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ORIGINAL REPORT

ARM IMPAIRMENT AND WALKING SPEED EXPLAIN REAL-LIFE ACTIVITY OF THE AFFECTED ARM AND LEG AFTER STROKE

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Objective: **To determine to what extent accelerometer-based arm, leg and trunk activity is associated with sensorimotor impairments, walking capacity and other factors in subacute stroke.**

Design: **Cross-sectional study.**

Patients: **Twenty-six individuals with stroke (mean age 55.4 years, severe to mild motor impairment).**

Methods: **Data on daytime activity were collected over a period of 4 days from accelerometers placed on the wrists, ankles and trunk. A forward stepwise linear regression was used to determine associations between free-living activity, clinical and demographic variables.**

Results: **Arm motor impairment (Fugl-Meyer Assessment) and walking speed explained more than 60% of the variance in daytime activity of the more-affected arm, while walking speed alone explained 60% of the more-affected leg activity. Activity of the less-affected arm and leg was associated with arm motor impairment ($R^2 = 0.40$) and independence in walking ($R^2 = 0.59$). Arm activity ratio was associated with arm impairment ($R^2 = 0.63$) and leg activity ratio with leg impairment ($R^2 = 0.38$) and walking speed ($R^2 = 0.27$). Walking-related variables explained approximately 30% of the variance in trunk activity.**

Conclusion: **Accelerometer-based free-living activity is dependent on motor impairment and walking capacity. The most relevant activity data were obtained from more-affected limbs. Motor impairment and walking speed can provide some information about real-life daytime activity levels.**

Key words: stroke; accelerometry; clinical research; rehabilitation; ambulatory monitoring; wearable technology; outcome assessment (healthcare); outcome measures.

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LAY ABSTRACT

Activity data from accelerometers can help clinicians to better understand factors limiting physical activity levels. This study aimed to determine to what degree arm, leg and trunk activity, measured with accelerometers, is associated with sensorimotor impairments, walking and other factors in people with stroke in the subacute stage of recovery. Real-life activity, measured by accelerometers, was primarily associated with motor impairment and walking speed. Spasticity, dependency in walking, and disability level also showed association with real-life activity, although to a lesser degree. Accelerometers, placed on the more-affected wrist and ankle, provided most relevant clinical information and are therefore recommended for research and clinical practice. The strong associations observed in this study suggest that when accelerometers are not available, clinical assessments of arm motor function and walking speed can provide some information on real-life activity levels in people with stroke.

Individuals with stroke spend approximately 70–80% of their daytime in sedentary activities, and, when active, their activity level seldom reaches moderate-to-vigorous levels of intensity (1–3). To better understand which factors limit activity levels, wearable devices for movement monitoring, such as accelerometers, can be used effectively (4–6). Interest in using wearable technology for quantification of activity and motor function in real-life activities after stroke is increasing within the field of neurorehabilitation (7–9), although application in clinical practice is sparse (7, 10, 11).

The Fugl-Meyer Assessment (FMA) is one of the most widely used clinical scales to assess sensorimotor function after stroke. The FMA has excellent psychometric properties (12, 13) and is commonly used as reference when validating new instruments. In addition to motor impairment, sensory function, spasticity, walking ability and speed are commonly assessed in clinical practice after stroke. In general, clinical assessments rely on therapists' observational skills, and the scoring is limited to predefined categories of the scale. Traditional clinical assessments provide a snapshot of how the patient is functioning at the time of testing, which does not always overlap with the real-life functioning in daily activities (7, 8). Here accelerometers can offer several advantages, by measuring movements and activity continuously over a defined period of time in free-living conditions, and providing an objective measure of motor functioning (9, 14). Such measurements are complicated by the fact that there are numerous different accelerometer

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devices available, the placement of devices differs, and the metrics obtained are diverse. To overcome this limitation, the use and reporting of accelerometer data in acceleration metrics (m/s^2) is advocated to allow comparison between systems, studies and conditions (10). Even though the number of studies using accelerometers is increasing, the validation of the obtained measures is critical for meaningful use in clinical research and practice (14, 15).

Moderate-to-strong correlations have been reported between accelerometer-based activity measures and FMA scores (16, 17) as well as Action Research Arm Test (18) among stroke-survivors at different phases of recovery after stroke. Accelerometer-based arm ratio (i.e. the ratio between more-affected and less-affected arm) showed strong correlation with FMA, after controlling for cofactors, such as age, sex, time since stroke, sensory deficit, neglect, apraxia or lower extremity function (17). Knowledge is, however, limited regarding how different relevant cofactors might be associated with real-life activity in people with stroke in a multifactor model. Such knowledge is necessary to advance the routine use of technology-based assessment in clinical practice (19–21).

