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Towards Upright Pedalling to drive recovery in people who cannot walk in the first weeks after stroke: movement patterns and measurement.

Introduction

Repetitive practice of goal-directed, skilled functional tasks enhances the brain changes that underly recovery of motor function after stroke (e.g. Askim *et al.* 2009; Perez *et al.*2004). But, people who cannot walk, and hence cannot practice walking, cannot benefit. Indeed, these people are unlikely to have good recovery of walking function in response to the current package of rehabilitation interventions (Kwakkel & Kollen, 2013). Better methods of walking rehabilitation are in the top-ten research priorities set by stroke survivors (Pollock *et al.* 2012).

Body-weight support treadmill training (BWSTT) has been proposed as a tool to meet this challenge but provides no benefit over over-ground walking training (Dobkin & Duncan, 2012). Robotic systems and exoskeletons have emerged as possible interventions for walking practice after stroke but research findings are preliminary and it is recommended that electromechanical gait training should be used only in the context of research studies (NICE, 2013). Such devices are also expensive and potentially challenging to deploy in rehabilitation settings that include people's homes.

A potential way forward is to provide static reciprocal upright pedalling exercise (Hancock *et al*. 2012). Pedalling is a repetitive, functional activity with muscles organised into phasic groups (Raasch & Zajac, 1999). Such muscle synergies have been demonstrated to be similar between walking and pedalling in a small sample of healthy adults during ergometer pedalling (Barroso *et al.* 2014). For stroke survivors the majority of published developmental studies employed recumbent-type pedalling equipment (e.g. Fujiwara *et al.* 2003; Katz-Leurer *et al.,* 2003, Katz-Leurer *et al.* 2006). Whilst this equipment may be easier for stroke survivors to use, it does not provide the upright posture for lower limb activity congruent with walking practice. Some support for UP is provided by the finding that participation in a modified vertical pedalling task produced an increase in quadriceps activity and increased net positive work output in response to verticality in people late after stroke (Brown *et al.* 1997). Upright pedalling could, therefore, provide task-specific training of walking-like movement in a more functional posture than sitting.

The focus of the study reported here was on the potential use of UP to train walking in those unable to actually walk early after stroke. As a first stage of investigation we examined:

1) whether stroke survivors who are within 31 days of stroke onset and unable to walk are able to produce controlled lower limb movement during Upright Pedalling (UP), as measured by smoothness of pedalling activity;
2) the phasic activity in antagonistic lower limb muscle groups during UP.

Methods

Design and ethics:

This observational study used data from participants for whom muscle activity and/or kinematic data were available (n=8) from a feasibility study (n=13) investigating UP early after stroke (Hancock *et al.* 2011). Ethical approval and Research Governance approval were in place. All participants provided informed consent.

Participants:

All participants:

- Were adult in-patients of an acute stroke unit;
- Were between three and 30 days from stroke onset
- Had unilateral lower limb paresis
- Were unable to walk without assistance (scoring 0, 1 or 2 on the Functional Ambulatory Categories, Holden *et al.* 1984)
- Were considered fit to participate as assessed by a physician-led medical team with resting oxygen saturations of 95% or above, resting heart rate of 90 bpm or less and resting systolic blood pressure of 100-160mmHg
- Were able to follow a one-stage command
- Were able to participate in UP for at least one, one-minute session.

UP equipment and instrumentation:

To provide (a) Upright Pedalling therapy for people with substantial lower limb paresis early after stroke and, (b) movement-based, physiological measurements to characterise motor impairment, we designed a novel prototype Upright Pedalling device (U-Ped). 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 (Hancock *et al.* 2011). Postural support for the trunk and pelvis and variable seat height enables the upright posture required (figure 1). Upright here refers to the participant's trunk being aligned with the seat tube and the angle between the seat tube and horizontal approximately 90 degrees (Chen *et al*. 2001).

The U-Ped wheel was divided into eight 45 degree position bins with reflective markers. During pedalling a LED sensor, placed at a fixed point on the bike frame, was triggered as each of the markers passed. This caused a spike in the software, recorded synchronously with surface electromyography (sEMG) data (*DataLink* system, Biometrics, UK). Thus muscle activity was mapped to the position of the pedal during the 360 degree turn. The crank angle was recorded between the right crank and the seat tube where 0 degrees represents top dead centre (TDC) and 180 degrees represents bottom dead centre (BDC) (figure 2).

