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# Wireless Accelerometry is Feasible in Acute Monitoring of Upper Limb Motor Recovery after Ischemic Stroke

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**Key Words**
Stroke · Acute ischemic stroke · Accelerometry · Monitoring · Acute stroke management

**Abstract**
***Background:*** Clinical deterioration in the acute stage of ischemic stroke powerfully predicts outcome and may serve as a marker for urgent intervention. However, accurate monitoring of acute stroke patients is hampered by the lack of validated continuous monitoring devices. We sought to assess the use of wireless accelerometry in this setting, hypothesizing that stroke patients would have a greater difference in movement between upper limbs than controls and that the magnitude of correlation between upper limb movements would be negatively associated with the National Institutes of Health Stroke Scale (NIHSS) score. ***Methods:*** In this pilot study, 20 patients with acute ischemic stroke and unilateral upper limb weakness and 10 controls were recruited from a comprehensive stroke centre. All subjects were fitted with two 3-axis accelerometers and underwent 24 h of continuous accelerometry recording of upper limb movements and repeat NIHSS assessments. The intra-class correlation coefficient (ICC), assessing the similarity (or otherwise) of spontaneous movements in each arm was calculated. The association between NIHSS (total and motor subset scores) and the magnitude of ICC was estimated by Spearman's rank correlation, receiver-operating characteristic curve analysis was performed and the optimal diagnostic threshold value of ICC was calculated. ***Results:*** The magnitude of the ICC was significantly associated with the baseline NIHSS score ($p = 0.02$) and non-significantly associated with the baseline NIHSS motor score ($p = 0.08$). At the optimal diagnostic threshold of ICC magnitude = 0.7, wireless accelerometry distinguished patients from controls with a sensitivity of 0.95, a specificity of 0.6 and a diagnostic odds ratio of 28.5. ***Conclusions:*** The wireless accelerometry system successfully detects a motor deficit in the setting of acute ischemic stroke, accurately differentiating patients from controls, and correlates well with the baseline NIHSS score. Its use is feasible in the acute stroke setting. Overall, it shows promise as a diagnostic tool to continuously monitor acute stroke patients but requires validation in a larger trial.

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## Introduction

Since the publication of the landmark NINDS trial in 1995 [1], intravenous thrombolysis with tissue plasminogen activator (IV-tPA) has significantly altered the treatment approach to stroke. IV-tPA improves clinical outcomes after acute ischemic stroke [1, 2], but requires rapid and cohesive management of patients to maximize benefit. It is recognized that the acute clinical course after thrombolysis predicts longer-term functional status [3]. Between 18 and 35% of patients demonstrate rapid motor recovery within 2 h of IV-tPA, leading to a high proportion of good outcomes at 3 months [3–5]. Conversely, those patients who deteriorate or fail to improve in the acute stages after thrombolysis have a poor prognosis; this group may require urgent investigation and intervention [6–8].

Whilst the trajectory of acute recovery therefore predicts the outcome following stroke, continuous monitoring of this recovery is currently problematic. The National Institutes of Health Stroke Scale (NIHSS) is the most commonly used measure in the acute stroke setting, but it is not ideally suited to intensively monitoring a patient. It is labour intensive, reliant on patient cooperation and subject to significant inter-rater variability [9]. Furthermore, it is a single time point assessment rather than a continuous measure. This is particularly relevant because motor symptoms can fluctuate or change trajectory [7]. The implication is that a single time point assessment may miss the overall trajectory of a patient's clinical course in this acute period.

Wireless accelerometry-based systems allow objective, continuous, standardized recording of body movement. The utility of accelerometry in measuring movement is well established in the exercise field, where recordings from a triaxial accelerometer system correlate well with the energy expenditure of a limb [10]. The use of accelerometry is increasing in different areas of neurology, including Parkinson's disease [11], epilepsy [12] and dementia [13]. Within the stroke field, accelerometry has been used to assess long-term functional recovery, to aid rehabilitation and to predict long-term outcomes [14]. However, its use in the acute stages of stroke as an aid to guide management has, to our knowledge, never been reported.

We have developed a wireless accelerometry system [15], and we aimed to investigate the utility of this device for intensively monitoring the motor function of the affected upper limb in the acute period following ischemic stroke. In the first phase of the project, we aimed to demonstrate that accelerometry can accurately differentiate between stroke and control subjects. We therefore hypothesized that the magnitude of the correlation between the left and right arm movements over a period of time is associated with the NIHSS score and could successfully distinguish between stroke and control subjects.