The aim of this study was to determine to what degree arm, leg and trunk activity, measured with accelerometers, is associated with sensorimotor impairments and activity limitations as well as clinical and demographic characteristics in individuals with subacute stroke.

MATERIALS AND METHODS

Subjects

The patients were consecutively recruited from an inpatient rehabilitation ward at Sahlgrenska University Hospital during a period of 8 months between 2015 and 2017 (22). Preliminary sample size calculations were performed in our previous study investigating differences in activity levels between weekdays and weekends (22). For the current study accelerometer data from 26 patients were available. Inclusion criteria were: ischaemic or haemorrhagic first-ever stroke, based on World Health Organization (WHO) criteria (23); age ≥18 years; ability to walk a minimum of 10 m with or without assistance; and hemiparesis due to stroke (FMA < 66 points for arm or < 34 points for leg motor score). Patients with other condition that could limit the functional use of the arm or leg, or who were unable to understand or follow oral instructions in Swedish or English, were excluded. Clinical and demographic characteristics of the study group are shown in Table I.

All patients at the rehabilitation unit followed an individualized rehabilitation programme according to the National Swedish Stroke Guidelines (24). The rehabilitation included at least one 45-min session with physiotherapist and one 45-min session with an occupational therapist, 5 days per week. In addition, different group activities (gaming, walking, arm/hand training, gardening, kitchen activities and hippotherapy) as well as scheduled self-training and individual therapy with speech therapist or psychologist were part of the rehabilitation when appropriate. The participants were also asked to complete an activity log. Subsequently, each participant´s daily schedule along with the activity log were used to estimate the time (mean) spent in scheduled activities during the days on which the accelerometer measurement was performed (22). Ethics approval for the study was provided by the Regional Ethical Board in Gothenburg, Sweden (507-15) and written informed consent was obtained from all participants.

Activity monitoring with accelerometers

Accelerometer data were collected with 5 wireless 3-axial accelerometers (Shimmer 3, Shimmer, Dublin, Ireland), which were attached to the trunk, wrists and ankles with custom-made Velcro straps. In total, the accelerometers were worn for 4 days divided into 2 separate 48-h sessions, 1 over 2 weekdays and 1 over a weekend (Saturday and Sunday). The sampling rate was set to 51.2 Hz with an accelerometer range of ± 8 g. The accelerometers' weight was 24 g and dimensions 51 × 34 × 14 mm. Patients were instructed to wear the sensors both during the day and night, but remove them during showering and aquatic activities, since the sensors were not waterproof.

Accelerometer data was filtered using a Butterworth bandpass filter (0.2-10 Hz passband) and analysed using a custom-made Matlab software program (MATLAB. R2015b-2016b. Mathworks Inc. Natick, Massachusetts, United States). Only activity during daytime (08.00–20.00 h) was extracted for analysis. The acceleration data were inspected visually to identify periods of

Table I. Demographics and participant characteristics

Characteristics, *n* = 26	
Age, years, mean (SD) [min–max]	55.4 (11.9) [26–82]
Sex, female, *n* (%)	10 (38.5)
Days since stroke onset, mean (SD)	56 (24)
Stroke type, *n* (%)	
Ischaemic	21 (81)
Haemorrhagic	5 (19)
Affected side (right), *n* (%)	13 (50)
Hand dominance, *n* (%)	
Right hand	22 (85)
Left hand or bimanual hand	4 (15)
Dominant arm affected, *n* (%)	12 (46)
Arm motor function (FMA-UE, 0–66), median (Q1–Q3)	35 (15–50)
Leg motor function (FMA-LE, 0–34), median (Q1–Q3)	20 (16.5–26)
Decreased sensation UE/LE (≤ 11 points), *n* (%)	19 (73)/22 (85)
Decreased ROM UE (≤ 23 FMA-UE), *n* (%)	22 (85)
Decreased ROM LE (≤ 19 FMA-LE), *n* (%)	22 (85)
Joint Pain UE (≤ 23 FMA-UE), *n* (%)	14 (54)
Joint Pain LE (≤ 19 FMA-LE), *n* (%)	4 (15)
Spasticity arm/leg (≤ 1 mAS), *n* (%)	19 (73)/16 (61)
Walking speed (m/s), mean (SD)	0.69 (0.47)
Functional Ambulation Categories (FAC 0–5), median (Q1–Q3)	3.5 (2–4)
Dependent in walking (FAC 4–5), *n* (%)	13 (50)
Modified Rankin Scale (mRS, 0–5), median (Q1–Q3)	3.5 (2–4)
Arm activity, more-affected, m/s^2, mean (SD)	1.17 (0.52)
Arm activity, less-affected, m/s^2, mean (SD)	2.33 (0.44)
Leg activity, more-affected, m/s^2, mean (SD)	0.67 (0.28)
Leg activity, less-affected, m/s^2, mean (SD)	0.92 (0.26)
Arm activity ratio (log), mean (SD)	−0.33 (0.28)
Leg activity ratio (log), mean (SD)	−0.16 (0.19)
Trunk activity, m/s^2, mean (SD)	0.58 (0.15)

