Title:

Identification of neuromuscular targets for restoration of walking ability after stroke: precursor to precision rehabilitation

Abstract:

Objectives:

Restoration of walking is a priority for stroke survivors and key target for physical therapies. Upright Pedalling (UP) can provide functional walking-like activity using a variety of muscle synergies; it is unclear which synergies might be most useful for recovery of walking. Objectives here were:

-To examine whether neuromuscular measures derived during UP might identify targets for walking rehabilitation after stroke

-To determine test-retest repeatability and concurrent validity of the measures.

Design: Prospective correlational study

Setting: Movement science laboratory

Participants: Eighteen adults with stroke (StrS); ten healthy older adults (HOA).

Intervention/measurement: StrS and HOA took part in two identical measurement sessions. During UP, EMG and kinematic data were recorded, then processed to derive three measures: (1) reciprocal activity of quadriceps and hamstrings; (2) percentage muscle activity ‘on’ according to crank angle (3) smoothness of movement.

Results

HOA and StrS demonstrated differences in reciprocal muscle activity ($p=0.044$) and quadriceps activity according to crank angle ($p=0.034$), but pedalled similarly smoothly ($p=0.367$). For muscle activation according to crank angle in StrS, ICCs (95% CI) showing acceptable repeatability were: 0.46 (0.32, 0.58) affected quadriceps; 0.43 (0.28, 0.56) affected hamstrings; 0.67 (0.56, 0.75) unaffected quadriceps.

Conclusion

Muscle activation according to crank angle is a promising measure of lower limb impairment during functional activity after stroke; subsequent investigation should determine magnitude of variance between testing sessions. Reciprocal activity of quadriceps and hamstrings muscles and quadriceps activity according to crank angle are both potential targets for physical therapies to improve motor recovery. Further investigations are warranted.

Key words: stroke, walking, rehabilitation, lower extremity

Introduction

Restoration of walking ability after stroke is a priority for stroke survivors (Pollock *et al.* 2012). Provision of evidenced-based task-specific walking practice is especially challenging for people with substantial impairments, such as those unable to walk even with assistance of two others. This challenge is particularly pertinent early after stroke when it is important to provide intensive input, focused on restoring neuromuscular function, whilst people are still in the period of injury-induced neuroplasticity (Nudo, 2013; Pomeroy *et al.* 2011). Here, recovery is defined as "the extent to which body structure and functions, as well as activities, have returned to their pre-stroke state" (Bernhardt *et al.* 2017).

Upright Pedalling (UP) has potential to address this challenge by providing reciprocal lower limb exercise with similar kinematics and muscle synergies to those underlying walking ability (Barroso *et al.* 2014; Raasch & Zajac 1999). Indeed, people with substantial paresis, unable to walk (Functional Ambulation Categories score of 0), 11 days or less after stroke were found to produce smooth movement during UP using a variety of muscle synergies (Hancock *et al.* 2017). However, whilst the pedalling task was achieved, it is unclear whether such synergies are compensatory and hence which should be encouraged or discouraged to restore walking ability. Clarification of which muscle synergies to target to restore motor function is unlikely to emerge through undertaking the next investigations with people early after stroke. This is because people early after stroke are likely to experience change in muscle synergies due to injury-induced recovery mechanisms. Therefore it will be important to examine the muscle synergies used by people in the ‘chronic’ phase after stroke when further recovery is not expected. In this way a comparison of muscle synergies used by stroke survivors and aged-matched volunteers is more likely to identify the compensatory muscle synergies to avoid during rehabilitation.

