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ORIGINAL ARTICLE

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Effect of push frequency and strategy variations on economy and perceived exertion during wheelchair propulsion

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Abstract Wheelchair locomotion is a cyclical activity and participants are free to select any push frequency–propulsion strategy combination that suits their needs at a given power output. The aim of the study was to examine the physiological effects of varying push frequency and strategy on pushing economy. Twelve male, able-bodied participants completed four, randomly assigned, 5-min bouts of submaximal exercise at 32 W on a wheelchair ergometer. Each bout of exercise combined two different push frequencies (40 and 70 push min^{-1}), with one of two different push strategies [synchronous (SYN): both arms pushing together, and asynchronous: one arm applying force to the wheel at a time). Physiological measures included oxygen uptake ($\dot{V}O_2$), heart rate (HR) and blood lactate $[La]_b$ concentration. Differentiated ratings of perceived exertion (RPE) were also recorded (overall, local and central). Separate ANOVA were used for $\dot{V}O_2$, HR, $[La]_b$ and RPE as the dependent variables. Where significant differences were identified, a Bonferroni post hoc test was used. The main effect for push frequency by strategy was significant for $\dot{V}O_2$ ($P < 0.01$). Scrutiny of the HR values showed that the SYN 40 condition was significantly less stressful than all other frequency–strategy combinations ($P < 0.01$). RPE data supported these findings although they were found to be non-significant. When looking at $[La]_b$, both of the main effects were also significant showing the concentration was lower on average when the push rate was 40 as opposed to 70 (1.65 vs 2.14 mmol l^{-1}; $P < 0.01$). This study provides further evidence that a low push frequency provides the most economical form of wheelchair propulsion especially when combined with a SYN strategy.

Keywords Synchronous · Asynchronous · Push rate · Oxygen uptake · Blood lactate

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Introduction

Wheelchair propulsion is somewhat more complex than cycling and although both movement patterns are repetitive and of a cyclical nature, if we were to consider two wheelchair users exercising at a given power output, then clear differences in choice of push frequency and propulsion techniques would be evident (Goosey and Campbell 1998; Goosey et al. 1998, 2000). For example, unlike cycling, not only can the arm movement patterns vary, but also the point of contact with the hand-rim, the time in contact with the hand-rim, the force applied to the wheel with each push, and the movement about the trunk (Goosey et al. 2000). Furthermore, because the movement pattern is not constrained, then wheelchair users propelling a conventional wheelchair can adopt either a synchronous or asynchronous upper-limb movement pattern. A synchronous (SYN) push strategy can be best described as when both arms work in unison, applying force to the hand-rim at the same time. On the other hand, an asynchronous (ASY) push strategy would be described as when the arms work in an alternate fashion, with one arm applying force to the hand-rim at a time.

Wheelchair users typically propel their chairs using a SYN push strategy, with those using a lower frequency demonstrating better economy than those who select a high push frequency (Gaines et al. 1984; Jones et al. 1992; Goosey and Campbell 1998; Goosey et al. 1998, 2000).

Whilst the pertinent literature in this area has focused primarily on manipulations of push frequency (Woude et al. 1989; Goosey et al. 2000), variations in push strategy have recently begun to interest performers. Observations made during competitive wheelchair basketball at the recent 2002 World Championships, and during laboratory physiological testing of elite wheelchair basketball players, it is clear that some players are selecting an ASY push strategy.

A very limited amount of research has been conducted examining the physiological differences between SYN and ASY arm exercise, and these have almost exclusively used arm cranking as the mode of exercise (Hopman et al. 1995; Mossberg et al. 1999). These two studies carried out direct comparisons of SYN and ASY arm crank ergometry, while Glaser et al. (1980) examined wheelchair propulsion, with manipulation of strategy and drive ratio. Despite little statistical significance, the submaximal physiological data of all three studies indicated trends supporting the fact that ASY arm exercise was physiologically less stressful when compared with SYN arm exercise. However, the application of these data is limited due to differences in mode of activity. Moreover, for the study focusing on wheelchair propulsion (Glaser et al. 1980) there was no control or monitoring of push frequency. Studies on limb frequency and economy, from both a cycling (Hagberg et al. 1981; Marsh and Martin 1993, 1997; Marsh et al. 2000) and a wheelchair propulsion perspective (Woude et al. 1989; Goosey et al. 2000) have found that optimum frequencies do exist. Thus any differences found between ASY and SYN conditions within the work of Glaser et al. (1980) may not necessarily have been the result of the strategy alone, but may have been influenced by frequency differences.