SD: standard deviation; Q1: 1st quartile; Q3: 3rd quartile; FAC: Functional Ambulation Categories; mAS: modified Ashworth Scale; FMA-UE: Fugl-Meyer Assessment of Upper Extremity; FMA-LE: Fugl-Meyer Assessment of Lower Extremity; UE: upper extremity; LE: lower extremity; ROM: range of motion.

non-motion sensor data. First and foremost, such periods were identified as sensors being removed for taking a shower, or missing data due to, for example, battery or sensor failure. All periods of non-activity sensor data were recognized and taken off the measured data. To be included in the analysis at least 20 out of 24 h of available registered acceleration data were required from either measurement session (weekdays/weekend) (22).

Activity levels were derived from the acceleration measurements from each accelerometer. Each accelerometer measures linear acceleration along 3 orthogonal directions x, y and z. The linear acceleration is consequently a 3-dimensional vector quantity

$$\vec{a} = (a_x, a_y, a_z).$$

The accelerometer-based activity was calculated as activity magnitude and expressed as signal magnitude area (SMA, m/s²). The SMA was calculated from the 1-norm of the acceleration vector averaged over a fixed epoch $T = 120\ s$.

$$SMA = \frac{1}{T}\int |a_x| + |a_y| + |a_z|\,dt.$$

Furthermore, the SMA ratio of more- and less-affected extremity was computed for arms and legs as a measure of activity asymmetry. The logarithm of the SMA ratios was used to obtain a measure that was symmetrical with respect to the limbs, in which the value zero indicates perfect symmetry between limbs, while a positive or negative value indicates a lower activity in the less-affected or more-affected limb, respectively. Finally, all SMA-derived measures were averaged over the entire measurement period to produce a single value for each activity metric.

Clinical assessments

Sensorimotor function for upper and lower extremity was assessed with the FMA (25). The maximum score of FMA that indicates unimpaired upper (FMA-UE) or lower extremity (FMA-LE) motor function, is 66 points and 34 points, respectively. FMA, the most widely used and recommended impairment-level scale for stroke, has shown excellent reliability and validity (12, 25, 26). The non-motor domains of the FMA; sensation, range of motion and pain during passive joint motions, were also assessed. A maximum score of 12 points of the upper and the lower extremity sensory domains indicate good sensory function and a maximum score of 24 (upper extremity) and 20 points (lower extremity) for range of motion and pain domains indicate full passive motion and no pain, respectively.

Spasticity in the elbow, wrist and ankle joints was assessed using the modified Ashworth Scale (mAS) (27, 28). Spasticity was defined as present when any of the tested muscle groups had a score ≥ 1. The self-paced comfortable walking speed (m/s) was calculated using the timed 10-m walk test (10mWT) (29). Functional Ambulation Categories (FAC) was used to classify walking dependency, wherein a score of 0–3 indicates dependency and 4–5 independency in walking (29, 30). The Modified Rankin Scale (mRS) was used to assess disability after stroke, in which 0 specifies no disability and 5 severe disability (31). A physiotherapist with approximately 25 years of experience completed all clinical tests. All clinical assessments were conducted prior to the accelerometer measurements.

Statistical analysis

Statistical analyses were conducted using IBM Statistical Package for Social Sciences™ (SPSS) version 23 (IBM Corporation, Armonk, New York, USA). Descriptive statistics were used to summarize the scheduled activities at the rehabilitation ward, demographic and clinical characteristics.

Multivariate linear regression was performed separately for SMA activity data derived from accelerometers placed on each arm, each leg and the trunk (dependent variables). A forward stepwise selection was used to determine a set of independent variables that showed significant associations with each dependent variable in a multivariate model (32).

First, univariate regression analyses were performed, from which variables with associations at significance level of $p < 0.20$, were considered for multiple regression analysis. The variable with the highest R^2 value (lowest *p*-value) from the univariate analyses was selected first, and thereafter the other variables were tentatively added, one at a time. The variable with the largest partial F statistics (lowest *p*-value) was kept in the model if both variables had $p \leq 0.20$. This procedure was continued as long as the *p*-values for all included variables were ≤0.20. However, in the final multilinear models only variables with a *p*-value less than 0.05 were retained.

Multicollinearity between independent variables was determined by Pearson's correlation coefficient ($r \geq 0.70$) and variance inflation factor ($VIF > 4$) (33). Independent variables that showed multicollinearity (Table SI[1]) were not included in the same regression model. The model assumptions were verified by means of residual analysis. Adjusted explained variances (R^2), unstandardized coefficient B and partial unique contribution were obtained for each final model.