## Methods

A total of 20 patients with acute ischemic stroke (confirmed by clinical and radiological assessment) and weakness in at least a single arm were recruited within 48 h of presentation to a comprehensive stroke centre in Melbourne, Australia, between August 2011 and February 2012. Patients who were unable to consent, required intensive care admission or had suffered haemorrhagic stroke were excluded; 10 controls without stroke or underlying upper limb motor impairment were recruited from patients within the same hospital. Subjects were assessed by an NIHSS-accredited neurologist at baseline and at 1, 2, 4 and 24 h, and the corresponding NIHSS total and arm motor score was obtained at these time points. Demographic data were collected, and stroke subtype was classified as per the Oxfordshire stroke classification system criteria [16].

All subjects were fitted with two 3-axis accelerometers (one on each wrist), model Crossbow Imote2 (fig. 1). Accelerometry data were recorded continuously for the first 4 h from baseline, and then for 1 h at 24 h from baseline. The accelerometer output was collected using a wireless sensor node and transmitted to a (remote) base station. Data were collected at a sampling frequency of 100 Hz and transmitted to the base station 3 times per second. At the base station the data were pre-processed using a high-pass filter and aggregated over sequential 10-min intervals using 1,024-point fast Fourier transformation with a maximum power measure [for details, see Gubbi et al. 15]. This maximum power measure represents the highest activity for arm movement recorded during each 10-min interval. For each patient, over the whole data collection period, this resulted in a time-matched series of power readings for both arms.

To quantify the overall difference in arm movements in a given patient over the whole observation period, taking into consideration the longitudinal nature of the data, an intra-class correlation coefficient (ICC) of this time-matched series of power readings for both arms was estimated for every patient, using the ICC calculation ICC(3,k).

The association between baseline NIHSS (both total and motor score) and the magnitude of ICC within the stroke group was assessed by Spearman's rank correlation using Stata/IC version 12 statistical software.

Receiver-operating characteristic (ROC) curve analysis with the absolute value of subject-specific ICC as a diagnostic variable was utilized to distinguish between stroke and control subjects. Corresponding values for sensitivity, specificity, positive and negative predictive values, and diagnostic odds ratios were calculated. To maximize the correct classification rate, the optimal diagnostic threshold value was calculated using the maximum Youden index (sensitivity plus specificity minus one) and further validated by fitting separate normal distribution curves to patient and control ICC values and choosing the threshold that was 1 standard deviation larger than the midpoint between the means of the resulting distributions. The analysis was performed using MATLAB vR2012b software on a laptop with 4GB RAM and an Intel i7 processor with MySQL database.



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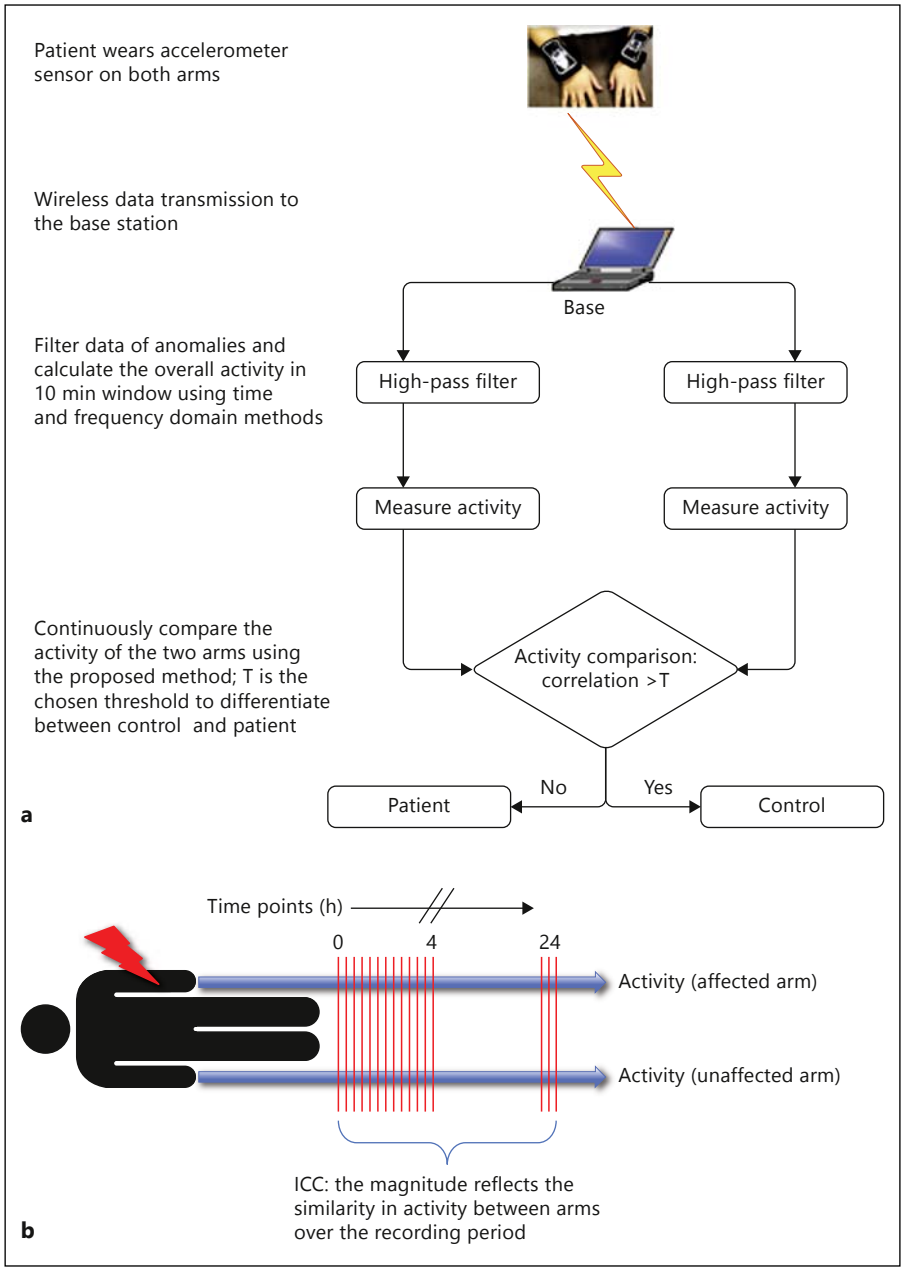


