitions in free-living environments using the activPAL thigh-worn activity monitor

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ABSTRACT

Purpose: Standing up, sitting down and walking require considerable effort and coordination, which are crucial indicators to rehabilitation (e.g. stroke), and in older populations may indicate the onset of frailty and physical and cognitive decline. Currently, there are few reports robustly quantifying sit-to-stand and stand-to-sit transitions in free-living environments. The aim of this study was to identify and quantify these transitions using the peak velocity of sit-to-stand and stand-to-sit transitions to determine if these velocities were different in a healthy cohort and a mobility-impaired population.
Methods: Free-living sit-to-stand and stand-to-sit acceleration data were recorded from 21 healthy volunteers and 34 stroke survivors using activPAL3™ monitors over a one-week period. Thigh inclination velocity was calculated from these accelerometer data. Maximum velocities were compared between populations.
Results: A total of 10,299 and 11,392 sit-to-stand and stand-to-sit transitions were recorded in healthy volunteers and stroke survivors, respectively. Healthy volunteers had significantly higher overall mean peak velocities for both transitions compared with stroke survivors [70.7°/s ± 52.2 versus 44.2°/s ± 28.0 for sit-to-stand, $P < 0.001$ and 74.7°/s ± 51.8 versus 46.0°/s ± 31.9 for stand-to-sit; $P < 0.001$]. Mean peak velocity of transition was associated with increased variation in peak velocity across both groups.
Conclusion: There were significant differences in the mean peak velocity of sit-to-stand and stand-to-sit transitions between the groups. Variation in an individual's mean peak velocity may be associated with the ability to perform these transitions. This method could be used to evaluate the effectiveness of interventions following injury such as stroke, as well as monitor decline in functional ability.

1. Introduction

The measurement and quantification of free-living physical behaviour using body-worn monitors has been fundamental to understanding how these behaviours are related to health [1,2]. The two major components of free-living physical behaviours, physical activity and sedentary behaviour, and their relationship to health outcomes have been extensively studied [3–5]. To date, there have been two main methods of assessing free-living physical behaviour: energy expenditure estimation and classifying postures [6–9]. It has been shown that it is possible to robustly classify the primary activity postures such as lying, sitting, standing and stepping, and quantify their patterns [2,4,10]. Using a posture-based approach, which clearly identifies the sitting and standing periods, it can be hypothesised that the transition between postures in the free-living condition can be evaluated and quantified.

Standing-up and sitting-down are the most common and physically demanding manoeuvres that an individual performs [11–14], and the ability to stand up and sit down is a key factor in the maintenance of functional independence. Any change in the capability to perform these transitions in older individuals could be useful in determining the onset of frailty and provide an indicator of physical and cognitive impairment [12,13,15]. For those groups of people who have mobility related conditions, such as a stroke, the recovery of the ability to stand up and sit down is crucial and quantification of the quality of these movements could be useful for monitoring progress of recovery. There is a wealth of research on these transitions when they are performed in the laboratory

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[8,15,16] but few studies have been performed quantifying the performance of these transitions in the free-living condition. Previous studies using accelerometers on the trunk and thigh have derived the duration of the sit-to-stand transition and have shown how it can be used to enhance our understanding of the performance of free-living activities of daily living [17–19]. This approach relied on the correct detection of the start and the end of the movement using the trunk sensor, which has been acknowledged as a limitation.

The activPAL [PAL Technologies Ltd, Glasgow, UK] is a small, lightweight, thigh-worn, accelerometer-based activity monitor that classifies postures of sedentary [sitting and lying], standing and ambulatory events. The activPAL has been validated against direct observation [7,17,20–22] and it has been shown that using the acceleration profile from the axial rotation of the thigh with device it is possible to discriminate between the activities of sitting and lying [23]. Therefore, we hypothesised that it would be possible to use the peak angular velocity of thigh rotation (derived from the device's acceleration data) during the transitions between sitting and standing as a means of quantifying these transitions in the free-living environment. It has been reported that using maximum velocity may be a more important measurement parameter of mobility-related activity and performance than acceleration [15,24].

The aim of this study was to quantify the sit-to-stand and stand-to-sit transitions using the peak angular velocity derived from the acceleration profile of the thigh, a potential relevant and "easy to measure" metric of "motor performance"; and then determine if this metric could be used to compare groups that differ in performance (for example a healthy cohort from a group of stroke survivors) and if this metric has the ability to show an age effect.