Subjective reports from all subjects in the studies mentioned previously also indicated that ASY was less stressful than SYN (Hopman et al. 1995; Mossberg et al. 1999). The subjective reporting of exertion is another area that has received little attention in the scientific literature examining wheelchair propulsion. It is important to investigate how the combined manipulation of push strategy and push frequency not only affect physiological parameters in terms of economy, but also the local, central and overall perceptions of physiological stress.

Therefore, the purpose of the study was to examine the effects of push strategy at two imposed push frequencies on pushing economy during wheelchair propulsion. It was hypothesised that: (1) an ASY strategy would be physiologically less stressful and RPE differentiated ratings would also be minimised during this strategy and (2) the low push frequency at either push strategy would be more economical than at the corresponding high push frequency condition.

Methods

Participants

Twelve healthy, active, able-bodied participants gave their written informed consent to participate in the study. None of the participants had any prior experience of wheelchair sport or training in a wheelchair. Conducting this study with able-bodied participants meant that no individual already had a desirable frequency–strategy combination of their own. As a result this mode of locomotion was a complex new task for which economy changes due to frequency–strategy manipulations could be examined (Woude et al. 1999). Prior to participation, all participants were made fully aware of the requirements for participation. Body mass and sitting height were recorded to the nearest 0.1 kg and 0.01 m. Subject characteristics are given in Table 1. Approval for the study was obtained from the research ethics committee of the Manchester Metropolitan University, Crewe and Alsager Faculty.

Instrumentation

All testing was carried out using a computerised wheelchair ergometer (WERG) connected to a PC laptop computer, calibrated with software (Kingcycle Trainer System (6.8), High Wycombe, UK). All subjects were tested in the same wheelchair, an RGK basketball wheelchair (Interceptor, Serial Number SQ942-02), fitted with 0.61-m diameter wheels with 0.56-m diameter hand-rims and consisting of 12° camber. The WERG consisted of a single cylinder (length, 1.17 m; circumference, 0.48 m). A flywheel sensor connected to the roller and interfaced to the laptop computer calculated and displayed the power output. The laptop was visible to the participants at all times during testing, to allow them to maintain a constant power output. Once secured onto the WERG, each participant performed a standard calibration procedure as described previously (Goosey et al. 2000; Tolfrey et al. 2001).

Table 1 Participant characteristics. Values are means. $\dot{V}O_{2peak}$ Peak rate of oxygen uptake, *HR* heart rate

Participant no.	Age (years)	Sitting height (m)	Body mass (kg)	$\dot{V}O_{2peak}$ ($l\ min^{-1}$)	Peak HR (beats min^{-1})	Peak power output (W)
1	26	1.38	80.1	3.34	157	44
2	28	1.37	68.2	2.46	183	40
3	29	1.36	71.9	1.80	174	40
4	36	1.38	87.8	3.06	161	42
5	28	1.34	69.8	2.41	181	42
6	22	1.38	84.6	3.36	193	40
7	25	1.43	88.7	2.97	183	42
8	24	1.38	68.9	2.37	172	40
9	23	1.39	79.3	2.04	152	42
10	28	1.37	75.7	1.86	156	44
11	22	1.38	75.3	2.21	206	40
12	22	1.37	70.6	2.29	184	42
Mean	26	1.38	76.7	2.51	175	42
SD	4	0.02	7.3	0.54	16	1.5

Experimental procedure

An initial testing session was used to determine the participants' peak oxygen uptake ($\dot{V}O_{2peak}$) using a continuous WERG test starting at 20 W with 4-W increments every 2 min until volitional exhaustion. The initial power output was determined during a warm-up period and set to ensure that volitional exhaustion occurred within 8–14 min. Expired air was collected during the final 2 min of the test. The results of the peak test were used to establish the subject's aerobic power status during this mode of exercise to then ensure that during the submaximal discontinuous test, an appropriate submaximal power output was chosen.