An associated potential benefit of UP is the provision of measurement of neuromuscular function during a functional task. Such information can support decision making on whether a physiotherapy intervention is actually restoring body structure and function (Bernhardt *et al.* 2017; Hardwick *et al.* 2017; Kwakkel *et al.* 2017). At present, motor impairment is often measured with stroke survivors in static postures such as sitting (e.g. the Motricity Index), rather than during those functional movements that directly relate to recovery of tasks such as walking. Laboratory systems are available to provide objective, sensitive measures, but are expensive and inaccessible to most clinical services. Even in the presence of access to a gait laboratory many stroke survivors cannot ambulate sufficiently to participate in gait measurement. However, they might be able to take part in UP (Hancock *et al.* 2017) to provide more clinically relevant measures. These include EMG-derived measures of muscle synergies (reciprocal activation of quadriceps and hamstrings, muscle activation timing according to crank angle) and a kinematic measure (smoothness of lower limb movement), even in stroke survivors with severe paresis who are unable to walk (Hancock *et al.* 2017) Before these neuromuscular measures during UP can be used for both clinical practice and research it is important that they are tested for test-retest repeatability and concurrent validity with existing clinical measures.

Hence, the aims of this study are: (a) to explore whether UP neuromuscular measures may identify potential targets for physiotherapy interventions designed to improve recovery of walking ability, and, (b) to determine both the test-retest repeatability of neuromuscular measures during UP and their concurrent validity with existing measures of motor impairment and ambulation. Specific objectives were, for UP neuromuscular measures- namely, reciprocal activity of quadriceps and hamstrings muscles, smoothness of movement and muscle activation according to pedal crank angle; a) to compare between stroke survivors and healthy older adults; and, b) to determine test-retest repeatability and concurrent validity with the Motricity Index and the Functional Ambulatory Categories (FAC)

Methods

-Design, ethics and setting

This was a prospective correlational study in a movement science laboratory. Ethical and Research Governance approval were in place (Norfolk REC: 11/EE/0002). All participants provided informed consent.

-Participants

Participants with stroke (StrS):

- Were aged 18+
- Had sustained a unilateral stroke with motor hemiplegia
- Scored 1,2,3,4 or 5 on the Functional Ambulatory Categories, FAC (Holden *et al.* 1984)

- Had resting oxygen saturations of 95% or above, resting heart rate of 90 bpm or less and resting systolic blood pressure of 100-160mmHg
- could follow a one-stage command
- could participate in one, one-minute UP session

StrS were excluded if:

- Their GP indicated that participation was not appropriate
- They had co-existing pathology contributing to substantial impairment in the paretic lower limb

All healthy older adult participants (HOA):

- Were adults of 50 years or over
- Were independent in community ambulation
- Had a resting heart rate of 90 beats per minute or less and resting systolic blood pressure of 100-160mmHg
- Had no underlying condition that might limit participation in the measurement session
- had no lower limb pathology contributing to substantial impairment

-Recruitment

StrS were recruited via researcher visits to local stroke groups, a poster placed in community settings and contact with participants who had recently completed another study with our team. HOA volunteers were recruited via posters.

-UP equipment/instrumentation

To provide movement-based, physiological measurements to characterise motor impairment, a novel prototype instrumented Upright Pedalling device (U-PED) was designed (see Hancock *et al.* 2017). U-PED provides appropriate trunk and lower limb support for people with poor postural control and is instrumented to enable neural-biomechanical measurement of pedalling. This includes division of the wheel into 45-degree position bins to enable muscle activity recorded via surface EMG (sEMG), here from quadriceps and hamstrings muscles, to be mapped to the position of the pedal during the 360 degree turn.

-Procedure- StrS participants:

Motor behaviour measures taken:

- Ability to produce voluntary muscle contraction in the lower limb measured by the Motricity Index (Demeurisse *et al.* 1980). The MI was chosen as it is a simple, clinically applicable measure that provides a more detailed assessment of muscle strength than the MRC scale.
- Ability to walk measured by the FAC. The FAC is a widely used, clinical classification of gait.

The experimental procedure is detailed in figure 1. In summary, following skin preparation, sEMG electrodes were applied over right and left quadriceps and hamstrings muscle groups. Resting data were recorded for 30 seconds. StrS participants began pedalling, and data were marked electronically when at comfortable cadence and again after one minute. This pedalling session was repeated again after a one-hour rest period.

-Procedure- HOA participants:

HOA participants took part in two measurement sessions separated by a one hour rest as described for StrS. Here, EMG data were recorded during pedalling for one minute at cadences of: 10, 20, 30, 40 and 50rpm. Different cadences were used to enable comparisons with possible cadences achieved by StrS. Ordering of cadence was randomised prior to testing using a computerised randomisation programme.