2. Methods

2.1. Participants

Accelerometer data collected using activPAL3™ (PAL Technologies Ltd, Glasgow, UK) were extracted from three previous physical activity studies. Data from stroke patients (n = 34) were taken from the study UKCRN15472, which was approved by the West of Scotland Ethics committee (13/WS/0150); all participants had provided written informed consent [25]. The stroke group comprised individuals with varied levels of mobility, and who were recently discharged from hospital (< 14 days) and still receiving daily rehabilitation input as part of their early supported discharge. Data from healthy participants (n = 21) were taken from one study of staff and students from the University of Salford (n = 12), and from the "Salford Exercise for All" study in healthy adults (n = 9). All participants provided written informed consent, and ethical approval for both studies was granted by the Ethics Committee of the School of Health Sciences, University of Salford.

2.2. Data collection of free-living physical behaviour

For all participants, free-living activity data were collected using the activPAL3™ activity monitor. The monitor was placed on the upper anterior aspect of the thigh and secured using PAL Stickies™ and medical grade adhesive (Fig. 1A). The alignment of the accelerometer axes is shown in Fig. 1B. The rotation of the accelerometer during sit-to-stand transitions was about the y-axis (Fig. 1C). Data were recorded continuously over a one-week period at a sampling frequency of 20 Hz.

2.3. Analysis of accelerometer data

Raw accelerometer data were downloaded from the activPAL3™. Sit-to-stand and stand-to-sit transitions were identified using proprietary algorithms from PAL Technologies Ltd, and then manually checked. These algorithms generated data files of six seconds in length centred on the transition, containing raw acceleration data from all three orthogonal axes.

Following the identification of sit-to-stand and stand-to-sit transitions, the data were analysed using an autoregressive power spectral density estimate (Burg's method) to identify an appropriate cut-off frequency for low-pass filtering. This method of parametric analysis is better suited to shorter segments of signal analysis. This signal power analysis found that using a zero-phase low-pass 1 st order filter with a cut-off frequency of 0.18 Hz had a frequency response which would attenuate the signal amplitude by half during (removing 'noise') without significantly affecting these raw accelerometer data. This was then applied to all these accelerometer data signals.

To calculate the thigh inclination during these transitions from, the three axes were first combined, $Pitch\ (p) = tan^{-1}(X\ /\ \sqrt{Y^2+Z^2})$ [Equation 1], where X, Y and Z are the acceleration vectors of the orthogonal axes [26]. This algorithm was implemented using custom written scripts in MATLAB (version 8.6) and applied to the filtered accelerometer data containing the sit-to-stand and stand-to-sit transitions.

Angular velocity was calculated as the difference in angle between adjacent data points, divided by the time interval between data points (0.05 s). For each transition the peak angular velocity was identified.

2.4. Statistical analysis

Transition data for thigh inclination and thigh angular velocity are presented as mean ± standard deviation (SD). Histogram frequencies of peak angular velocities are presented as normalised counts. Mean and SD of all peak angular velocities were calculated for the two transitions for all individuals. An average mean (with a SD) and an average SD (with an SD) for the two transitions of both groups were then calculated. Inter-group differences between the healthy and stroke groups for both peak angular velocities and for the SDs of peak angular velocities for individuals were compared using Mann-Whitney U Test (to compare differences between the two independent groups when the dependent variable is considered to be not normally distributed); the statistical level of significance was set at $\alpha_2 = 0.05$.

2.5. Preliminary data collection and analysis

To determine the level of validity of the peak angular velocity algorithm used in this study, the peak angular velocity of the thigh, as derived from the accelerometer data (described above), was compared with peak angular velocity as derived from data collected using a Vicon motion tracking system (Oxford Metrics Ltd., Oxford, UK). For this, a subset of seven participants from the stroke group were invited to a laboratory setting to repeat five sit-to-stand movements while wearing the activPAL3™ activity monitor (placed on the upper anterior aspect of the thigh, as described above). The sit-to-stand and stand-to-sit transitions movements were simultaneously recorded using a 12-camera Vicon system at a sampling rate of 100 Hz to track the 3D motion of 13 body segments from retro-reflective markers placed on each major body segment (whole body Plug-in-Gait model).