Procedure:

Motor behaviour measures were made (details below). Participants were then assisted into an upright position on the U-Ped and the trunk support and straps adjusted as required for each individual. Following skin preparation, surface EMG electrodes were positioned over right and left quadriceps and hamstrings muscle groups, using current guidelines (SENIAM, 2013) with a slight variation for hamstring electrode placement due to participant inability to lie prone or stand independently. A single researcher placed the electrodes for each participant.

Resting muscle data was then recorded at a voltage of 1000Hz with the foot supported on a box and the limb in 15 degrees of flexion for 30 seconds (see ‘data processing’ below). Participants were then asked to pedal and when they reached their comfortable cadence data were recorded for one minute. During pedalling, EMG data were recorded continuously using the *DataLink* system (Biometrics UK; high and low pass filters, 15 to 450Hz).

Data Processing:

Muscle activity data were processed using custom-written scripts in *Microsoft Excel 2007*. Raw signal was rectified and to reduce signal variability and present an accurate mean trend of signal development, a moving average of 50ms was used to create linear envelopes. These values represented the area under the curve for the selected epoch of 50ms.

Establishing muscle activity bursts:

Baseline muscle activity was recorded from each muscle in supported upright sitting on the bike with the feet resting on blocks, knee resting at approximately 15 degrees of flexion. This procedure was designed so that any additional activity above this baseline would reflect that used to pedal the crank in the same upright posture.

Onset and offset of muscle activity was determined using a threshold of three standard deviations (3SD) above a participant’s mean resting activity (e.g. Brown et al. 1996; Neptune et al. 1997). Baseline (threshold) EMG values were then calculated from the processed signal as the mean ± 3 SD during the 30 seconds resting data collection period. Where activity was above this threshold value, the muscle was considered “on” and where below this threshold value, the muscle was considered “off”.

Each data set was then manually checked to determine any need for additional filters. Raw output was visualised in the *SPIKE 2 5.13* (Cambridge Instruments, Cambridge UK) package and the pattern compared with the expected “on/offs” in *MS Excel* calculated as above. Where there was any discrepancy between the two, power spectral analyses were carried out. Where these demonstrated regular harmonics from external noise, a band stop filter was applied in addition to the built-in filters of the *DataLink* system. This occurred in two of the data sets reported here.

Bursts of activity were mapped according to both the time of onset/offset and the crank angle. For each 45 degree position bin, onset of activity was described by the exact amount of time for which the activity was above the threshold, expressed as a percentage of total time for the relevant position bin. For example, if the muscle was continually above the threshold throughout a whole position bin, this would be 100% on, and if not above the threshold at all within a position bin, it would be 100% off, with any variations of percentage activity in between. This technique enabled a precise determination of muscle activity according to crank angle and removed the need to arbitrarily select a timeframe above which the muscle was considered active. It quantified the activity occurring during pedalling and could enable potential comparisons between pedalling sessions and individuals. It allowed for the production of phase diagrams to accurately depict activity (figure 3) and is therefore a reproducible methodology for measuring muscle activity during UP.

Measurement Battery:

Motor behavioural measures:

- ability to produce voluntary muscle contraction in the lower limb as measured by the Motricity index (Demeurisse *et al.* 1980),
- ability to walk as measured by the Functional Ambulatory Categories (FAC; Holden *et al.* 1984), and
- trunk control as measured by the Trunk Control Test (Collin & Wade, 1990).

Reciprocal activation of antagonistic muscle groups during UP:

Values were produced using Jaccard's Coefficient (J): a cross-tabulation analysis of the processed data using *SPSS (v18)* with rectified, processed EMG data for each antagonistic muscle group. The formula used was:

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

where a= muscles active together, b=quadriceps active, hamstrings inactive and c= hamstrings active, quadriceps inactive

A J-value of 1.0 therefore indicated perfect positive correlation, and therefore complete co-contraction, or no reciprocal activation, of an antagonistic muscle pair. A J-value of 0 indicates a perfect negative correlation, with no co-contraction between the two muscles at all, and therefore complete reciprocal activation of antagonistic muscle groups.