RESULTS

The demographic and clinical characteristics of the included 26 patients are shown in Table I. The age of the participants varied from 26 to 82 years (mean 55.4 years (standard deviation (SD) 11.9 years) and 39% were women. The time spent in scheduled activities during weekdays was approximately 3 h, of which 2 h were spent in 1-to-1 therapy and 1 h in group activities. Motor function, assessed by FMA, ranged from 7 to 65 points for upper extremity and from 8 to 33 for lower extremity, indicating that individuals with mild-to-severe sensorimotor impairment were included (34). Half of the patients were independent in walking, at least on level surfaces, and 77% used a walking aid. All participants followed the study protocol, although some participants needed additional support from carers when taking the accelerometers on and off, e.g. when showering.

Univariate associations between the dependent variables (more- and less-affected arm and leg activity, trunk activity, arm and leg ratio) and all potential independent variables are shown in Tables II and III.

Arm activity

Upper extremity motor function, as determined by FMA-UE, and walking speed, determined by 10mWT, showed strongest univariate associations with the more-affected arm activity, explaining 67% and 62%

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Table II. Univariate adjusted estimates for all independent variables considered for multiple regression analysis of arm and leg activity

	Arm activity				Leg activity			
	More-affected arm		Less-affected arm		More-affected leg		Less-affected leg	
Independent variables	Adj R^2	*p*-value	Adj R^2	*p*-value	Adj R^2	*p*-value	Adj R^2	*p*-value
Fugl-Meyer Assessment of Upper Extremity	**0.67**	**<0.001**	**0.40**	**0.001**	**0.39**	**<0.001**	0.03	0.569
Fugl-Meyer Assessment of Upper Extremity ROM	**0.45**	**<0.001**	**0.16**	**0.035**	**0.18**	**0.018**	0.01	0.262
Fugl-Meyer Assessment of Upper Extremity pain	**0.35**	**0.001**	**0.05**	**0.161**	**0.15**	**0.027**	**0.10**	**0.061**
Fugl-Meyer Assessment of Upper Extremity sensation	**0.09**	**0.072**	0.01	0.383	**0.15**	**0.028**	0.04	0.929
Spasticity Arm	**0.05**	**0.151**	**0.21**	**0.016**	**0.04**	**0.179**	0.01	0.387
Fugl-Meyer Assessment of Lower Extremity	**0.52**	**<0.001**	**0.24**	**0.010**	**0.29**	**0.003**	0.03	0.670
Fugl-Meyer Assessment of Lower Extremity ROM	**0.11**	**0.056**	0.01	0.414	0.03	0.577	0.04	0.741
Fugl-Meyer Assessment of Lower Extremity pain	0.02	0.241	0.05	0.981	0.01	0.370	0.03	0.636
Fugl-Meyer Assessment of Lower Extremity sensation	0.04	0.745	0.05	0.896	0.02	0.239	0.01	0.397
Spasticity Leg	**0.13**	**0.041**	0.03	0.506	0.02	0.231	0.03	0.577
10-meter Walking Test	**0.62**	**<0.001**	**0.11**	**0.073**	**0.60**	**<0.001**	0.01	0.277
Functional Ambulation Categories	**0.48**	**<0.001**	0.03	0.526	**0.40**	**<0.001**	**0.08**	**0.091**
Independent in walking	**0.50**	**<0.001**	**0.09**	**0.055**	**0.41**	**<0.001**	**0.59**	**<0.001**
Modified Rankin Scale	**0.37**	**0.001**	0.02	0.235	**0.29**	**0.003**	**0.11**	**0.053**
Age, years	**0.15**	**0.029**	0.03	0.787	0.01	0.274	0.02	0.210
Sex	0.04	0.791	0.01	0.245	0.001	0.332	0.03	0.939
Days since stroke onset	**0.09**	**0.079**	0.02	0.234	**0.11**	**0.058**	0.04	0.901
Affected side	**0.19**	**0.015**	**0.08**	**0.110**	0.04	0.996	0.02	0.241
Stroke type	0.04	0.851	0.05	0.826	0.04	0.929	0.04	0.841
Dominant arm affected	**0.14**	**0.035**	0.03	0.210	0.04	0.934	0.01	0.290

Adj R^2: explained adjusted variance; ROM: range of motion. Variables in bold with $p<0.20$ were considered in the multivariate regression analysis.

of the total variance, respectively (Table II, Fig. 1A and B). Due to collinearity between these independent variables 2 different models were built. In the first final multivariate model (M1), motor function uniquely explained approximately 29% of the total variance in the more-affected arm activity, whereas arm spasticity additionally explained approximately 6%, and walking dependency level approximately 4% (Table IV). In the second final multivariate model (M2), walking speed uniquely explained approximately 31% of the total variance in the more-affected arm activity. Passive range of motion of the arm, and having the dominant arm affected, contributed uniquely, with 4% and 5%, respectively. Both final models (M1 and M2) with all 3 independent variables explained 77% of the total variance (Table IV).