A Bland-Altman analysis [27,28] was used to determine the level of agreement between the peak angular velocities calculated from the activPAL3™ data and the peak angular velocities calculated using the Vicon data. These data demonstrated strong agreement between the activPAL3™ and Vicon system for the peak angular velocities of the recorded transitions. The mean difference (Vicon data - activPAL3™ data) for the maximum velocity measurement was 0.97°/s (± 7.15 SD), and the 95% limits of agreement ranged from -13.04°/s to 14.98°/s. Though there is some variability in the level of agreement between these two measurement techniques this nevertheless did not affect the sensitivity and specificity of the peak angular velocity algorithm in correctly determining the transition between these activities.

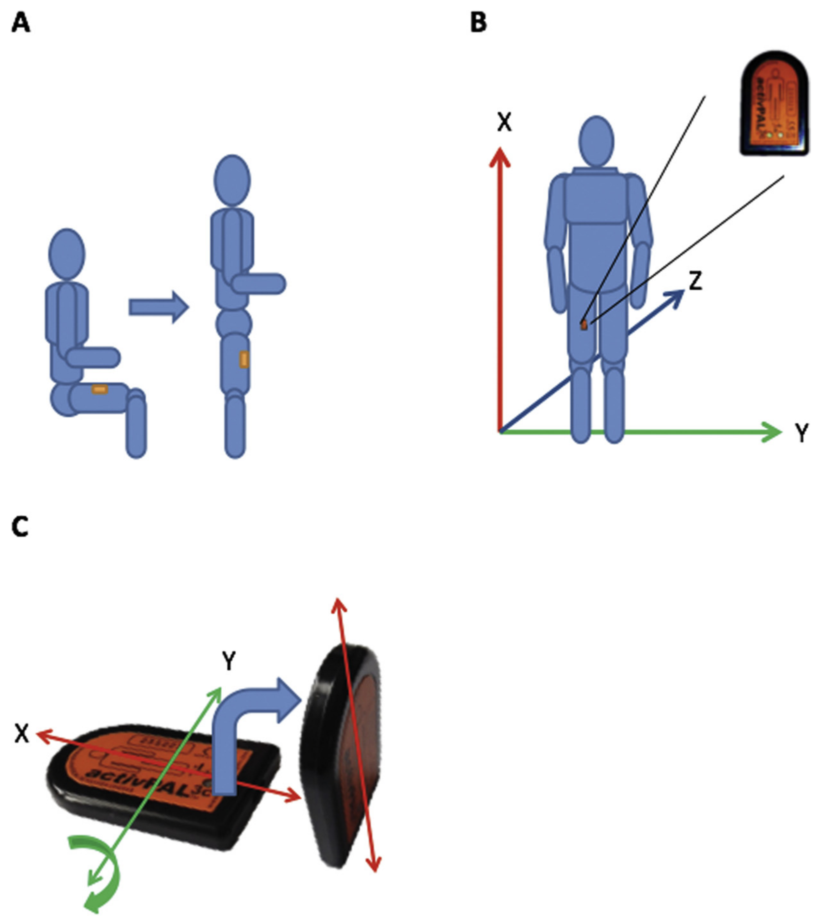

Fig. 1. Positioning and typical transitions using the activPAL3™ activity monitor. (A) Illustration of a sit-to-stand transition indicating location of the activPAL™ on the thigh. (B) Labelling of the axes and alignment on the thigh. (C) Rotation of the activPAL3™ corresponding to a sit-to-stand transition.

3. Results

3.1. Participant details

Stroke participants (18 males and 16 females) had a mean age of 68.9 ± 11.8 years (range, 48–89 years), with mean height 1.67 ± 0.2 m, and mean weight 73.1 ± 18.6 kg. Healthy participants (10 males and 11 females) had a mean age of 61.0 ± 10.1 years (range, 42–85 years). Data collected for the healthy group involved 4970 sit-to-stand and 5484 stand-to-sit transitions and for the stroke group involved 5329 sit-to-stand and 5908 stand-to-sit transitions.

3.2. Peak angular velocity of transitions

The healthy group had a significantly higher overall mean peak angular velocity for both transition types than the stroke group (Fig. 2A–D) [70.7°/s ± 52.2 versus 44.2°/s ± 28.0 for sit-to-stand, and 74.7°/s ± 51.8 versus 46.0°/s ± 31.9 for stand-to-sit; $P < 0.001$ for both transition types]. In addition, the standard deviations of the peak angular velocities for each transition was significantly higher in the healthy group than the stroke group (52.2°/s [healthy] versus 28.0°/s [stroke] for sit-to-stand, and 51.8°/s [healthy] versus 31.9°/s [stroke], for stand-to-sit; $P < 0.001$ for each transition type).