-Data Processing

Data were processed exactly as described in Hancock *et al.* (2017). In summary; firstly, the muscle activity raw signal was rectified using custom written scripts and smoothed using a moving average of 50ms. Then, to establish muscle activity bursts:

- Baseline (threshold) EMG values were calculated from the processed signal as the mean ± 3 SD during the 30 seconds resting period - muscles considered “on” above this threshold and “off” when below it.
- For each 45 degree position bin, onset of activity was expressed as a percentage of total “on” time for that specific position. If the muscle was continually above the threshold throughout a whole 45^0 position bin, this would be 100% on, and if not above the threshold at all within that position bin would be 0% on. This classification enabled determination of muscle activity according to crank angle, removing the need to relate EMG activity to a specific timeframe.

To derive a measure of reciprocal activation of antagonistic muscle groups during UP, Jaccard's Coefficient (J) was used (Real & Vargas, 1996):

$$J = \frac{a}{a + b + c}$$

where a= % muscles on together, b= % quadriceps on, hamstrings off and c= % hamstrings on, quadriceps off

A J-value of 1.0 therefore indicates complete co-contraction, no reciprocal activation, of an antagonistic muscle pair. A J-value of 0 indicates no co-contraction between the two muscles at all, therefore complete reciprocal activation of antagonistic pairs. For both StrS and HOA, reciprocal activation was calculated for each leg separately; data from right leg of HOA was used for relevant comparisons (see *statistical analysis)*

Smoothness of pedalling movement (S-Ped) was the standard deviation of the time spent in each of the eight position bins for each 360 degree turn, over the central ten turns of the wheel, extracted from the complete number of turns for each participant. Hence, a lower standard deviation- a lower S-Ped score, indicates smoother pedalling than a higher standard deviation, hence S-Ped, score.

-Statistical analysis

To test for differences between StrS and HOA for the measure of reciprocal muscle activity, two-sample t-tests with 95% confidence intervals were used; for smoothness of activity, a two-sample Wilcoxon text was used. For differences between StrS and HOA for the measure of muscle activation according to crank angle, a repeated measures ANOVA was used (i.e. the crank position, or 'bin' was used as a repeated, within individual factor.) For testing for differences between StrS and HOA, data collected at pedalling cadence 40rpm for HOA was used, most closely reflecting the mean pedalling cadence of the StrS group (41.4 rpm). Data from the right leg of HOA were used for all comparisons.

To determine test-retest repeatability of all measures the intra-class correlation coefficient (ICC) plus 95% confidence intervals (95% CI) were used. Interpretation of ICC values was made as: 0.0-0.20=slight; 0.21-0.40=fair; 0.41-0.60=moderate; 0.61-0.80=substantial; and 0.81-1.00=almost perfect (Eilasziw *et al.* 1994). The interpretation was made on the lower limit of the 95% CI.

Concurrent validity of each UP measure with the Motricity Index and FAC was quantified using Spearman's rank correlation coefficient.

Results

-Participant characteristics

Eighteen StrS participated (eight female), with mean age 61 years (table 1). Mean time after stroke was 6.3 (range 1.2 to 19.8) years. All had motor impairment in their lower limb,(mean MI 66.2/100; range 38 to 92/100) All could walk; some with assistance of one person, ranging to able to ambulate independently (FAC score median 3, range 1- 5; table 1).

Ten HOA participated (four female) with mean age 58 years (table 1).

-Differences between StrS and HOA

1. Reciprocal activity of quadriceps and hamstrings muscles

Fifteen of the 18 data sets for StrS were available after processing for the more affected limb and 17 for the less affected limb. This was due to marked external noise for one measurement session for one participant and insufficient muscle activity above baseline from which to calculate the J-value for the more affected limb for two participants.

