The physiological and biomechanical effects of forwards and reverse sports wheelchair propulsion

Abstract

Objective: To explore the physiological and biomechanical differences between forwards and reverse sports wheelchair propulsion.

Design: Fourteen able-bodied males with previous wheelchair propulsion experience pushed a sports wheelchair on a single-roller ergometer in a forward (FOR) and reverse (REV) direction at three sub-maximal speeds (4, 6 & 8 $km \cdot h^{-1}$). Each trial lasted 3 minutes, and during the final minute physiological and biomechanical measures was collected.

Results: The physiological results revealed that oxygen uptake (1.51 ± 0.29 vs. 1.38 ± 0.26 $L \cdot min^{-1}$, $P = 0.005$) and heart rate (121 ± 19 vs. 109 ± 14 $beats \cdot min^{-1}$, $P < 0.0005$) were significantly greater during REV than FOR only during the 8 $km \cdot h^{-1}$ trials. From a biomechanical perspective, push frequencies were similar between FOR and REV across all speeds ($P > 0.05$). However greater mean resultant forces were applied during FOR ($P < 0.0005$) at 4 $km \cdot h^{-1}$ (66.7 ± 19.5 vs. 49.2 ± 10.3 N), 6 $km \cdot h^{-1}$ (90.7 ± 21.9 vs. 65.3 ± 18.6 N) and 8 $km \cdot h^{-1}$ (102.5 ± 17.6 vs. 68.7 ± 13.5 N) compared to REV. Alternatively, push times and push angles were significantly lower ($P \leq 0.001$) during FOR at each speed.

Conclusions: The current study demonstrated that at higher speeds physiological demand becomes elevated during REV. This was likely to be associated with an inability to apply sufficient force to the wheels, thus requiring kinematic adaptations in order to maintain constant speeds in REV.

Keywords: Push strategy, physiology, biomechanics, wheelchair sport

Introduction

Hand-rim wheelchair propulsion remains the most common form of ambulation for athletes competing in the wheelchair court sports (basketball, rugby and tennis). During these sports athletes perform a variety of multi-directional movements, which include sprinting, accelerating, braking and turning.[1,2] Although wheelchair propulsion is a guided movement when in contact with the hand-rim, athletes are responsible for self-selecting the type and direction of movements they perform on court. As such, a number of scientific studies have investigated the effects of different push frequencies,[3-5] and push strategies,[6-9] in order to optimise wheelchair propulsion technique. In brief this research has demonstrated that lower push frequencies require a larger magnitude of force application,[9] are more economical,[4] and optimal push frequencies tend to be very close to an experienced athletes freely chosen frequency.[5] A synchronous push strategy, whereby the hands couple the wheels in unison, has demonstrated a reduction in physiological demand compared to an asynchronous strategy.[6,8] Intermittent versus constant push strategies have also been explored, although no significant effects on performance have been observed.[7]

It is evident form the aforementioned studies that the major focus of previous research has been on interventions associated with the optimisation of forwards propulsion. Only a limited amount of research has focused on propulsion in a reverse direction.[10-11] By comparison, reverse wheelchair propulsion is considered a relatively minor action, with only 3% of the total distance covered during wheelchair tennis matches performed in this direction.[12] Previous comparisons of forwards and reverse wheelchair propulsion using inexperienced able-bodied participants has revealed that reverse wheelchair propulsion is characterised by a reduction in push frequency.[10,11] However, Linden et al.[10] revealed that reverse propulsion represented an improvement in pushing economy, whereas Salvi et al.[11] reported a reduction in economy. The discrepancy in economy between these two studies was likely to be associated to methodological differences. Linden et al.[10] simulated wheelchair propulsion on a stool placed between two independent wheels, which is not as ecologically valid as the approach adopted by Salvi et al.[11] who conducted testing in a daily life wheelchair on a wheelchair ergometer. Despite the differences in physiological results, both studies had focused on maximising the efficiency of daily life wheelchair propulsion, as demonstrated by the wheelchairs used and the lower power outputs imposed (≤ 30 W). Subsequently, the effects of reverse wheelchair propulsion in a sports wheelchair configuration have never been investigated. In addition to this, a biomechanical comparison of forwards and reverse propulsion has never been considered, which would not only help to interpret the physiological data, it would also allow the injury risk of each push strategy to be explored.

