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The Sensewheel: an adjunct to wheelchair skills training

Andrew Symonds[1], Stephen J.G. Taylor[1] and Catherine Holloway[2]

[1] Centre for Rehabilitation Engineering and Assistive Technology, University College London, London, HA7 4LP, United Kingdom
[2] University College London Interaction Centre, University College London, London, WC1E 6EA, United Kingdom
E-mail: andrew.symonds.12@ucl.ac.uk

The purpose of this study was to investigate the influence of real time verbal feedback to optimise push arc during over ground manual wheelchair propulsion. 10 healthy non wheelchair users pushed a manual wheelchair for a distance of 25 metres on level paving, initially with no feedback and then with real time verbal feedback aimed at controlling push arc within a range of 85˚-100˚. The real time feedback was provided by a physiotherapist walking behind the wheelchair, viewing real time data on a tablet personal computer received from the Sensewheel, a lightweight instrumented wheelchair wheel. The real time verbal feedback enabled the participants to significantly increase their push arc. This increase in push arc resulted in a non-significant reduction in push rate and a significant increase in peak force application. The intervention enabled participants to complete the task at a higher mean velocity using significantly fewer pushes. This was achieved via a significant increase in the power generated during the push phase. This study identifies that a lightweight instrumented wheelchair wheel such as the Sensewheel is a useful adjunct to wheelchair skills training. Targeting the optimisation of push arc resulted in beneficial changes in propulsion technique.

1. Introduction: Wheelchair skills training focuses on minimising task repetition and peak forces to preserve upper limb function [1]. The specific aims of training are to achieve the required velocity, aiming for a push arc of 85˚-100˚ and a push rate of approximately 1 push per second [1]. The availability of instrumented wheelchair wheels enables the provision of real time feedback to optimise manual wheelchair propulsion [2]. Previous research has investigated the influence of real time feedback on push rim kinetics. Real time visual feedback has demonstrated a consistent capacity to reduce push rate and increase push arc [3-5]. Less consistent results are presented for minimising push force [3, 5] and increasing fraction of effective force [6, 7]. Real time visual feedback can be used in the laboratory or clinic, but it is not practical during outdoor propulsion. During outdoor propulsion, manual wheelchair users are required to focus their visual attention on the terrain that they are negotiating.

Alternative options for providing real time feedback include auditory and haptic feedback. The influence of these types of feedback on motor learning has been reviewed [8]. Auditory feedback has been suggested as a beneficial alternative to visual feedback as auditory feedback does not require a specific orientation or focus of attention [8]. Real time 'concurrent' auditory feedback has been successfully applied in different ways. Real time verbal feedback has been used successfully to alter biomechanics during running [9] and an alarm system to inform optimal knee flexion angle has been used during a kicking task [10]. Such alarms or triggers are easy to interpret and useful for detection of which direction the movement should be corrected, however such feedback does not provide precise information on how much a movement needs to be corrected.

The aim of this study is to investigate whether real time auditory feedback can be used to influence biomechanics during over ground manual wheelchair propulsion. The study will focus on optimising push arc, and will measure the cross variable effects of any change. It is hypothesised that real time auditory feedback will enable a significant increase in push arc, which will reduce task repetition.

2. Methods:
2.1. Participants: The study received ethical approval from the University College London (UCL) Research Ethics Committee (Approval number 4726/002). Healthy participants were recruited if they were aged between 18 and 65 years, were able to propel a manual wheelchair and reported no history of shoulder surgery and no shoulder pain within the previous 3 months. All participants provided written informed consent in advance of data collection.

2.2. Experimental protocol: Participants attended for a single visit and were asked to report their gender, age, and had their weight measured. Each participant transferred into the test wheelchair, the Vanos Excel G6 High Active 'Sport Edition'. The right rear wheel of the wheelchair was replaced with the Sensewheel Mark 1 (Movement Metrics, London, UK), a lightweight instrumented wheelchair wheel measuring 3-dimensional forces applied to the push rim and the temporal parameters of propulsion.