On their second visit to the laboratory, participants performed a discontinuous test on the WERG, consisting of four different conditions at 32 W (2 m s^{-1}). Each condition combined one of two push strategies, SYN or ASY, with one of two push frequencies (40 or 70 push min^{-1}); trunk movements were not restricted. The push frequencies were selected on the basis of previous research by Goosey et al. (2000), whereby push frequencies of 40 and 70 push min^{-1} were shown to be representative of low and high push frequencies among wheelchair athletes, respectively. A visual and audio metronome indicated the push frequency for each condition. The order of the four conditions was randomised to ensure that each participant carried out the conditions in a distinctly different order. Each condition lasted 5 min, with physiological and rating of perceived exertion (RPE) measurements recorded in the last minute of each condition. Preliminary investigations prior to data collection found no differences in physiological or RPE measures between minutes 3–4 and 4–5; therefore, the first minutes of each condition allowed the participants to habituate themselves with the designated strategy–frequency combination. An 8-min rest period separated each test condition and included a 4-min 'active recovery' where participants were instructed to maintain a very low but comfortable speed. The main aim of this recovery period was to keep the arms moving whilst having to apply only minimal effort to push the wheel. Thus, both the active recovery and the habituation period aided lactate diffusion away from the working muscles. The rest period also allowed the participant's HR to return as close to their baseline HR as possible. This sequence was repeated for the remaining four conditions. A one-way analysis of variance was carried out to determine if the order of conditions influenced the results. A non-significant result, $F_{(5,55)} = 1.32$, $P > 0.05$, indicated that an order effect was not apparent, and thus any differences found between the conditions were as a consequence of the manipulated variables, not the order in which the conditions were carried out.

Physiological measures

During the last minute of each condition, an expired air sample was collected using a 150-l Douglas bag connected to a mouthpiece with a two-way valve and low resistance, wide bore tubing. Oxygen and carbon dioxide concentrations of the expired air were analysed (Servomex, Crowborough, UK, series 1400) following calibration of the analyser with known concentrations of three calibration gases (oxygen, carbon dioxide, nitrogen). A Harvard dry gas meter, calibrated against a Tissot spirometer, determined expired ventilatory volume.

A capillary blood sample was collected from the earlobe immediately prior to and following each condition. Blood lactate $[La]_b$ concentration was determined with an automatic analyser (YSI 1500 sport, Yellow Springs, Ohio).

Once the expired air had been collected, the mouth and nosepieces were removed and three RPE values were recorded using the Borg scale (Borg 1970) as an index of perceived physiological stress. Differentiated measurements were taken for perceptions of (1) overall (total body), (2) peripheral (arms and shoulders) and (3) central (heart/lungs) exertion. Full instructions (Robertson et al. 2000) regarding each of the three RPE measurements were provided to the participants before the testing began, with the added verbal information that all three measurements were entirely separate from each other, and the ratings given could be similar, the same or completely different, and the local and central ratings did not need to equate to the overall rating.

Data analysis

The statistics package for the social sciences (SPSS, Chicago, Ill.) was used for all statistical analysis. A two-way analysis of variance with repeated measurements of push frequency and strategy was applied to all physiological data recorded. A Bonferroni post hoc test was applied to determine the location of any significant main effects.

Results

The participants in this study had a mean $\dot{V}O_{2peak}$ of 2.51 (0.54) l min^{-1}, which ranged from 1.80 to 3.36 l min^{-1}. Propulsion at 32 W elicited a mean (SD) oxygen uptake of 52 (12)$\%^{-1}$ $\dot{V}O_{2peak}$. There were no main effects for oxygen uptake ($\dot{V}O_2$; pushing frequency and strategy), but a significant interaction, $F_{(2,22)} = 8.78$, $P < 0.01$, revealed the SYN 40 condition to be the most economical in terms of $\dot{V}O_2$ [1.15 (0.18) l min^{-1}] (Fig. 1). Mean (SD) $\dot{V}O_2$ values for SYN 40 were 13% lower than ASY 40 ($P < 0.01$), and 12% lower than SYN 70 ($P < 0.01$). There was no significant difference between any of the remaining conditions. Of the ASY conditions, ASY 70 produced the lowest $\dot{V}O_2$ [1.25 (0.22) l min^{-1}]; however, this was still 9% higher than the SYN 40 condition. The HR data supported the $\dot{V}O_2$ results, again with significant interactions, $F_{(2,22)} = 9.18$, $P < 0.01$, between SYN 40 and ASY 40 ($P < 0.01$), and SYN 40 and SYN 70 ($P < 0.01$) (Table 2).