The multivariate model of the less-affected arm activity showed that upper extremity motor function, assessed with FMA-UE, alone explained approximately 40% of the total variance. (Table IV). This association was, however, negative, which means that a higher level of less-affected arm activity was associated with larger motor impairment.

Table III. Univariate adjusted estimates for all independent variables considered for multiple regression analysis of arm ratio, leg ratio and trunk activity

	Arm activity ratio		Leg activity ratio		Trunk activity	
Independent variables	Adj R^2	*p*-value	Adj R^2	*p*-value	Adj R^2	*p*-value
Fugl-Meyer Assessment of Upper Extremity	**0.63**	**<0.001**	**0.20**	**0.013**	**0.10**	**0.071**
Fugl-Meyer Assessment of Upper Extremity ROM	**0.39**	**0.001**	0.01	0.420	**0.12**	**0.047**
Fugl-Meyer Assessment of Upper Extremity pain	**0.31**	**0.004**	0.04	0.989	**0.22**	**0.10**
Fugl-Meyer Assessment of Upper Extremity sensation	**0.04**	**0.179**	**0.16**	**0.026**	0.001	0.321
Spasticity Arm	0.02	0.449	**0.14**	**0.036**	0.03	0.638
Fugl-Meyer Assessment of Lower Extremity	**0.39**	**0.001**	**0.38**	**<0.001**	0.03	0.20
Fugl-Meyer Assessment of Lower Extremity ROM	**0.20**	**0.018**	0.02	0.460	0.43	0.955
Fugl-Meyer Assessment of Lower Extremity pain	0.02	0.424	0.03	0.604	0.02	0.439
Fugl-Meyer Assessment of Lower Extremity sensation	0.05	0.962	**0.20**	**0.018**	0.43	0.99
Spasticity Leg	0.01	0.369	**0.05**	**0.148**	0.13	0.41
10-meter Walking Test	**0.31**	**0.003**	**0.27**	**0.004**	**0.34**	**0.001**
Functional Ambulation Categories	**0.24**	**0.010**	**0.06**	**0.118**	**0.33**	**0.002**
Independent in walking	**0.43**	**<0.001**	**0.18**	**0.006**	**0.35**	**0.001**
Modified Rankin Scale	**0.16**	**0.036**	0.03	0.534	**0.28**	**0.004**
Age, years	**0.10**	**0.045**	0.03	0.908	0.03	0.218
Sex	0.02	0.534	0.01	0.244	**0.10**	**0.066**
Days since stroke onset	**0.06**	**0.139**	**0.10**	**0.062**	0.02	0.449
Affected side	**0.29**	**0.005**	**0.09**	**0.076**	0.04	0.941
Stroke type	0.04	0.655	0.03	0.645	0.03	0.608
Dominant arm affected	**0.24**	**0.010**	**0.08**	**0.090**	0.40	0.789

Adj R^2: explained adjusted variance; ROM: range of motion. Variables with $p<0.20$ were considered as potential determinant variables in the multivariate regression analysis (marked in bold).