The wheelchair propulsion tasks were completed outdoors, over a 25m stretch of straight, level paving slabs. Participants were provided with a practice period. The participants then completed an initial 'baseline' propulsion task, during which propulsion parameters were measured. The task was then repeated with the addition of real time verbal feedback to optimise push arc, whilst propulsion parameters were measured.

2.3. Real time feedback: During the propulsion tasks, data was streamed in real time from the Sensewheel to a tablet personal computer (Samsung XE7001TC-A05UK). A custom LabView (National Instruments Corp, Tx, USA) graphical user interface (GUI) provided real time data on chair velocity, peak force and push arc.

The tablet was carried by a physiotherapist. The physiotherapist provided real time feedback on push arc, with the aim of maintaining a push arc of 85˚-100˚ [1]. The format of the feedback was explained to the participant before the intervention. Feedback was provided during the recovery period of the push cycle. If the previous push was applied over an arc less than 85˚, the participant was instructed to 'push longer'. If the previous push was applied over an arc greater than 100˚, the participant was instructed to 'push shorter'. If the previous push was applied over an arc between 85˚ and 100˚, no instruction was provided.

2.4. Push rim kinetics: Push rim parameters were recorded using the Sensewheel. This lightweight modification to a pillar connected push rim type of wheel involves the inclusion of three load cells to replace the pillars. An example of a Sensewheel load cell is shown in Fig 1. These 'slaves' are each instrumented with 8 strain gauges and contain local amplification and data processing, and connect to a 'master' controller and telemeter mounted at the wheel hub. Load cells are pre-calibrated for tangential, radial and axial force, with raw data telemetered by ultra high frequency radio.

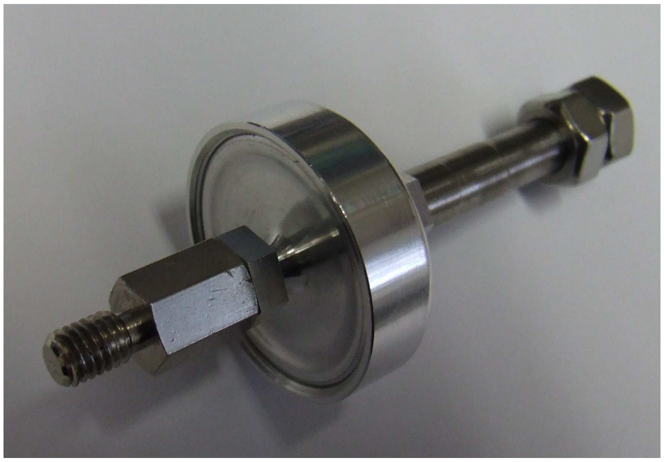

Fig. 1 Sensewheel load cell

Data are received in real time by a LabView program on the tablet which decodes measured strains back into forces, for combination and display. Local load cell co-ordinate systems are resolved into a global wheel co-ordinate system for finding the resultant instantaneous tangential, radial and axial forces acting on the wheel. Slave accelerometers measure wheel angle and allow for co-ordinate transformation. A gyroscope measures the wheel rotation speed.

2.5. Sensewheel data processing: Push rim parameters were calculated from each of the pushes required to complete the baseline and real time feedback tasks, using the Python programming language (Python Software Foundation, https://www.python.org/). Each push from each propulsion task was analysed. The start of the task was defined when the wheel moment increased above 1N·m until the start of the braking phase, defined when the wheel moment decreased below 1.5N·m. The number of pushes, push rate and mean chair velocity were calculated from the duration of the task. The individual push phases were identified when the wheel moment was in excess of the threshold of 1N·m. The mean push arc and percentage push phase were calculated from each push. The mean push phase moment and angular velocity (ω) were used to calculate mean push phase power (1) [11]:

$$\text{Power (W)} = \text{Moment (N·m)} \cdot \omega\ (\text{rad·s}^{-1}) \qquad (1)$$

Peak resultant force (F_{Res}) was calculated using measured tangential (F_x), radial (F_y) and axial (F_z) forces (2):

$$F_{Res} = \sqrt{(F_x^2 + F_y^2 + F_z^2)}\ \text{(N)} \qquad (2)$$

Mean peak force for the task was calculated from each of the pushes.