The $[La]_b$ data revealed slightly different results. The main effects for push frequency, $F_{(2,22)} = 5.92$, $P < 0.01$, indicated, regardless of pushing strategy, that pushing at 70 push min^{-1}elicited a significantly higher $[La]_b$ than pushing at 40 push min^{-1}(2.12 vs 1.65 mmol l^{-1}, respectively). Significant main effects for push strategy, $F_{(1,11)} = 25.67$, $P < 0.01$, revealed that, regardless of push frequency, using an ASY strategy produces a significantly

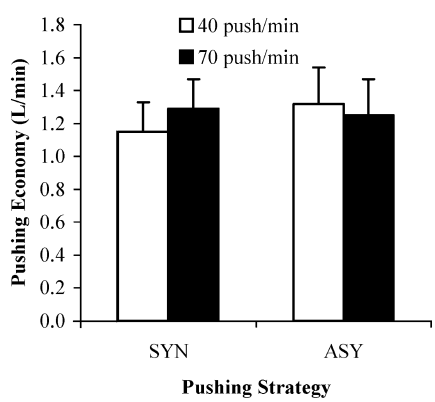

Fig. 1 Pushing economy (oxygen uptake) for the push frequency–strategy combinations at 32 W. *SYN* Synchronous push strategy; *ASY* asynchronous push stategy

Table 2 Physiological responses to wheelchair propulsion at the different push frequencies and strategies [mean (SD)]. *SYN*, Synchronous push strategy (at 40 and 70 push min^{-1}); ASY asynchronous push strategy (at 40 and 70 push min^{-1}); $[La]_b$ blood lactate concentration; RPE rating of perceived exertion

Physiological parameter				Condition			
	Push frequency	Push strategy	Frequency–strategy interaction	SYN 40	SYN 70	ASY 40	ASY 70
HR (beats min^{-1})			**	109 (14)[a,b]	117 (17)	118 (18)	115 (17)
$[La]_b$ (mmol l^{-1})	**	**	**	1.61 (0.71)[b]	2.60 (0.68)[c]	1.68 (0.85)	1.68 (0.61)
Overall RPE				11.0 (1.7)	12.9 (1.3)	11.8 (1.3)	11.8 (1.3)
Local RPE				11.0 (1.5)	14.1 (1.3)	12.3 (1.4)	12.8 (1.1)
Central RPE				9.0 (1.9)	10.9 (2.4)	10.3 (1.7)	10.2 (2.2)

**($P \leq 0.01$) A main effect and significant difference
[a]Significant difference ($P < 0.01$) across the 40 push min^{-1} conditions
[b]Significant difference (P < 0.01) between the SYN 40 and SYN 70 conditions
[c]Significant difference ($P < 0.01$) across the 70 push min^{-1} conditions

lower $[La]_b$ than a SYN strategy (1.69 vs 2.11 mmol l^{-1}, respectively). The interaction, $F_{(2,22)} = 5.79$, $P \leq 0.01$, indicated that the SYN 40 condition produced significantly lower $[La]_b$ levels than the SYN 70 condition ($P < 0.01$, 1.61 vs 2.56 mmol l^{-1}, respectively).

Despite the lack of significance, the RPE values indicated that of the four conditions, participants perceived the SYN 40 condition as the least physiologically stressful, with the SYN 70 condition as the most physiologically stressful.

Discussion

The main findings of the present study revealed a low push frequency combined with a SYN style of wheelchair propulsion to be the most economical, least physiologically stressful, and despite non-significant findings, the preferred frequency–strategy combination, as reflected by differentiated RPE measures. In addition, although not statistically significant, the ASY strategy appeared to elicit reduced levels of physiological and perceived levels of stress as the push frequency increased from 40 push min^{-1} to 70 push min^{-1}.