Reciprocal activity of muscles in the affected limb of StrS was significantly less than in HOA (HOA: mean=0.248, SD=0.255, StrS: mean=0.500, SD=0.305, difference= -0.249 [95% CI -0.491 to -0.010]; p=0.044). There was no significant difference for the unaffected limb of StrS and HOA (HOA: mean=0.248, SD=0.255, StrS: mean=0.393, SD=0.298, difference= -0.146 [95% CI -0.379 to 0.087]; p=0.208) (table 2).

2. Smoothness

Measurement of smoothness demonstrated no significant differences between groups (HOA: median=0.014, semi-IQR=0.0015, StrS: median=0.017, semi-IQR=0.0050; p=0.367) (table 2).

3. Muscle activation according to crank angle

For the between groups comparison of mean percentage activity across each complete turn of the crank, no difference was demonstrated for either quadriceps (p=0.111) or hamstrings (p=0.347) (table 3). However, consideration of the separate position bins did show differences between StrS and HOA (table 3) for percentage of muscle activity “on” between position bins (e.g. for bin 1, quadriceps “on” for 84.3% of the time for HOA and 71.7% of the time for StrS; table 3), a significant difference between bins was found for quadriceps (p=0.034) though not for hamstrings (p=0.202).

-Test-retest repeatability

1. Reciprocal activity of quadriceps and hamstring muscles

Whilst point estimates alone suggest fair agreement for both the unaffected and affected limb of StrS (unaffected: ICC=0.38 [95% CI 0,0.80]; affected limb: ICC=0.35 [95% CI 0, 0.70]), and substantial agreement at faster speeds for HOA (e.g. at 50rpm: ICC=0.72 [95% CI 0,0.85]), confidence intervals were wide in all cases, with lower 95% CIs at zero; hence, repeatability was not established for reciprocal muscle activity (table 4).

2. Smoothness

Similarly, repeatability was not established for smoothness of movement in StrS (ICC=0.28 [95% CI 0,0.65], nor in HOA at any cadence (e.g. at 20rpm: ICC=0.59 [95% CI 0.01, 0.88]; at 40rpm: ICC=0.64 [95% CI 0.10, 0.90]) (table 4)

3. Muscle activation according to crank angle

Affected quadriceps and hamstrings muscles in StrS demonstrated fair agreement between sessions (quadriceps ICC=0.46; 95% CI: 0.32, 0.58; hamstrings ICC=0.43; 95% CI: 0.28, 0.56). Unaffected quadriceps in StrS demonstrated moderate agreement between sessions (ICC=0.67; 95% CI: 0.56, 0.75). Substantial correlation was demonstrated for quadriceps in HOA (ICC=0.76; 95% CI: 0.65, 0.84) (table 5).

-Concurrent validity with the Motricity Index and Functional Ambulatory Categories

1. Reciprocal activity of quadriceps and hamstrings muscles

There was no significant association between reciprocal muscle activity and the MI in either the affected limb (r=0.278, p=0.316); or unaffected limb (r=0.075, p=0.775), similarly, no association was demonstrated for the FAC (affected limb, r=0.030, p=0.916; unaffected limb, r=0.136, p=0.604).

2. Smoothness

For smoothness of movement, no significant association was demonstrated with the MI (r=0.375, p=0.130) or the FAC (r=-0.165, p=0.513).

3. Muscle activity according to crank angle

No associations were demonstrated between percentage muscle activity "on" according to crank position and either the MI or the FAC.

Discussion

The main findings suggest that UP neuromuscular measures:

i) differ between stroke survivors and healthy older adults for measurement of a) reciprocal activity of quadriceps and hamstrings muscles, and b) quadriceps muscle activation according to crank angle.

ii) do not differ between stroke survivors and healthy older adults for measurement of smoothness of pedalling

iii) have a) fair test-retest repeatability for quadriceps and hamstrings muscle activity according to crank angle in the affected leg of stroke survivors, and b) substantial test-retest repeatability for quadriceps muscle activity according to crank angle in healthy older adults

Assessment of test-retest repeatability for UP derived neuromuscular measures:

Findings of test-retest repeatability were variable for measures across participant groups and muscles tested. Wide 95% confidence intervals around the ICC's for reciprocal muscle activity and smoothness measures meant that repeatability could not be determined with any precision. It is likely that the small sample size (n=17) and possible heterogeneity of stroke survivors' movement patterns and abilities contributed. However, fair to substantial repeatability was demonstrated in muscle activity according to crank angle in both groups. This is again promising, as it is a potentially important indicator of underlying strategies adopted to produce controlled voluntary movement and might provide a specific target for lower limb rehabilitation (Hortobagyi *et al.* 2009). In a previous investigation of muscle activity onset and offset during cycling, in a range of lower limb muscles in non-impaired younger adults, Jobson *et al.* (2012) demonstrated strong repeatability in all muscles; this inter-session reliability was markedly better for temporal than magnitude components of activity. Hence, temporal components of muscle activity, such as those explored in the current study, might be more suitable for evaluation of long-term change in activity. The findings of Jobson *et al.* are unsurprising in a group of young, experienced cyclists; further work on their psychometric properties, in people with motor impairment, is indicated.

Comparisons between Strs and HOA for UP derived neuromuscular measures:

The findings of differences between stroke survivors and healthy older adults for both measurement of reciprocal activity of quadriceps and hamstrings muscles and quadriceps muscle activity according to crank angle indicate that both are potential targets for physical therapies to improve motor recovery. Such measures can provide quantitative information about the control and quality of voluntary movement (Hortobagyi *et al.* 2009; Demers & Levin, 2017). Accurate measurement of movement quality variables by such measures is therefore of clinical importance, to characterise and monitor response to walking interventions in stroke survivors, and to understand whether such responses are restorative or compensatory (Jolkkonen & Kwakkel, 2016).

Smoothness of movement, as defined for this study, did not discriminate between stroke survivors and healthy older adults. This is an important finding with clinical relevance, demonstrating that stroke survivors can achieve similarly smooth, repetitive movement to people without stroke, in upright postures during a task analogous to walking. The current findings contrast to Chen *et al.* (2005) who also addressed such a measure, but found that smoothness of pedalling in a small group of stroke survivors (n=13) was significantly lower than in people without stroke (n=8). However, Chen *et al.* calculated smoothness using instantaneous velocity over four wheel phases, a methodological difference which might account for contrasting findings to the current study. In addition, Chen *et al.* used a semi-recumbent cycle for their testing process; we suggest that the more upright posture used in the current study enabled stroke survivors to achieve a more normal, functional movement, enabling similarly smooth movement to older adults without stroke. Furthermore, this smooth movement was established here without significant difference in reciprocal muscle activity between the *unaffected limb* of the stroke survivors and healthy older adults. It is possible, therefore, that people greater than one year after stroke can activate strategies to produce smooth movement without abnormal, compensatory muscle activation patterns in their unaffected limb.

Earlier, preliminary work with people within 30 days of stroke onset and substantial paresis, also found that smooth movement was achievable during UP (Hancock *et al.* 2017). It is therefore possible that UP might have potential as a rehabilitation tool, as well as providing indicators of change in movement performance and potential targets for therapy.

Agreement of UP derived neuromuscular measures with other commonly used measures; concurrent validity

The findings reported here suggest that it would not be appropriate to use the UP neuromuscular measures interchangeably with the MI as a lower limb motor impairment measure, nor to associate UP measures with walking ability classified by the FAC.

This is likely due to the nature of the measures developed in the current study, being derived from detailed analysis of physiological characteristics underlying motor output during upright pedalling. The MI, whilst regarded as an impairment measure, is a “hands-on” tool for measuring the end output of that physiological behaviour: voluntary muscle contraction. It is possible that the measures investigated are indicative of pre-clinically-observed change and provide information for shaping ensuing clinical therapy. This is important, as rehabilitation studies have been criticised for many years for their measures being insufficiently responsive to detect small but clinically relevant change in impairment (Jolkkonen & Kwakkel, 2016; Pomeroy & Tallis, 2000). The reported UP measures might, in the future, be used to enhance physiological measurement of lower limb activity and walking ability after stroke. Additionally, such sensitive measurement of impairments underpinning functional movement performance in clinical environments could enable therapists to more optimally target therapies, encouraged as they are to optimise dose and intensity of rehabilitation therapy with a focus on impairment (Krakauer *et al.* 2012).