Since the majority of wheelchair court sports movement is performed in a forwards direction, muscular imbalance can also occur due to overuse of upper body extensor muscle groups, which are the agonists for forwards wheelchair propulsion.[13] This imbalance is brought about when insufficient strengthening of the opposing antagonist muscle groups has occurred and can result in reduced flexibility and upper limb injuries.[13] Training programmes including resistance training, flexibility training,[13-15] rowing and even reverse wheelchair propulsion,[16] have all been employed to actively engage and strengthen the antagonist muscles to help prevent injury in wheelchair users. Although the electromyographical analysis by Olenik et al.[16] revealed that rowing and weight training programmes were more effective in recruiting scapular retractor muscle activity, reverse wheelchair propulsion offers greater sports specificity for wheelchair athletes and thus its inclusion in training programmes appears justified. However, only a limited number of field tests incorporating reverse wheelchair propulsion such as 'backward partner pulls', 'backward hills' and 'clovers' for wheelchair basketball,[17] 'up and backs' for wheelchair rugby,[18] and 'the half court map' for wheelchair tennis,[19] have been advocated in the scientific literature to promote muscular balance during wheelchair skills training. Therefore, despite being a seemingly minor movement during competition, the value in understanding more about reverse propulsion could benefit the training environment for wheelchair athletes.

The aim of the current investigation was to compare the physiological and biomechanical effects of forwards and reverse wheelchair propulsion in a court sports wheelchair configuration. It was hypothesised that reverse wheelchair propulsion would increase physiological demand compared to forwards propulsion. Given the lower push frequencies that have been observed during reverse wheelchair propulsion,[10,11] and the inverse relationship that exists between push frequency and force magnitude,[9] it was also hypothesised that a larger magnitude of force application would exist during reverse propulsion.

Method

Participants

Fourteen physically active, able-bodied males (age = 26 ± 4 years; mass = 81.1 ± 10.7 kg; height = 1.81 ± 0.07 m) with previous wheelchair propulsion experience participated in the current study. To eliminate the introduction of learning effects participants had to have experience of wheelchair propulsion having previously participated in numerous previous studies of a similar nature. All participants were physically active and upper body trained, yet had to abstain from any physical activity at least 24 hours before testing. Written informed consent was obtained prior to participating in the study, which had been approved by the University's ethical advisory committee.

Design

Participants pushed a sports wheelchair on a single-roller wheelchair ergometer (WERG) using two separate push strategies: forwards propulsion (FOR) and reverse propulsion (REV) at three sub-maximal speeds (4 $km \cdot h^{-1}$, 6 $km \cdot h^{-1}$ and 8 $km \cdot h^{-1}$) commonly used in the scientific literature.[20-22] All testing was performed in the same sports wheelchair (RGK Quattro, England, UK) configured with 15° rear-wheel camber. A 0.66 m force sensing SMART^{Wheel} (Three Rivers Holdings, Arizona, USA) inflated to 110 psi was fitted on the left hand side during all testing. The SMART^{Wheel} weighs 4.7 kg, which was counterbalanced using a wheel of equal size and mass on the right hand side, giving a total wheelchair mass of 19.1 kg. The front of the wheelchair was attached to the WERG (Bromakin Wheelchairs, Loughborough, UK; length = 0.92 m; circumference = 0.48 m) to ensure that the centre of the main wheels was in line with the centre of the roller (Figure 1). A flywheel sensor connected to the WERG and interfaced with a laptop computer (Toshiba Satellite 4060XCDT) allowed participants to monitor their speeds, which were visually displayed on a screen in real time.