3.3. Distribution of peak angular velocities

Fig. 3A shows the peak angular velocity data for the healthy group and the stroke group. The healthy group had a median sit-to-stand peak angular velocity of 41.4°/s (range, 0°–350°) compared with a median of 20.6°/s (range, 0°–350°) for the stroke group. The distribution of peak angular velocities for the stroke group was broader and was also more positively skewed. Similar findings were observed for the stand-to-sit transitions, where peak angular velocities for the stroke group were more tightly distributed than those of the healthy group, although to a lesser extent than for the sit-to-stand transition. The median peak angular velocity for stand-to-sit for the healthy group was 100.2°/s (range, 0°–350°), compared with 67.3°/s (range, 0°–350°) for the stroke group (Fig. 3B).

The peak angular velocity values for all transitions, for each individual, were extracted. The mean and standard deviations of these were calculated and results were ordered by age (Fig. 4**)**. For both the healthy and stroke groups, peak angular velocities showed a downward trend with increasing age for both the sit-to-stand and stand-to-sit transitions. In addition, increased peak angular velocity of transition was associated with increased variation in peak angular velocity for both transitions, in both groups (Fig. 4). The overall mean peak angular velocity of all individuals was significantly higher in the healthy group compared with that of the stroke group, for both transitions (90.1°/s ± 14.0°/s versus 56.5°/s ± 15.3°/s, for sit-to-stand, and 39.1°/s ± 11.3°/s versus 13.6°/s ± 8.8°/s for stand-to-sit, respectively; $P < 0.001$ for each transition type). When comparing the spread of values within the healthy group with that of the stroke group, there were no significant differences.

4. Discussion

To our knowledge, this is the first study to report on the quantification of the sit-to-stand and stand-to-sit transitions in the free-living