Limitations of the study

It is likely that a larger sample size of stroke survivors would have increased precision of findings reported; especially considering the loss of a few data sets for analysis in part due to signal noise.

Participants in the study were younger, mean age 61 years, than the average age of stroke onset in the UK (75 years). However, approximate age matching with the healthy older adults group (mean 58 years) was achieved .

To enable synchronous recording of crank angle during UP we were limited to four channels on the subject unit available for EMG recording of muscle activity and were able to collect from two muscle groups only. This meant that we were unable to assess the properties of the measures in other muscle groups that have a role in walking. The current study did not intend to make comparisons of muscle synergies on U-PED and during overground walking but it is acknowledged that this would be useful to investigate in future U-PED studies.

Strengths of the study

Exploration of EMG derived measures presents several challenges including: electrode placement; movement artefacts; and non-standardised methods of signal processing. All could contribute to potential errors in interpretation and analysis (Hug & Dorel, 2009). A strength of the current and previous study (Hancock *et al.* 2017), is the use of well-defined, replicable procedures for the use of sEMG, including the precise determination of muscle activity according to crank angle. Such standardised procedures are increasingly important as EMG technology is becoming increasingly portable and usable for clinical settings, meaning that the potential impact of derived measures is substantial.

Whilst the sample size was not ideal, participants demonstrated a wide range of lower limb impairment and walking ability, increasing the potential generalisability of findings from this group.

Conclusion

We have identified, using UP, that reciprocal activity of quadriceps and hamstrings muscles, and quadriceps muscle activity according to crank angle are both potential targets for physical therapies to improve motor recovery, differentiating as they do between stroke survivors and healthy older adults. We have also found that people greater than one year after stroke can achieve similarly smooth movement to older adults without stroke, without abnormal reciprocal activity in their unaffected limb, during a functional activity in an upright posture. Furthermore, of the three neuromuscular measures investigated- reciprocal muscle activity of quadriceps and hamstrings, smoothness of movement and muscle activation according to crank angle - our preliminary findings suggest that muscle activation according to crank angle is promising as a measure of lower limb impairment during a functional activity for people with stroke. Subsequent investigation should determine the magnitude of variance between testing sessions and between HOA and StrS. This study is, to the best of our knowledge, the first investigation of the utility of instrumented Upright Pedalling as a clinical measure of lower limb impairment after stroke and presents promising findings about potential targets for therapy, warranting further investigation.

Implications for Physiotherapy Practice

This paper contributes knowledge both on the measurement of impairment during functional activity after stroke, and on identification of potential targets for rehabilition of walking after stroke, a priority for stroke rehabilitation. Stroke survivors more than one year after stroke could produce similarly smooth movement to healthy older adults during a functional task in an upright posture. Activation of quadriceps muscles according to crank angle during upright pedalling is one potential target for physical therapies to improve recovery of walking after stroke.

Declarations of Conflicts of Interest: None

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SENIAM: surface electromyography for the non-invasive assessment of muscles. 2013; *guidelines available at* http://www.seniam.org