INSERT FIGURE 1 HERE

Prior to data collection, all participants performed 5-minutes of propulsion in each direction to warm-up and familiarise themselves with the wheelchair, WERG and speeds in FOR and REV. Each experimental trial was 3-minutes in duration to ensure that steady-state exercise had been achieved, which was verified, and was then followed by 3-minutes rest to prevent the effects of fatigue influencing the results. The order for direction and speed of propulsion was randomised between participants. On completion of all trials, a deceleration test was performed in each direction according to Theisen et al.[23], so that rolling resistance could be calculated.

Measures

During the 3-minute trials expired air was collected using a breath-by-breath system (Cortex metalyser 3B, Cortex, Leipzig, Germany), which had been calibrated using a known concentration and volume of gas. Respiratory data was recorded continuously (1 Hz sampling frequency) with oxygen uptake ($\dot{V}O_2$) values averaged during the final minute for analysis. Heart rate (HR) was monitored using radio telemetry (PE4000 Polar Sports Tester, Kempele, Finland) and was also averaged over the final minute at 5-second intervals.

Kinetic and temporal features of wheelchair propulsion were also collected during the first 30 seconds of the final minute of each trial via the SMART$^{\text{Wheel}}$. The SMART$^{\text{Wheel}}$ collects raw force (F) and moment (M) data in three dimensions at a 240 Hz sampling frequency. Data is wirelessly transmitted to a laptop (IBM Lenovo Thinkpad, New York, USA) using infrared signals and then filtered using a 4th order Butterworth low-pass digital filter with a 20 Hz cut-off frequency. The forces can be defined as follows: Fx = horizontally forward; Fy = vertically downward; Fz = horizontally inward and Mz = moment produced the around the hub in the plane of the wheel.[24] All speed, angular velocity and Mz values collected during REV were inverted so that all negative values became positive to allow for direct comparisons with FOR. No force variables were modified between FOR and REV since the principal force measure, resultant force ($Fres$), was calculated from the vector sum of the individual force components:

$$Fres\ (\mathrm{N}) = \sqrt{\left(Fx^2 + Fy^2 + Fz^2\right)} \qquad \text{(Cooper et al.}^{25}\text{)}$$

The filtered Fz values were used to describe the lateral force ($Flat$) being applied. Filtered Fx and Fy were used to calculate the radial forces ($Frad$) being directed towards the wheel axle, according to Cooper et al.[25] The filtered Fy values were also analysed with a negative value relating to a downwards force and a positive value indicating an upwards force. Additional kinetic variables were calculated as follows:

The tangential force ($Ftan$) describes the force that directly contributes the rotation of the wheels, whereby Rr^{-1} refers to the radius of the hand-rims:

$$Ftan\ (\mathrm{N}) = Mz / Rr^{-1}\ (\mathrm{m}) \qquad \text{(Robertson et al.}^{26}\text{)}$$

Using the previous two equations, the fraction of effective force (FEF), which describes the ratio of force that contributes towards forwards motion ($Ftan$) in relation to the resultant force ($Fres$) was calculated:

$$FEF\ (\%) = (Ftan / Fres) \cdot 100 \qquad \text{(Cooper et al.}^{25}\text{)}$$

Mean power output (PO) was calculated from the mean Mz and angular velocity (ϖ) of the wheel:

$$\mathrm{PO}\ (\mathrm{W}) = Mz\ (\mathrm{N{\cdot}m}) \cdot \varpi\ (\mathrm{radians{\cdot}s^{-1}}) \qquad \text{(Niesing et al.}^{27}\text{)}$$

Mean work per cycle was calculated from the mean PO and push frequency (f):

$$\mathrm{Work}\ (\mathrm{J}) = \mathrm{PO} / \mathrm{f}\ (\mathrm{pushes{\cdot}s^{-1}}) \qquad \text{(van der Woude et al.}^{28}\text{)}$$

A push cycle simply referred to the period of time between the start of one push (indicated by hand contact on the wheel) to the start of the following push. A complete push cycle was comprised of two distinct phases: i) push phase – when the hands were in contact with the wheel (hand contact to hand release) and ii) recovery phase – when the hands were not in contact with the wheel (hand release to hand contact of the following push). All kinetic data were expressed as mean values per push except for PO. The calculation of mean PO also incorporated the recovery phase of propulsion and as such was calculated from the mean Mz and angular velocity values from the onset of the first push cycle to the completion of the last push cycle during each 30 seconds of data collected.