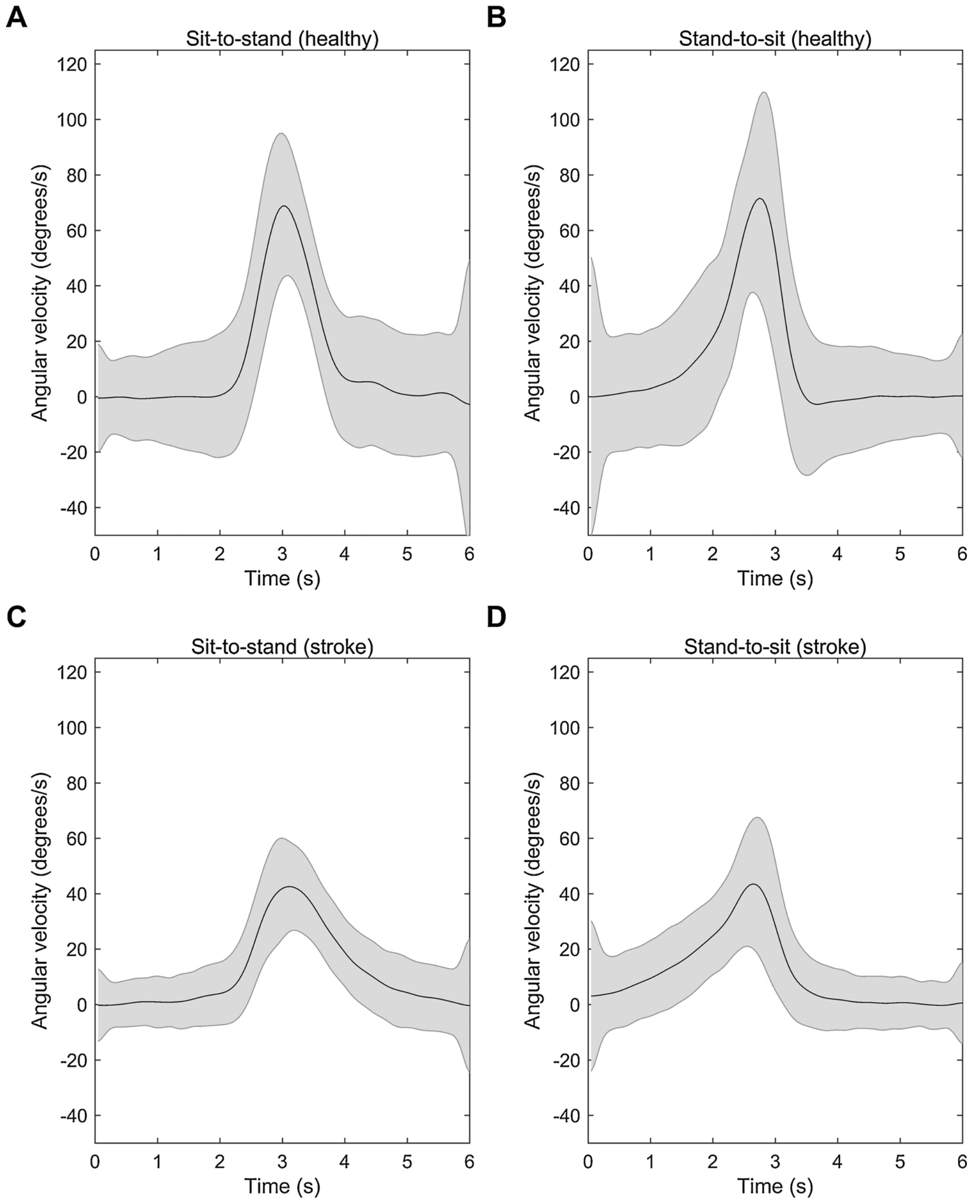

Fig. 2. Thigh angular velocity profiles comparing healthy and stroke individuals. The black line shows the mean of the mean transition profile per individual for healthy individuals, and stroke individuals. Grey band shows standard deviation of the mean of all individuals.

environment using the inclination of the thigh. In this study, both the sit-to-stand and stand-to-sit transitions were quantified using the peak angular velocity. It has been previously shown the duration of the sit-to-stand transition can be quantified using a trunk worn and two thigh-worn sensors [17–19], which depended on determining the start and the end of movement. This has been acknowledged as being difficult [18], and in addition there can be movements of the trunk that are preparatory movements at the start of these transitions. The main part of the sit-to-stand transition is when the body begins to rise and the thigh leaves the chair, and using peak angular velocity of the thigh as a measure of the speed of the movement removes any uncertainties in the determination of the start and end of the movement.

In the stroke group, both the sit-to-stand and stand-to-sit transitions were performed considerably more slowly than in the healthy group (Fig. 2). For stroke survivors, these transitions are challenging and the factors determining these differences have been previously described, and are related to the impairment of lower limb muscles and impaired postural control [29]. These free-living profiles also demonstrated that the stroke group carried out these transitions with a lower degree of variability than the healthy group, there being a low distribution in peak angular velocities (Fig. 3).

The healthy group had a larger peak angular velocity and a greater variation in peak angular velocity for these transitions than the stroke group. This observation could indicate that the healthy group was more able to vary the way in which they performed these transitions. This could be due to motivational circumstances as well as the physical environment, such as the use of a range of different seats.

Subjects in the stroke group who had a low mean peak angular velocity also had a low variation in peak angular velocity (Fig. 4). We postulate that a reduction in mean peak angular velocity, and a low inter-transition variation in peak angular velocity, could be an indicator of impairment for an individual. For the stroke group, the data suggest a more controlled sit-to-stand manoeuvre, and perhaps a more controlled movement back into a chair during the stand-to-sit transition.

The sit-to-stand transition is arguably the most demanding of all free-living physical activities, particularly for the older and more frail population [30], and it has received relatively little attention in the physical activity literature [8,15,16]. The quantification of sit-to-stand