Smoothness of pedalling movement (S-Ped):

Smoothness of pedalling movement (S-Ped) was determined from the standard deviation of mean time spent in each of the eight position bins for each turn, over ten complete turns of the wheel taken from a central portion of each pedalling session (figure 2). Hence, a high standard deviation represented less smooth pedalling than a low standard deviation.

Analysis

Smoothness of pedalling, reciprocity of muscle activity and cadence were tabulated for individual participants and described alongside visual depictions of muscle activity using phase diagrams.

Results

Participant characteristics:

Table 1 presents participant characteristics. In summary, participants were eleven days or less from stroke onset (Mdn 8, IQR 2.25), unable to walk (FAC = 0, all participants), severe to moderate lower limb paresis (MI score Mdn 48.5, IQR 33.5), a range of trunk control (TCT score Mdn 43.5, IQR 37).

Smoothness of lower limb movement (aim 1):

Pedalling smoothness ranged from S-Ped 0.012 to S-Ped 0.164 (table 2). Whilst all participants demonstrated smooth pedalling activity, the lowest S-Ped scores were achieved by participants with the lowest comfortable pedalling cadences; conversely, smoothest pedalling activity was achieved by those with higher comfortable pedalling cadences.

Reciprocal activation of quadriceps and hamstrings (aim 2):

Different muscle activation patterns, hence J-values, were found during UP (table 3), both in the affected and unaffected lower limb. This heterogeneity is illustrated by a selection of phase diagrams created from the percentage activity throughout the pedalling cycle (figure 3). Pattern variation included: reciprocal muscle activity in the affected leg (figure 3a, J=0.053) accompanied by hamstring activity throughout much of the cycle in the less affected leg, with quadriceps contributing to the upstroke (figure 3b, J=0.245); and, no activity in the affected leg (figure 4a) with pedalling entirely by reciprocal muscle activity in the less affected leg (figure 4b, J=0.038).

Table 1: Participant characteristics

Participant characteristics	**N=8 early stroke survivors; n=6 males;** Mdn (IQR)
Age, years	76.5 (18)
Time since stroke onset, days	8 (2.25)
Functional Ambulatory category (/5)	0 (0)
Motricity Index (/100)	48.5 (33.5)
Trunk Control Test (/100)	43.5 (37)

Table 2: Individual participant smoothness scores and pedalling cadence

Participant ID	Smoothness Score (S-Ped) lower score=smoother pedalling	Cadence (rpm)
01	0.016	41.5
02	0.047	39.5
03	0.136	20.0
04	0.012	53.2
05	0.012	43.1
06	0.068	37.5
07	0.164	18.0
08	0.065	28.1

Table 3: Participant Reciprocity scores, expressed as J-values

Participant ID	Reciprocity Score affected leg (J-value 0-1*)	Reciprocity Score unaffected leg (J-value 0-1*)
01	excessive signal noise	excessive signal noise
02	excessive signal noise	excessive signal noise
03	No quadriceps activity	0.005
04	No muscle activity	Quadriceps activity only
05	No muscle activity	0.038
06	0.288	0.531
07	0.468	0.608
08	0.053	0.245

* J-Value closer to 0= better reciprocal activity; J-value closer to 1= less reciprocal activity.

Discussion

Smooth pedalling was observed in this group of early stroke survivors, with a range of S-Ped scores from 0.012 to 0.164. Inter-participant differences in muscle activity patterns were found, in terms of phasic activity according to wheel position and reciprocity between muscle groups in both the affected and unaffected limbs. Results for smoothness and phasic muscle activity will now be considered in more detail.

Smoothness of lower limb movement during UP

Smoothness varied across participants; notably, the least controlled movement was observed at lowest pedalling speeds (S-Ped 0.164 at 18rpm; S-Ped 0.136 at 20rpm). Demands on stroke survivors pedalling early after onset are likely to be considerable as they attempt to re-establish coordinated movement patterns following damage to motor control systems. If able to achieve higher pedalling speeds, motor units are required that can rapidly activate and deactivate to meet the increasing frequency of the task (Ansley & Cangley, 2009) but at slower speeds it is possible that agonist/antagonist co-contraction, with its associated negative work, contributes to less smooth movement.