**Fig. 1.** Schematic drawing of the accelerometry recording process (**a**) and calculation of the ICC (**b**).

The research protocol was approved by the Royal Melbourne Hospital Human Research Ethics Committee (2010.245). Consent was obtained from all subjects.

## Results

The median age was 77 years in the patient group (interquartile range, IQR, 59–82) and 64 years in the control group (IQR 48–71). The patient group had a higher ratio of males than the control group. Overall stroke severity was mild-to-moderate in the patient group, with a median NIHSS score of 5.5 (IQR 3–9). 75% of patients were recorded within 4 days of symptom onset. Of the 20 ischemic strokes, 19 involved the anterior circulation (with 11 affecting the right hemisphere and 8 the left hemisphere) and 1 involved posterior circulation (table 1); 15 of the anterior circulation strokes involved cortical regions and 4 were lacunar.

There was a significant association between the baseline NIHSS score and the magnitude of ICC (Spearman's



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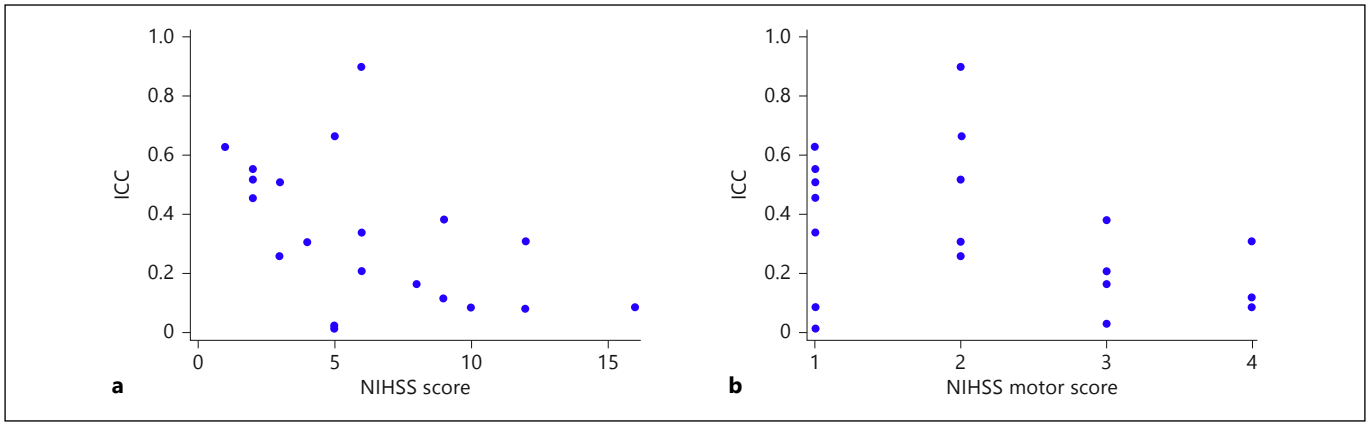


**Fig. 2.** Scatter plots showing ICC magnitude vs. NIHSS score at baseline (**a**) and NIHSS motor score (**b**). There is a significant negative association (p = 0.02) between NIHSS score and ICC magnitude, with higher NIHSS score associated with a lower magnitude of ICC (i.e. greater difference in activity between the affected and unaffected limb) and a trend towards negative association between NIHSS motor score and ICC magnitude, with higher motor NIHSS score associated with a lower magnitude of ICC.