Table 1: Participant characteristics

	Stroke Survivor Group, StrS						Healthy Older Adult Group, HOA		
Participant	**Gender**	**Affected side**	**Age (years)**	**Time since stroke onset (years)**	**MI Score (lower limb /100)**	**FAC Score (/5)**	**Participant**	**Gender**	**Age (years)**
RePed, STK 01	M	Right	58	1.5	92	5	**RePed, HV01**	M	56
RePed, STK 02	F	Left	70	3.0	84	4	**RePed, HV02**	F	52
RePed, STK 03	M	Right	58	4.3	48	1	**RePed, HV03**	M	54
RePed, STK 04	M	Left	70	1.2	84	4	**RePed, HV04**	F	59
RePed, STK 05	F	Left	71	12.7	78	4	**RePed, HV05**	F	62
RePed, STK 06	F	Left	41	19.8	65	4	**RePed, HV06**	M	56
RePed, STK 07	M	Right	57	5.8	49	2	**RePed, HV07**	M	53
RePed, STK 08	M	Right	75	10	38	1	**RePed, HV08**	M	64
RePed, STK 09	M	Right	69	3.5	53	5	**RePed, HV09**	F	68
RePed, STK 10	M	Right	58	5.8	43	2	**RePed, HV10**	M	51
RePed, STK 11	F	Right	47	9.3	65	4			
RePed, STK 12	F	Left	51	10.7	76	4			
RePed, STK 13	F	Right	53	6.0	51	1			
RePed, STK 14	M	Right	62	4.6	92	3			
RePed, STK 15	M	Right	51	1.7	60	2			
RePed, STK 16	M	Left	71	5.2	65	4			
RePed, STK 17	F	Right	47	2.8	73	5			
RePed, STK 18	F	Left	75	6.1	76	2			
Summary	8/18 F	11/18 R	61 (41 to 75)*	6.3 (1.2 to 19.8)*	66.2 (38 to 92)*	3 (1 to 5)**		4/10 F	58(51 to 68) *

*mean (range) **median (range)

Table 2: Results of analysis of difference between stroke survivor group, StrS, and healthy older adult group, HOA, for the measurement of lower limb motor impairment by UP: reciprocal muscle activity & smoothness

Clinical measure		**Healthy older adult group, HOA**	**Stroke survivor group, StrS**	**Mean Difference (95%C.I) p-value**
Reciprocity (affected limb)	N	10	15	-0.249
	Mean	0.248	0.500	(-0.491 to -0.010)
	StdDev	0.255	0.305	P=0.044*
Reciprocity (unaffected limb)	N	10	17	-0.146
	Mean	0.248	0.393	(-0.379 to 0.087)
	StdDev	0.255	0.298	P=0.208*
Smoothness	N	10	18	-0.003
	Median	0.014	0.017	P=0.367**
	Semi IQR	0.0015	0.0050	

*two-sample *t*-test **two-sample Wilcoxon

Table 3: Results of analysis of difference between stroke survivors and healthy volunteers for the measurement of lower limb motor impairment by UP: muscle activation timing

Muscle	Wheel Bins	Mean percentage activity on		p-value[1]
		Healthy volunteers N=10	Stroke Patients N=17	
Quadriceps	1	84.3	71.7	
	2	74.7	68.3	
	3	58.8	69.4	**Group:** p = 0.111
				Bins: p = 0.034
	4	27.7	76.4	**Bin*Group:** p = 0.084
	5	37.2	77.7	
	6	62.2	82.2	
	7	89.4	83.0	
	8	98.5	79.6	
Hamstrings	1	32.3	56.8	
	2	36.8	60.8	
	3	47.9	68.3	**Group:** p = 0.347
				Bins: p = 0.202
	4	58.5	70.3	**Bin*Group**: p = 0.240
	5	63.6	68.9	
	6	44.0	68.5	
	7	35.5	51.4	
	8	34.0	50.9	

[1] Based on Wilk's Lambda from a Multivariate Analysis of Variance; **Group**=between-groups comparison of mean activity across each turn, **Bins**=difference between percentage activity 'on' between bins. i.e. comparison of activity in each position bin; **Bin*Group**=significance of pattern of activity, between groups.

Table 4: Results of analysis of test-retest repeatability for reciprocal muscle activity and smoothness of pedalling: agreement between testing sessions for HOA at each of five speeds and StrS pedalling at comfortable cadence

	Clinical measure			
	Reciprocal Activation		Smoothness	
	N	ICC (95% CI)	N	ICC (95% CI)
HOA				
Cadence 10rpm	10	0.28 (0, 0.75)	10	0.46 (0, 0.83)
Cadence 20rpm	9*	0.18 (0,0.73)	10	0.59 (0.01, 0.88)
Cadence 30rpm	9*	0 (0, 0.63)	10	0.12 (0, 0.67)
Cadence 40rpm	9*	0.61 (0.10, 0.90)	10	0.64 (0.10, 0.90)
Cadence 50rpm	9*	0.72 (0, 0.85)	10	0.52 (0, 0.85)
StrS			18	0.28 (0, 0.65)
Unaffected Limb	10	0.38 (0, 0.80)		
Affected Limb	17	0.35 (0, 0.70)		