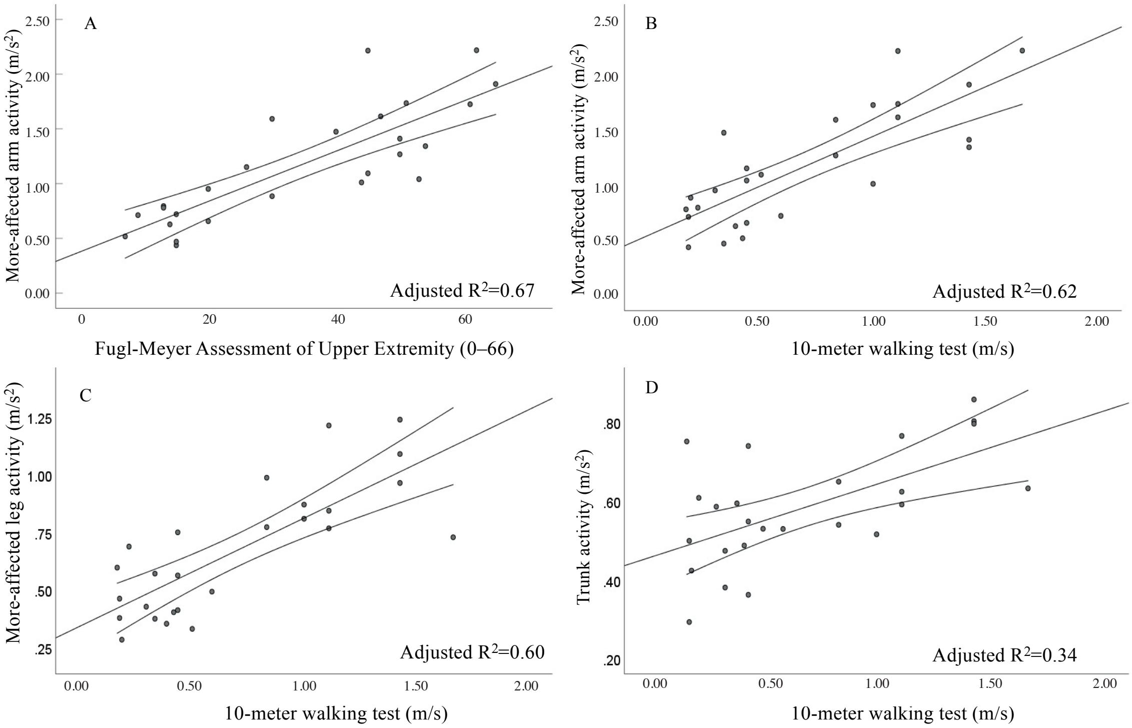

Fig. 1. Scatterplots showing correlations and R² values between (A) more-affected arm activity and Fugl-Meyer Assessment of Upper extremity, (B) more-affected arm activity and walking speed, (C) more-affected leg activity and walking speed, and (D) trunk activity and walking speed.

Table IV. Final models of multivariate linear regression analyses for accelerometer-derived arm, leg and trunk activity. Only significant independent variables in the final models are displayed

		Unstand B	Stand B	*p*-value	Partial unique contribution, %	Model Adj R^2
Arm activity: dependent variable						
More-affected arm						
M1	FMA-UE	0.02	0.86	< 0.001	29	0.77
	Spasticity UE	−0.36	−0.31	0.022	6	
	FAC	0.09	0.26	0.045	4	
M2	10mWT	0.72	0.65	< 0.001	31	0.77
	FMA-UE ROM	0.05	0.26	0.040	4	
	Dominant arm affected	0.26	0.25	0.028	5	
Less-affected arm						
M1	FMA-UE	−0.02	−0.66	0.001	–	0.40
Leg activity: dependent variable						
More-affected leg						
M1	10mWT	0.47	0.79	< 0.001	–	0.60
Less-affected leg						
M1	Independent in walking	0.48	0.78	< 0.001	–	0.59
Activity ratio: dependent variable						
Arm ratio						
M1	FMA-UE	0.01	0.80	< 0.001	–	0.63
Leg ratio						
M1	FMA-LE	0.02	0.64	< 0.001	–	0.38
M2	10mWT	0.22	0.55	0.004	–	0.27
Trunk activity: dependent variable						
M1	Independent in walking	0.18	0.61	0.001	–	0.35
M2	10mWT	0.19	0.61	0.001	–	0.34
M3	FAC	0.06	0.60	0.002	–	0.33
M4	mRS	−0.08	−0.56	0.004	–	0.28

Unstand B: unstandardized coefficient B; Stand B: standardized coefficient B; Adj; adjusted; R²: explained variance; M: model; FMA-UE: Fugl-Meyer Assessment of Upper Extremity; UE: upper extremity; FAC: Functional Ambulation Categories; 10mWT: 10-meter Walking Test; ROM: range of motion; mRS: Modified Rankin Scale.

Leg activity

Walking speed during the 10mWT alone explained 60% of the total variance in the more-affected leg activity (Table IV, Fig. 1C). For the less-affected leg, being able to walk independently alone explained 59% of the total variance (Table IV).

Arm and leg activity ratio

Approximately 63% of the total variance in arm activity ratio measure, indicating asymmetry between the more- and less-affected arms, was solely explained by the FMA-UE in the final model (Table IV, Fig. 2A).

Regarding the leg activity ratio measure, motor function assessed by FMA-LE and walking speed assessed by 10mWT, both showed high univariate associations with the leg activity ratio. Since these independent variables showed collinearity (r = 0.73) 2 different models were composed. The final models showed that FMA-LE alone explained 38%, and 10mWT 27%, of the total variance in the leg activity ratio measure (Table IV). The association between leg activity ratio and FMA-LE is shown in Fig. 2B.