**Table 1.** Subject demographics and stroke characteristics

| | Patient | Control |
|---|---|---|
| Number | 20 | 10 |
| Median age, years | 77 (59–82) | 64 (48–71) |
| Sex (M/F) | 11/9 | 2/8 |
| Right-handed, % | 100 | 100 |
| Median NIHSS total score | 5.5 (3–9) | 0 |
| Median NIHSS motor upper limb score | 2 (1–3) | 0 |
| Median time from stroke onset, h | 54 (47–100) | NA |
| Stroke subtype, n | | NA |
| TACI | 5 | |
| PACI | 10 | |
| POCI | 1 | |
| LACI | 4 | |
| Arm affected (R/L) | 9/11 | NA |

Values in parentheses are IQR. Age: p value for age was 0.11 (Student's t test assuming unequal variances). Handedness: information on handedness was not available for 2 controls and 4 patients. Stroke subtype: Oxfordshire stroke classification system. TACI = Total anterior circulation infarct; PACI = partial anterior circulation infarct; POCI = posterior circulation infarct; LACI = lacunar infarct; NA = not applicable.

Rho = –0.53, p = 0.02), with a greater stroke impairment being associated with lower absolute values of ICC (fig. 2). A similar analysis of the association between baseline NIHSS motor score (0–4) and magnitude of ICC did not quite achieve statistical significance (Spearman's Rho = –0.4, p = 0.08; fig. 2).

The optimal diagnostic threshold for ICC magnitude was 0.7. At this threshold, ROC curve analysis using the ICC magnitude to distinguish stroke patients from controls yielded an AUC of 0.84 (fig. 3). Utilizing this threshold distinguished patients and controls, with a sensitivity of 0.95, a specificity of 0.6, a positive predictive value of 0.83 and a negative predictive value of 0.86. The diagnostic odds ratio at this threshold was 28.5.

## Discussion

We have shown in this pilot study that a wireless accelerometry system can detect a motor deficit in the setting of acute stroke and can accurately differentiate stroke subjects from controls. We have also found an association between the ICC magnitude (calculated from a 24-hour period of monitoring) and severity of stroke at baseline (measured by the NIHSS), further validating the ICC measure. Finally, we have demonstrated the feasibility of using accelerometry in the acute stroke setting, which is particularly relevant given that wireless accelerometry may be used to monitor these patients and ultimately inform treatment decisions.

The diagnostic use of the ICC to differentiate between stroke patients and controls was our primary outcome measure. This analysis is an important validation step. The magnitude of ICC is derived from a comparison of motor activity in a subject's upper limbs. An absolute value of ICC = 1 suggests that both limbs show an equal degree of activity, whilst a lower ICC indicates greater asym-



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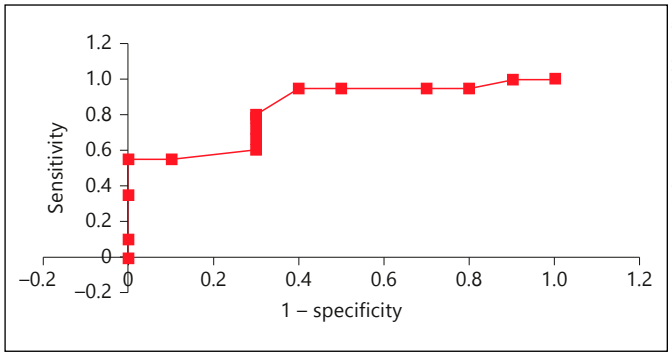


**Fig. 3.** ROC analysis of the ICC magnitude at diagnostic threshold steps of 0.05. The AUC is 0.84. A diagnostic threshold of 0.7 yields a sensitivity of 0.95 and a specificity of 0.6.

metry. Hence, we would expect a subject with no weakness to have an ICC magnitude close to 1, whilst severe (unilateral) weakness would be closer to 0. Because of intrinsic fluctuations in activity an ICC of 0.7 (rather than higher) proved to be the best diagnostic threshold, with a sensitivity of 0.95, a specificity of 0.6 and a diagnostic odds ratio of 28.5. Overall, this technique proved effective at differentiating between the two groups, with the main error rate occurring in misclassifying some controls as patients.