2.6. Statistical analysis: Statistical analysis was completed using IBM SPSS Statistics version 22 (IBM Corp, NY, USA). The Kolmogorov-Smirnov and Shapiro-Wilk tests were used to analyse whether the differences between baseline and intervention results were normally distributed. When data were normally distributed, the influence of the intervention was assessed using the dependent samples t-test. When data were not normally distributed, the Wilcoxon signed rank test was used. The significance level was set at $P<0.05$.

3. Results: Ten non wheelchair users (2 women, 8 men) participated in the study. Each participant reported no previous experience using a manual wheelchair. On average, the participants were 30.1 ± 7.3 years of age and weighed 68.3 ± 7.6 kg.

The push rim parameters measured during the baseline test and with the addition of real time feedback are presented in Table 1. The intervention of real time verbal feedback resulted in a 47.22% increase in push arc that was statistically significant (53.75° vs. 79.13°, P = 0.005) (Fig. 2). This increase resulted in a non significant reduction in push rate (0.80sec^{-1} vs. 0.73sec^{-1}, P = 0.252) (Fig. 3) and a significant increase in peak force of 26.16% (44.07N vs. 55.60N, P = 0.003) (Fig. 4).

Table 1: Push rim parameters measured during baseline and with the addition of real time feedback

	Baseline	**Feedback**	**P-value**
Push rate (sec^{-1})	0.80 (0.20)	0.73 (0.18)	0.252
Push arc (°)	53.75 (8.97)	79.13 (11.10)	**0.005**
Percentage push phase (%)	32.91 (7.58)	34.22 (5.97)	0.721
Mean velocity (m·sec^{-1})	0.76 (0.14)	0.95 (0.17)	**0.000**
Number of pushes	25.20 (5.70)	17.80 (3.46)	**0.000**
Mean moment (N·m)	7.55 (2.30)	8.99 (3.19)	**0.024**
Mean angular velocity (°·sec^{-1})	131.89 (25.35)	163.49 (28.40)	**0.000**
Mean power (W)	17.09 (5.61)	25.20 (8.98)	**0.003**
Peak force (N)	44.07 (10.72)	55.60 (16.77)	**0.003**

Data are mean (SD), statistically significant results in bold

The intervention resulted in participants completing the task at a significantly greater mean velocity (0.76m·s^{-1} vs. 0.95m·s^{-1}, P = 0.000) with significantly fewer pushes (25.20 vs. 17.80, P = 0.000). This was enabled by a significant increase in generation of power during the push phase (17.09W vs. 25.20W, P = 0.003), via a significant increase in mean push phase moment (7.55N·m vs. 8.99N·m, P = 0.024) and a significant increase in mean push phase angular velocity (131.89°·sec^{-1} vs. 163.49°·sec^{-1}, P = 0.000) with a similar percentage push phase (32.91% vs. 34.22%, P = 0.721).