Although a significant interaction revealed the SYN 40 condition to be the least physiologically stressful, there were no significant main effects for push frequency. This may have been due to the collapse of the strategy data in order to obtain the main effects for push frequency; therefore, significantly higher $\dot{V}O_2$ and HR values during the ASY 40 condition compared with the SYN 40 condition would have increased the mean data for the 40 push min^{-1} conditions. The SYN conditions produced $\dot{V}O_2$ and HR values that increased in correspondence with an increased push frequency. At 40 push min^{-1} the SYN strategy was the most economical. The double-armed stroke of the SYN strategy may have allowed the arms to 'share' the force generation, thus reducing the internal work for each arm. The effect of moving the arms at a rate greater (40 vs 70 push min^{-1}) resulted in increased oxygen uptake and increased $[La]_b$. These results support Goosey et al. (2000) and Woude et al. (1989) who found a 10–11% increase in $\dot{V}O_2$ with increasing push frequency above 100% of the freely chosen push frequency. It is possible that as the frequency increased by 30 push min^{-1} whilst the same push strategy (SYN) was maintained, that the increase in $\dot{V}O_2$ might be due to an increase in the recruitment of fast twitch fibres and at the same time the recruitment of slow twitch fibres operating at velocities beyond optimum for maximal efficiency (Suzuki 1979). Furthermore, any changes in technique may have been responsible for the increase in metabolic cost during the SYN 70 condition when compared with the SYN 40 condition.

Within the ASY conditions, $\dot{V}O_2$ decreased as push frequency increased, thus the $\dot{V}O_2$ values were higher at the lowest push frequency. During the ASY 40 condition, each participant pushed only 20 times min^{-1} with each arm. In addition, the longer time between pushes compared with the higher push frequencies meant that there was a greater period of time for the wheels to decelerate; the participants, therefore, had to apply more force with each stroke to ensure that a constant power output was maintained between conditions. The increased force of contraction within the muscle at this push frequency will also cause an increased recruitment of fast twitch fibres (Ahlquist et al. 1992), once more increasing the metabolic cost of the exercise. As the push frequency increased during the ASY strategy to 70 push min^{-1}, $\dot{V}O_2$ decreased and $[La]_b$ remained the same. The observed decrease in $\dot{V}O_2$ and similar $[La]_b$ as the arm movements increased during the ASY strategy cannot be explained at present and a closer examination of the trunk movement is warranted. However, the overall lower $[La]_b$ levels for the ASY strategy may be explained by the low push frequency for each arm. Compared with the SYN strategies, each arm was almost always pushing at a lower frequency during the ASY conditions. Increased arm and trunk movements will also promote a faster rate of $[La]_b$ accumulation compared with slower push frequencies (Cox et al. 1994). This is consistent with the findings in the present study. This may also indicate that the push frequencies in the ASY conditions (20 and 35 push min^{-1} for each arm) were too slow to produce any noticeable differences in $[La]_b$ across the different frequencies (Table 2).

As with the physiological data, although non-significant differentiated RPE measures tended to indicate that the SYN 40 condition was the preferred frequency–strategy combination. The subjective perception of the SYN 40 condition being the least stressful is supported by researchers such as Pandolf (1978, 1982) who believes that local RPE is influenced by factors such as $[La]_b$. It is important to note the heterogeneous nature of the $\dot{V}O_{2peak}$ and peak HR presented in Table 1. The relative exercise intensities across the sub-maximal conditions were highly variable (37–70% $\dot{V}O_{2peak}$); these data may probably interfere with the perceived exertion at sub-maximal exercise when comparisons are made between subjects. This is not a limitation of the present study as comparisons are made within subjects across conditions; however, it is an important factor to consider when examining $\dot{V}O_{2peak}$ and could reflect a difference of exercise limitation, i.e. peripheral versus central. The comparison of peak physiological responses during wheelchair propulsion and push strategy is currently been explored and warrants consideration from a biomechanical perspective.

Summary

In summary, our hypotheses that an ASY strategy would be physiologically less stressful and that RPE differentiated ratings would also be minimised during this strategy were not fully supported. However, a trend was observed at a push frequency of 70 push min^{-1} for the participants to prefer the ASY condition. Our second expectation that a low push frequency would be more economical at either push strategy than at the corresponding high push frequency condition was partly supported. Data from the present study supported a low push frequency combined with a SYN strategy as the most economical, least physiologically stressful and, despite non-significant findings, the preferred frequency–strategy combination. The additional support from the $[La]_b$ data is particularly important across low and high push frequencies and may be a topic of future interest. We speculate that the selection of different push frequency–strategy combinations may differ at relative exercise intensities and wheelchair experience may be an important determinant with this selection process. Investigating these differences from both a physiological and biomechanical perspective would be aid of understanding in the area of wheelchair propulsion. Furthermore, it would be of interest to examine the selection of freely chosen frequency during both SYN and ASY push strategies.

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