We also examined how the ICC varied depending on stroke severity. We showed a significant association between NIHSS total score and ICC magnitude, with a lower ICC magnitude observed in more severe strokes (fig. 2a). This result is consistent with a previous study which correlated the NIHSS total score with differences in accelerometry (actigraphy) measures during the acute phase of stroke [17] and further validates the use of this technique in the acute setting. We hypothesized that the ICC magnitude would also be associated with the motor severity subsection of the NIHSS. Although this data could be interpreted as showing a trend (fig. 2b), statistical significance was not reached ($p = 0.08$). Intuitively, it seems logical that asymmetry in movements would be greater with greater unilateral weakness, and we suspect that the failure to reach significance is related to the low power of this pilot study – larger numbers are likely to be needed to demonstrate this association. Additionally, we were comparing the baseline NIHSS motor score to accelerometry data derived over the subsequent 24 h. In some patients there was a change in motor score (improvement or deterioration) which would have influenced the final ICC but was not reflected in their initial NIHSS motor score. However, the small numbers in this study limited our ability to investigate this further. We plan to conduct a larger study that will allow us to analyse how the ICC correlates with a patient's motor weakness over time, with the goal of validating accelerometry as a continuous measure of limb power in the acute stroke period.

The majority of patients in this study had their wireless accelerometry recorded within 4 days of symptom onset, and generally within 24 h of presentation to hospital. The process of attaching the accelerometers and collecting data was straightforward, taking less than 5 min to set up, and did not interfere with patient care. We initially monitored each patient continuously for 4 h, as this is a realistic 'window' during which stroke management decisions may be changed in the acute setting and because current battery life will not extend for a full 24 h (we envisage this will lengthen in subsequent accelerometer models). Stroke severity was mild-to-moderate in this cohort and patients displayed an expected range of stroke territory distribution, given that arm weakness was a criterion for inclusion. One clear limitation of the study is that no patients were monitored within the first 6 h of their stroke, which is likely to be the critical time to identify non-responders to thrombolysis. Although this was beyond the scope of our pilot study and will be the focus of a future project, based on our experience in this study we believe this goal of early monitoring is feasible.

The ability to intensively monitor neurological motor recovery in the acute stroke setting is likely to be critical in guiding management decisions. The trajectory of recovery in the initial hours following stroke correlates with long-term outcome [3]. Rapid recovery is associated with a better outcome at 3 months. The odds of these patients experiencing a good functional outcome is approximately 7 (modified Rankin scale, mRS, 0 or 1) compared to those who do not have a rapid recovery [3, 5]. An analysis of the NINDS tPA data set revealed that only 32.5% of patients without early improvement achieved an mRS of 0 or 1 at 3 months compared to 60.7% of patients who showed early improvement [3]. Felberg et al. [8] found that in patients with middle cerebral artery territory ischemic stroke, those who had not shown a dramatic recovery by the end of their tPA infusion had a median 3-month mRS of 4 compared to an mRS of 1 in those who did show such a recovery. Early identification of the absence of rapid motor recovery will therefore be increasingly important, as it is likely that this is the group who stand to gain the most from early adjunctive therapies, such as endovascular clot retrieval, if this is validated by ongoing phase III trials.

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Currently, stroke unit care is hampered by a lack of continuous monitoring of function. Accelerometry offers many advantages in monitoring acute stroke recovery. It is an objective, continuous measure, and the data output can be displayed on a screen at the patient's bedside or a central station, allowing easy tracking of a patient's progress (or otherwise). The method still has some drawbacks – it will not be effective in unconscious patients, and other conditions (e.g. an arm fracture following a fall) could also confound the analysis. However, these situations are rare. Correlation with NIHSS is not 100% accurate, but in the context of continuous monitoring a single measurement will be less important than a patient's overall trend – something which current, intermittent methods of assessing patients may fail to identify.

To conclude, this study has shown that a wireless accelerometry system can accurately distinguish acute stroke patients from controls and that the ICC is significantly associated with a patient's NIHSS score. It illustrates the feasibility of using this system to continuously monitor patients in the acute stroke setting and opens the way for further trials in this area. Specifically, the system shows significant promise for identifying 'non-responder' patients, who may benefit from more aggressive re-intervention, as acute stroke management strategies attempt to emphasize individually tailored approaches.


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## Disclosure Statement

B.Y., M.P. and J.G. share a provisional patent on the accelerometry device.


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