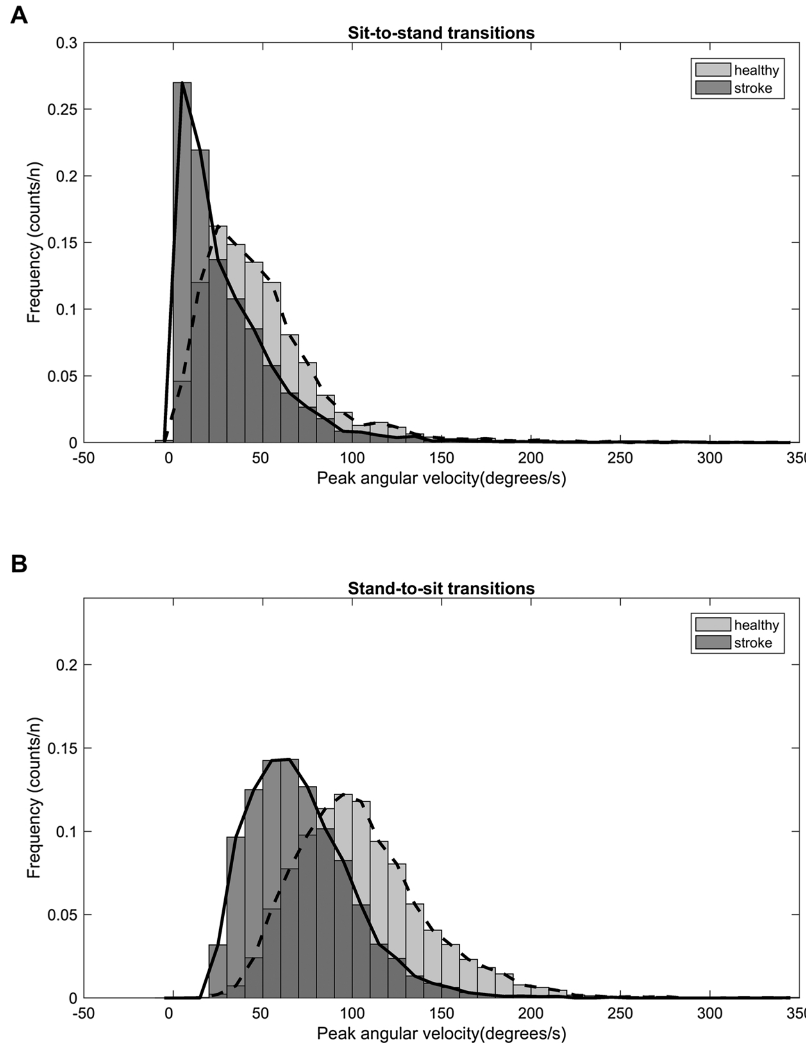

Fig. 3. Peak angular velocity frequency histogram of sit-to-stand and stand-to-sit transitions comparing healthy and stroke individuals. Healthy subject group data (light grey) and stroke subject group data (dark grey). These data are normalised so the height of each bar is the relative number of observations in each observation bin divided by the total number of observations.

and stand-to-sit transitions greatly enriches the information from free-living physical behaviour monitoring and may provide a link between the complexity of free-living physical behaviour and how it relates to health. The present study compared a healthy group with a stroke group, known to have motor impairments that affect the ability to perform sit-to-stand and stand-to-sit transitions. In this study, evaluation of accelerometer data from these important postural transitions showed significant differences between the two groups in terms of peak angular velocity and variation of peak angular velocity. The quantification of changes in physical capability could be a useful outcome measure for both rehabilitation post injury and for measurement of the effectiveness of interventions to improve mobility in frail elderly populations. As a person ages, their physical performance declines and this is more related to a reduction in muscle power rather than muscle strength [31]. Peak muscle power is a strong predictor of self-reported functional status in sedentary elderly community-dwelling women [32]. Given that the sit-to-stand transitions are probably the only manoeuvre in the free-living environment where peak muscle power is regularly needed [33], the quantification of these transitions might provide an insight into the change in functional status. Notably, in the present study, peak angular velocity generally showed a downward trend with increasing age, although this trend was more pronounced at the higher age bracket. In fact, the eldest individual in the healthy group had a higher sit-to-stand peak angular velocity than some of the youngest individuals in the stroke group (Fig. 4); this observation suggests that age is not the determining factor for peak angular velocity, and the nature of the co-morbidity or injury may be a much more important contributing factor.

This study used a thigh-worn accelerometer-based activity monitor, the activPAL3™, and was dependent only on the measurement of the inclination of the thigh. In addition to using only one sensor, this approach does not rely on trying to determine the start and end of the transitions. A further strength of this approach is that this technique can be retrospectively applied to data collected using the activPAL3™, and could be adapted to any accelerometer-based activity monitor worn on the thigh. It is acknowledged that this study had some limitations. Firstly, the data were drawn from two different sources with differences in demographics, although this would not have affected the performance of these transitions in the free-living environment. In addition, in the stroke group, we did not look at the use of assistive devices, such as walking aids, and we were also unable to look at the use of upper-limb involvement. The validation of the peak angular velocity output was performed on a seven stroke subjects and in further applications this aspect it might be worthwhile undertaking further validation work.