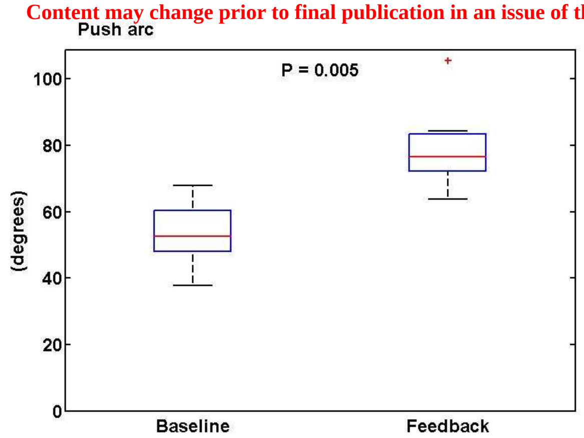

Fig. 2 Change in push arc

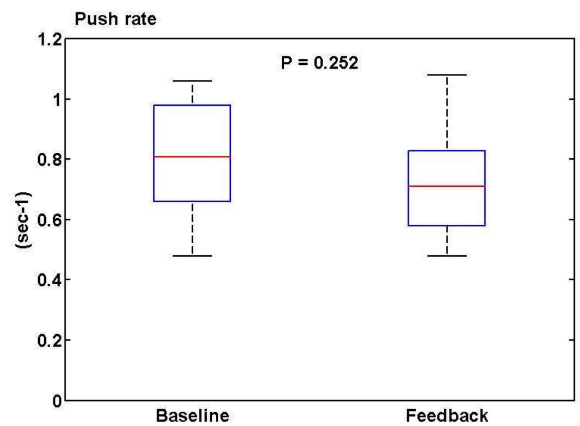

Fig. 3 Change in push rate

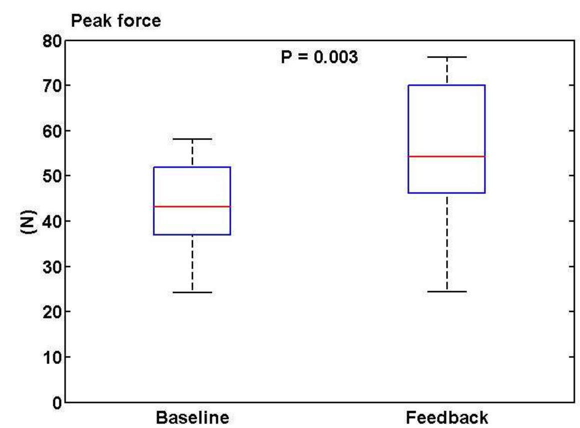

Fig. 4 Change in peak force

4. Discussion: The results demonstrated that real time verbal feedback was successful in increasing push arc during over ground manual wheelchair propulsion. Providing real time verbal instruction during the recovery phase of the propulsion cycle resulted in a statistically significant increase in push arc of 47.22%. This result supports previous research suggesting that push arc can be successfully modified with real time feedback. Previous studies have reported similar results using real time visual feedback during ergometer propulsion. Degroot *et al*. reported a 28.51% increase in push arc [3], Rice *et al*. a 10.01% increase [4] and Richter *et al*. up to a 31% increase [5].

The aim of the intervention was to achieve a push arc of 85˚-100˚, suggested as optimal by the propulsion training guidelines [1]. On average during the real time feedback task, the participants achieved an average push arc of 79.13˚. Further training may have enabled the participants to achieve the suggested push arc, but in reality during over ground propulsion, it may be difficult to achieve an average push arc in this range. This is due to the fact that some propulsion strokes are shortened to control the direction of travel of the chair and to manoeuvre the chair.

A previous study has demonstrated significant cross variable effects when maximising push arc using visual feedback [5]. Richter *et al.* reported a 31% increase in push arc, which resulted in a significant 30% reduction in push rate and a significant 34% increase in peak force. The current study intervention, leading to a 47.22% increase in push arc resulted in a non significant 8.75% decrease in push rate and a significant 26.16% increase peak force. In addition, increasing push arc resulted in a significant 29.37% reduction in the number of pushes required to complete the task.