*technical difficulties with one channel leading to data available for N=9 not N=10 for cadences 20, 30, 40 & 50rpm

Table 5: Results of analysis of test-retest repeatability for muscle activity according to crank angle

	N (no. of wheel bins)	ICC (95% CI)
Healthy Volunteers		
Quadriceps	10 (80)	0.76 (0.65, 0.84)
Hamstrings	10 (80)	0.56 (0.39, 0.69)
Stroke Survivor group		
Unaffected Quadriceps	17 (136)	0.67 (0.56, 0.75)
Unaffected Hamstrings	17 (136)	0.21 (0.05, 0.37)
Affected Quadriceps	17 (136)	0.46 (0.32, 0.58)
Affected Hamstrings	17 (136)	0.43 (0.28, 0.56)

Figure Legend:

Figure 1: Flow chart illustrating testing procedure for Stroke Survivor (StrS) participants

Figure 1:

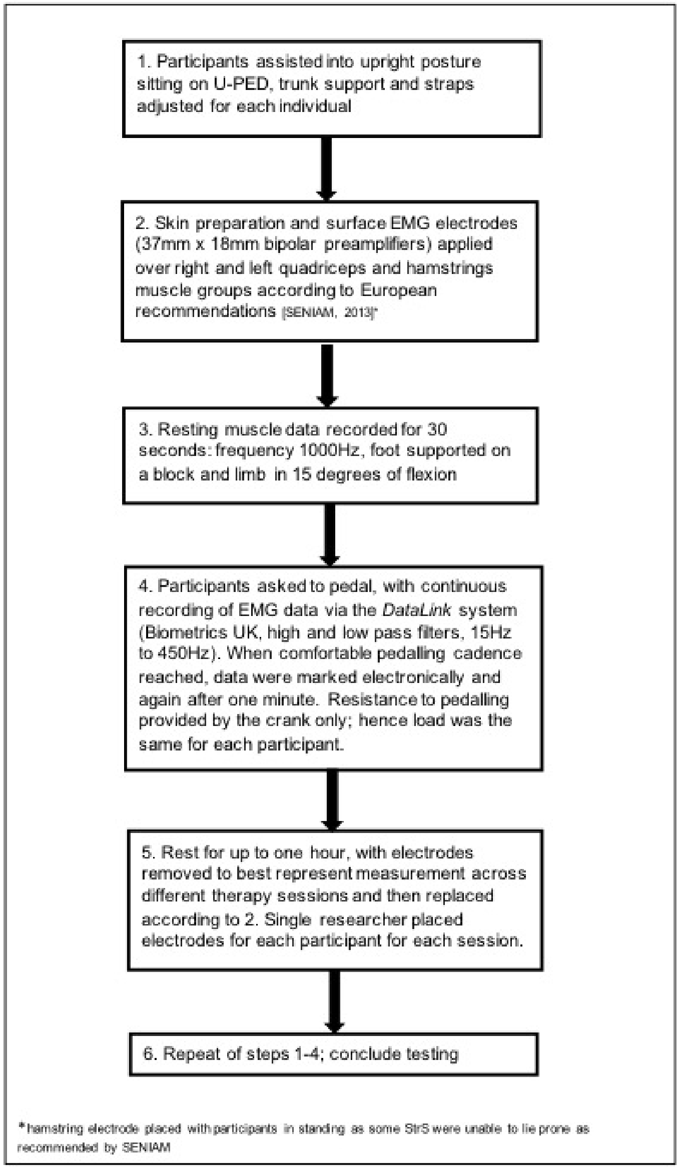

Figure 1: Flow chart illustrating testing procedure for Stroke Survivor (StrS) participants

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