Further work should focus on how the peak angular velocities of these postural transitions could be used to describe the change in functional capacity of individuals. It could also be used to look at differences between clinical populations and could also be used to

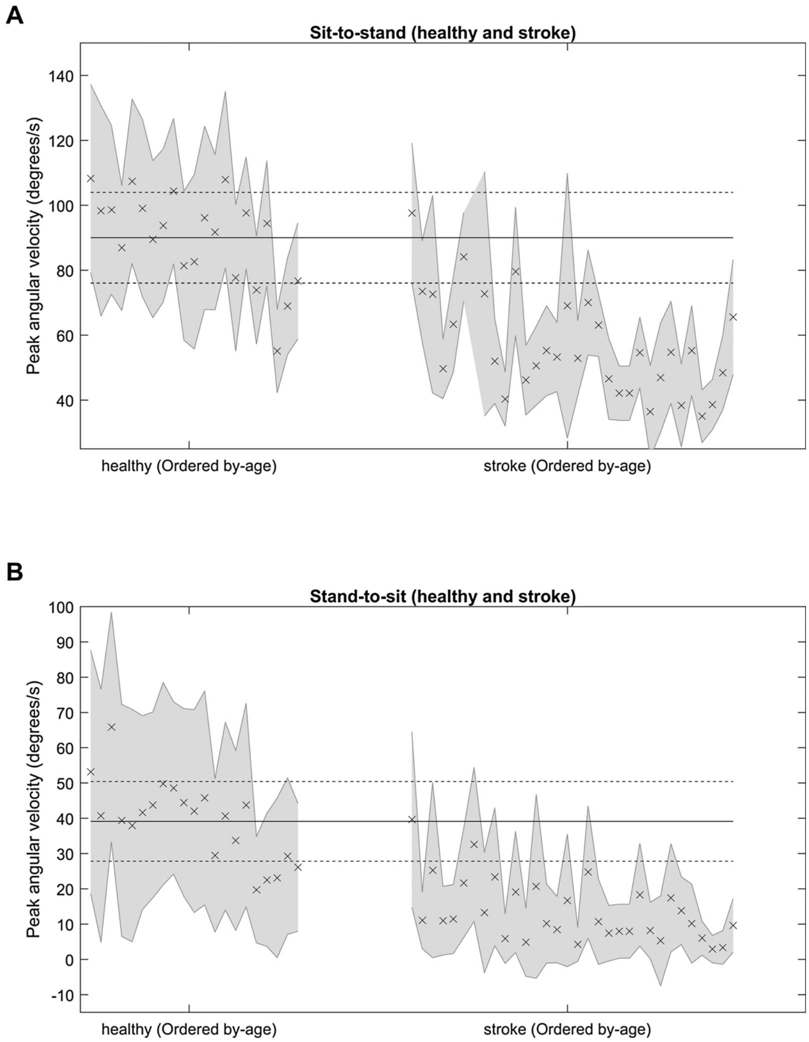

Fig. 4. Peak angular velocity plot comparing control and stroke groups. These data show mean peak angular velocities per individual (± SD shaded grey), based on the average of the actual peak angular velocity values for each transition performed by each individual. Mean and SD for the control group are shown as horizontal lines (solid black, and dashed, respectively). Data represent the mean peak angular velocity of the transitions. Data are arranged in ascending age order. SD, standard deviation.

quantify the effectiveness of a range of interventions for both attenuation of physical decline and for rehabilitation. Given that these measures are related to the ability to perform the most common challenging free-living physical activity involving the largest muscle groups in the body, the use of these measures might also be able to help quantify frailty [34].

In conclusion, this study has demonstrated that sit-to-stand and stand-to-sit transitions can be quantified in the free-living environment using thigh inclination. In addition, quantification of these postural transitions could be used to identify differences between a healthy and a mobility-impaired population. This study therefore provides additional physical behaviour information that could be used to quantify impairment and monitor age-related changes. The combination of peak angular velocity and variation in peak angular velocity could provide novel outcomes for rehabilitation, such as for assessing rehabilitation progress post stroke, and to assess the effectiveness of such interventions for long-term recovery [35].

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Declaration of Competing Interest

MHG is a co-inventor of the activPAL3™ physical activity monitor and a director of PAL Technologies Ltd. The remaining authors declare no competing interests.

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