Increased force application has been linked to an increase in shoulder joint loading [12] and degenerative changes [13, 14] and reduced push rate has been associated with a reduction in total muscle power requirement [15]. The published clinical guidelines suggest reducing frequency of the task and minimising peak forces to minimise risk of injury [1, 16]. In this study, the intervention to optimise (increase) push arc resulted in a significant reduction in the number of pushes required with a push rate within the suggested maximum, but a significant increase in peak propulsion force (55.60N). In a previous study using a musculoskeletal model to estimate shoulder joint contact force, a peak propulsion force of 59.30N resulted in a glenohumeral joint contact force of approximately 1050N (1.25 x body weight) [17]. Shoulder joint contact forces have been directly measured by a study assessing functional activities of participants with an instrumented shoulder joint prosthesis [18]. One of these activities was turning a steering wheel single handed and resulted in a shoulder joint contact force of 1.22 x body weight. This suggests that although increasing push arc did result in a significant increase in peak force, the resultant shoulder load would still be within the limits of standard daily activity.

Increasing the push arc also resulted in a significant increase in mean chair velocity during the task to 0.95m·sec^{-1}. This has important functional implications for the wheelchair user, as previous research has suggested that an average moving speed of 1.2m·sec^{-1} is required to safely negotiate a pedestrian crossing [19]. The intervention resulted in a greater mean chair velocity with fewer pushes required; due to an increase in push phase power via an increased mean push phase moment and angular velocity. Such technique changes show a similar pattern to the propulsion technique demonstrated by expert wheelchair users in comparison to novices [20].

4.1. Clinical application: The results of the study suggest that the Sensewheel could be a useful adjunct to the initial phase of wheelchair skills training. The graphical representation of the data to the therapist enables the provision of real time feedback to the patient. The results demonstrate that in a short time period, successful changes in technique can be facilitated. In addition, the outcome of the intervention can be recorded retrospectively to chart progress. The next generation of the Sensewheel is currently under development, to enable transfer of data via Bluetooth to the wheelchair user's smart phone. This development will include the automation of real time feedback to the user, to enable wheelchair propulsion training to continue away from the clinical setting.

4.2. Limitations: This study includes only novice non wheelchair users. Further research is needed to determine whether such an intervention could be successful with different populations of wheelchair users, considering the technique differences that exist [21]. In addition, further research should examine the intervention during propulsion over a variety of terrains and journeys. The majority of journeys completed by wheelchair users are completed over short distances, involving starting, stopping and manoeuvring [22], so the optimal technique for such tasks should be considered. Negotiating inclines is significantly more demanding than level propulsion [23]. Considering that novice wheelchair users may not have the required upper limb strength to achieve the optimal push arc against an increase in propulsion resistance, a graded training program may have to be implemented. This study only investigated the use of single variable auditory feedback for optimising push arc. Haptic feedback has been identified as another form of real time feedback, and has been used to alter biomechanics during walking [24]. It would also be useful to investigate how sonification of movement could be used to guide actual movement towards a reference movement [8] to combine feedback for more than one variable, for example push rate and push arc during wheelchair propulsion.

5. Conclusions: The purpose of this study was to identify whether providing real time verbal feedback to optimise push arc, using data presented in real time by the Sensewheel, could result in improved wheelchair propulsion technique. The results demonstrated that providing simple real time verbal feedback resulted in a consistent and significant increase in push arc during level over ground wheelchair propulsion. Relating to the risk of injury, the intervention demonstrated the beneficial effect of reducing push rate and the number of pushes required to complete the task, however peak force increased. On balance, it seems that reducing the task repetition is worth the increase in peak force, which would not load the shoulder in excess of common activities of daily living. In addition, the intervention resulted in increased mean velocity, achieved by increased generation of power during the push phase. The results suggest that a lightweight instrumented wheelchair wheel such as the Sensewheel could become a useful adjunct to wheelchair skills training, but should be trialled further during more demanding over ground propulsion tasks.

6. Acknowledgement: The authors would like to thank all of the study participants.

7. Funding and declaration of interests: This project formed part of the UCL Healthcare Engineering for an Ageing Population Studentship. This work was supported by The Engineering and Physical Sciences Research Council and Aspire. Dr Catherine Holloway is a guest Editor of *Healthcare Technology Letters*. Dr Catherine Holloway and Dr Stephen Taylor are Directors of Movement Metrics and Mr Andrew Symonds is a shareholder.

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