In the three participants for whom reciprocity was calculable for both legs, increased co-contraction was evident in the unaffected limb. It is possible here that the affected limb might be increasing negative work done throughout the cycle which in turn puts increased work on the unaffected limb of stroke survivors (Kautz and Brown, 1998). Further data are now required to explore a larger sample of participants and develop an understanding of what specific mechanisms UP might target.

Phasic muscle activity during UP

That we found inter-participant differences in muscle activity patterns during UP was unsurprising, as stroke does not have uniform effects on neural networks, and adaptive post-injury plasticity occurs in diverse regions both local to and remote from the primary site (Nudo, 2006). Indeed, inter-participant variability of muscle activity patterns during pedalling has been demonstrated in later-stage stroke survivors, using adapted ergometer pedalling in upright postures (Kautz & Brown, 1998). In contrast, these authors observed consistent patterns of activity in healthy older adults (Kautz &Brown, 1998; Brown &Kautz, 1998). Further work is needed to evaluate if patterning might continue or be disestablished with repeat UP sessions, and what the implication of that patterning might be to functional rehabilitation outcomes. For example, it might not be reasonable to assume homogeneity of activity this early after the onset of stroke; stroke survivors might need to adopt a variety of strategies to achieve functional movement that can then be refined with on-going therapy support.

It is of note that smooth pedalling activity despite no measurable activity above baseline in either muscle group in the affected leg was observed in one participant (figures 3c & 3d).This indicates pedalling by the unaffected limb alone and only passive movement of the affected limb due to the coupled crank, and highlights the importance of analysing activity in both limbs early after stroke. This use of the unaffected lower limb alone in pedalling activity early after stroke might not be deleterious- it has been suggested that up-regulation of ipsilateral excitatory pathways might assist the hemiplegic leg as the unaffected leg pedals (Kautz *et al.*2006). The functional implication here is that even single limb pedalling, as seen in one participant in the current study, might make beneficial contributions to bilateral motor patterns post-stroke.

Limitations of the study

Excessive signal noise was experienced for two data recording sessions in the hospital setting for this study, meaning that we were unable to calculate reciprocity scores in these cases. The reported sample was small (n=8), though stringent selection criteria ensured parity of some characteristics across participants.

Strengths of the study

The study recruited participants early after stroke, in the period in which the brain is most responsive to behavioural input. Meeting the challenge of recruiting people early after stroke is essential to the development of new rehabilitation interventions that can be initiated in the important first weeks after onset (Stinear, *et al.* 2013). It was carried out in a University Hospital Stroke Unit, hence a “real world” setting for people early after stroke. For this developmental investigation, and to inform comparisons with future studies of the intervention, well-defined, replicable procedures for the use of sEMG during UP, were designed and reported here.

Exploratory work such as this is considered an important foundation for the development of complex rehabilitation interventions and their translation to clinical use (Craig *et al.* 2008).

Conclusion

This is, to the best of our knowledge, the first examination of elements of the neurophysiology of upright pedalling in people during the first few weeks after stroke. These observational data indicate that people with substantial paresis early after stroke and who cannot walk, even with the hands-on assistance of therapists, can produce smooth movement during UP using a variety of muscle activation strategies. This work has provided a platform for future iterative studies of UP. The next stage in this investigation is to begin to test the hypothesis that UP can drive walking recovery in people with substantial paresis early after stroke.