Trunk activity

Four independent variables showed equivalent levels of correlation with trunk activity. Due to collinearity between these independent variables 4 separate mod-

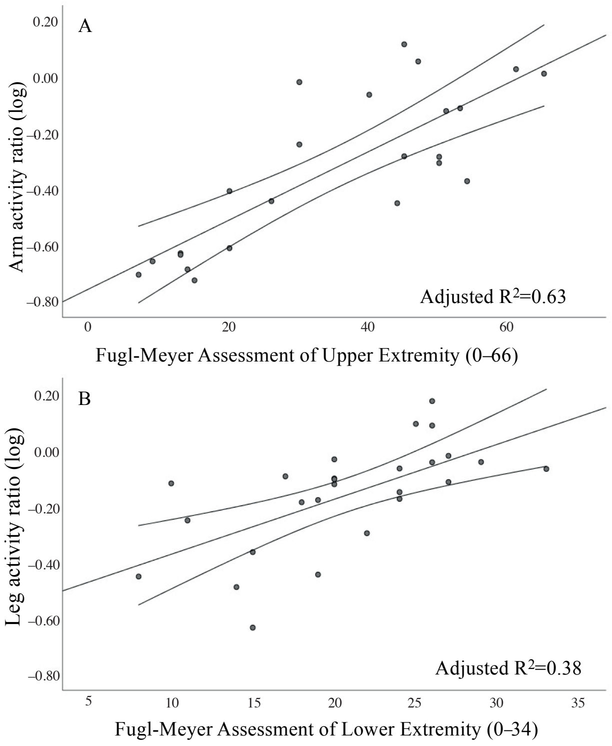

Fig. 2. Scatterplots showing correlations and R2 values between (A) arm activity ratio and Fugl-Meyer Assessment of Upper Extremity, and (B) leg activity ratio and Fugl-Meyer Assessment of Lower Extremity.

els were constructed. The final multivariate models revealed that being independent in walking explained 35%, walking speed 34%, walking dependency level (FAC) 33% and disability level (mRS) 28% of the total variance in accelerometer-derived trunk activity (Table IV). The association between the trunk activity and walking speed is shown in Fig. 1D.

DISCUSSION

The results of the current study show that the activity of the more-affected arm was, to a large extent, explained by arm motor impairment (67%) and walking speed (62%) in the subacute stage of stroke. The activity of the more-affected leg was primarily explained by walking speed (60%). Arm motor impairment explained approximately 63% of variance in arm activity ratio and leg motor impairment approximately 38% in leg activity ratio. In addition to leg motor impairment, walking speed explained approximately 27% of the variance in leg activity ratio. Approximately 30–35% of variance in trunk activity was explained by different walking-related variables. These findings are novel and bring new knowledge into clinical research and practice by improving our understanding and interpretation of sensor-based activity measures. Furthermore, the strong associations found between the accelerometer-derived activity and widely used clinical assessments of arm motor impairment (FMA-UE) and walking speed (10mWT), support the use of these scales as a proxy for estimating the amount of real-life arm and leg activity.

The association between upper extremity motor function and accelerometer-derived activity level of the more-affected arm was strong (R^2=0.67). Similar, and somewhat lower, levels of correlation between motor function, assessed by FMA-UE, and arm activity metrics from wrist-worn accelerometers have been reported in the acute (rho=0.70) (16), subacute (rho=0.60) (17) and chronic stages of stroke (rho=0.51–0.75) (18, 35). In agreement with our results, several demographic and clinical factors (age, sex, time since stroke, initial stroke severity, lower extremity impairment, hand dominance, sensory function or perception) added to the regression models did not significantly influence the associations (17, 35). Depression was, however, reported to confound the association between the arm acceleration magnitude and arm motor impairment in chronic stroke (35). In the current study, among many tested potential independent variables, arm spasticity and categorized walking dependency improved the final regression model of the more-affected arm activity (R^2 change from 0.67 to 0.77). Although the unique contribution of these variables was small, their contribution is relevant from a clinical perspective. The increased spasticity and decreased walking dependency both co-exist in people with more severe hemiparesis, and might thereby influence the activity levels of the more-affected arm.

In addition to motor impairment, walking speed was associated with more-affected arm activity, explaining a comparable amount of variance in the more-affected arm activity (R^2=0.62). The passive range of motion of the upper extremity and having the dominant arm affected both improved the final regression model (R^2 changed from 0.62 to 0.77), although the unique contribution of these added variables was small. The effect of walking speed on arm activity level was less expected, and has, to our knowledge, not been reported previously. Nevertheless, a moderate correlation (rho=0.41) between arm activity and the self-reported mobility subscale of the Stroke Impact Scale was found in a chronic stage of stroke (36). The arm movements are commonly larger in faster walking speeds, which might partly explain the observed strong association in the current study. Likewise, the strong correlation (r=0.81) between walking speed and arm motor function, as observed in the data from the current study, confirms that people with a better motor function are more likely to walk faster.