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Figures

Figure 1: U-Ped, demonstrating Upright Pedalling posture

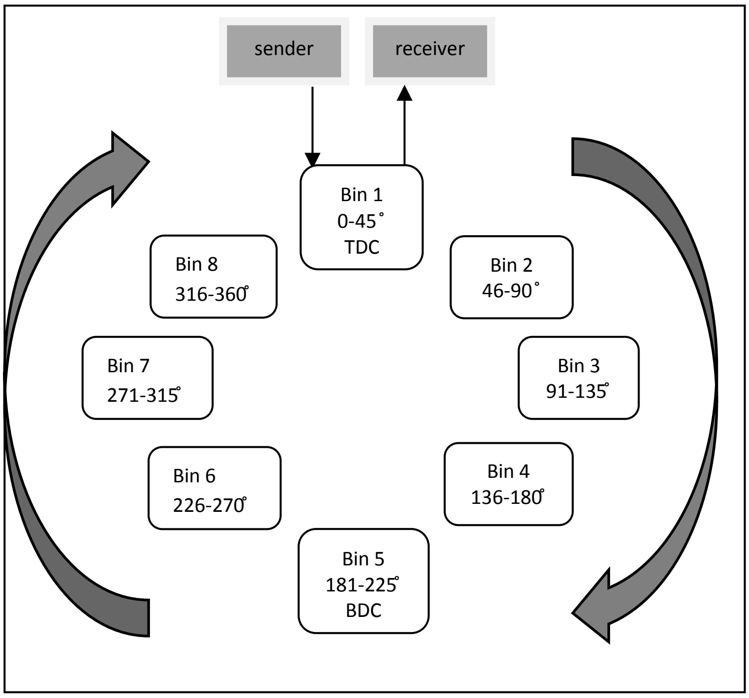
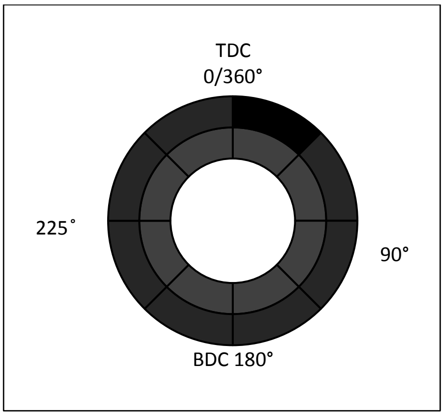
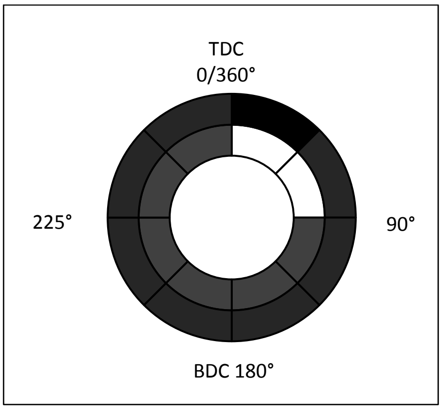


Figure 2: Schematic representation of wheel bins and crank angle sensor system. TDC= top dead centre, BDC= bottom dead centre

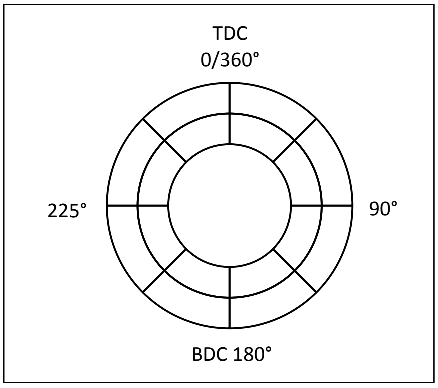
Figure 3: Phase diagrams demonstrating patterns of activity according to wheel position bin. Outer ring=hamstrings, inner ring=quadriceps. Grayscale used to indicate percentage activity, darker shading indicates more activity, lighter shading indicates less activity



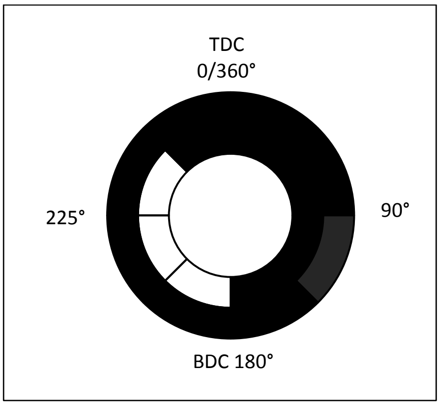
a. Participant 8; affected leg, demonstrating reciprocal muscle activity throughout cycle, J=0.053, accompanying moderately smooth pedalling (S-Ped=0.065)



b. Participant 8; unaffected leg, activity less reciprocal than in affected leg with hamstrings activity throughout the cycle and quadriceps contributing to the upstroke, J=0.245



c. Participant 5; affected leg demonstrating no activity in quadriceps or hamstrings above resting, but smooth pedalling activity demonstrated (S-Ped 0.012) due to contribution from the unaffected leg (see d.)



d. Participant 5; unaffected leg, demonstrating reciprocal muscle activity, J= 0.038, where the affected leg demonstrated no activity (see figure c.)