In line with these results, moderate-to-strong correlations were demonstrated between the arm motor function (FMA-UE) and arm activity ratio metrics in the acute (rho=0.60) (16), subacute (rho=0.85) (17), and chronic stage of stroke (rho = 0.60) (35). Notably, in a previous study in sub-acute stroke, the arm activity ratio demonstrated strong correlation (rho = 0.85) with arm motor impairment assessed with FMA-UE, while the correlation with more-affected arm movement duration was lower (rho = 0.60) (17). This finding was not confirmed in the current study. The findings instead showed similar associations, both for the arm ratio and the more-affected arm activity, with the arm impairment ($R^2 = 0.63$ and $R^2 = 0.67$, respectively). The arm activity ratio has previously been recommended for stroke, since it is considered to correct for the general body movements (17, 37, 38). The results of this study show, however, that both metrics (arm ratio and the more-affected arm activity) were equal in terms of correlation with arm motor impairment.

The walking speed alone explained 60% of the total variance in the more-affected leg activity. Furthermore, walking speed and leg motor impairment were both associated with leg activity ratio, explaining 27% and 38% of the total variance, respectively. Walking speed, together with age and employment status, explained approximately 57 % of the variance in step counts in a cohort of people after completed stroke rehabilitation (5). Another study with community-dwelling people in the chronic stage of stroke, found that walking speed explained approximately 45% of the variance in accelerometer-derived step frequency (39). These results demonstrate a close relationship between walking speed and step counts in the chronic stage of stroke. The findings of the current study extend these results by demonstrating a strong association between walking speed and accelerometer-derived leg activity in a subacute inpatient rehabilitation. Interestingly, leg motor impairment (FMA-LE) showed a significant association with the leg activity ratio, but not with the more-affected leg activity. This finding indicates that the leg-ratio measure, which primarily reflects the asymmetry in leg activity, was, in addition to walking speed, also dependent on motor impairment level, while the activity of more- and less-affected leg activity was primarily associated with walking speed and ability to walk independently.

Similar to the more-affected arm activity, the less-affected arm activity was associated with arm motor function ($R^2 = 0.40$), although the association here was negative. This illustrates well the compensatory movement strategy often seen in stroke. The data confirmed that a lower level of upper extremity motor function was associated with a higher level of activity of the less-affected arm. This kind of compensatory increased activity of the less-affected side was, however, not seen in the leg activity. The accelerometer-based activity of the less-affected leg was solely associated with the ability to walk independently. This finding indicates that leg activity is more closely connected with walking and that it is more difficult to use the less-affected leg more to compensate for the motor impairment.

The accelerometer-based activity of the more-affected arm and leg provided most detailed information regarding motor impairment and walking capacity in people with subacute stroke and could therefore be recommended as the first choice for clinical evaluations. Likewise, the arm and leg activity ratio metrics might be as informative in terms of motor impairment, but will require the use of accelerometer units on both sides and therefore may be less practical in clinical settings. The accelerometer data from the trunk sensor provided little information compared with the data collected from more-affected arm and leg and could therefore be redundant. The trunk accelerometer unit was also experienced by users as less comfortable and more difficult to administer (22).

Strengths and limitations

While interpreting the results of the current study, the following limitations should be considered. The results are specific to people with subacute stroke in the inpatient setting. The sample, however, included people with severe to mild sensorimotor impairment after stroke, which strengthens the representativeness of the sample. The study also included people with cognitive impairment and aphasia, as long as they could follow the instructions required to adhere to the study protocol. Psychological factors, such as depression and perceptual impairments, might influence the amount of physical activity (35), but no formalized testing of these functions was performed in the current study, which is a limitation. The use of multiple sensors allowed a more differentiated analysis, and the results can be used to guide the selection of sensor locations in future work and clinical practice. The use of raw acceleration data has also been advocated and strengthens the results of the current study. Adherence to the study protocol was satisfying, although additional support from carers was needed for some participants. Inclusion of participants with mild cognitive and perceptual impairments improves the ecological validity of the study, reflecting a vital function for a stroke study-protocol, since these deficits are common after stroke (40).

Conclusion

Arm motor impairment and walking speed explained approximately two-thirds of the real-life accelerometer-derived activity of the more-affected arm in people in the subacute stage after stroke. The more-affected leg activity was, to a large extent, explained by walking speed. The clinical assessments were more strongly associated with real-life activity measured from the more-affected side, compared with the less-affected side. The arm activity ratio showed a similar association with clinical assessments as the activity of the more-affected arm, although the latter requires use of only a single sensor, which might be more suitable in clinical settings. The activity data from the trunk accelerometer provided limited information and can therefore be considered redundant.

This study demonstrated that good-quality data can be derived from commercial accelerometers allowing raw-data handling. Accelerometers placed on the more-affected wrist and ankle provided the most relevant information and can therefore be recommended in research and clinical practice. In addition, since the accelerometers are not always easily accessible in clinical settings, the clinical assessment of motor impairment (FMA-UE) and walking speed (10mWT) can, to some degree, be used to gain understanding of potential levels of activity in real-life activities in people with subacute stroke.

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