Temporal data were also collected and analysed from the SMART$^{\mathrm{Wheel}}$ including push frequency, push angle and push time. Push frequency was calculated by dividing the number of complete push cycles in each 30-second collection by the change in time between the onset of the first to the end of the last cycle. Push times represented the time from initial hand contact to hand release, which was determined as the period of time when a change in Mz was exerted around the hub of the wheel to when values returned to zero. Push angles were calculated as the relative angle over which a push occurred using the same criteria for assessing push time.

Statistical analyses

The Statistical Package for Social Sciences (SPSS version 19.0; Chicago, IL) was used for all statistical analyses. Means and standard deviations (SD) were calculated for all variables, which were checked for normality using Shapiro-Wilk tests. This revealed that for each direction (FOR vs. REV) and speed (LOW vs. MOD vs. HIGH) of propulsion all data was normally distributed. A mixed design, two-way repeated measures ANOVA were used to quantify the mean differences between physiological and biomechanical measures during FOR and REV and to identify any interactions between direction and speed. Where significant main effects were identified ($P < 0.05$) paired sample t-tests with a bonferroni adjustment to the alpha level were performed.

Results

The results of the current investigation revealed that PO was not significantly affected by the direction of propulsion, although *P* values did approach statistical significance ($P = 0.114$), suggesting PO was slightly elevated during FOR compared to REV (Table 1). The mean rolling resistance experienced during FOR (16.6 ± 1.5 N) was also slightly, although not statistically higher ($P = 0.075$) than during REV (15.9 ± 1.9). However, the mean speeds ($P = 0.843$) were not influenced by direction (Table 1).

INSERT TABLE 1 HERE

Physiological demand

Direction of propulsion was shown to have a significant effect on $\dot{V}O_2$ ($P = 0.001$). A significant interaction also existed between direction and speed of propulsion ($P = 0.020$). No significant differences in $\dot{V}O_2$ existed between FOR and REV at 4 $km \cdot h^{-1}$ ($P = 0.232$) and 6 $km \cdot h^{-1}$ ($P = 0.158$). However, at 8 $km \cdot h^{-1}$ $\dot{V}O_2$ was significantly greater during REV (1.51 ± 0.29 $L \cdot min^{-1}$ $P = 0.005$) than FOR (1.38 ± 0.26 $L \cdot min^{-1}$) as demonstrated in Figure 2. Heart rate was also significantly affected by direction of propulsion ($P < 0.0005$), with a significant interaction established between direction and speed ($P < 0.0005$). Although no significant differences were observed at 4 km·h^{-1} ($P = 0.702$), HR was significantly greater during REV at both 6 km·h^{-1} (98 ± 15 vs. 94 ± 13 beats·min^{-1}; $P = 0.003$) and 8 km·h^{-1} (121 ± 19 vs. 109 ± 14 beats·min^{-1}; $P < 0.0005$) in comparison to FOR (Figure 2).

INSERT FIGURE 2 HERE

Propulsion technique

The effects of direction on propulsion kinetics are listed in Table 2. Although a significant main effect was observed for work per cycle ($P = 0.049$) to be lower during REV, post-hoc analysis revealed that these differences were not significant at 4 km·h^{-1} ($P = 0.088$), 6 km·h^{-1} ($P = 0.503$) or 8 km·h^{-1} ($P = 0.109$). The magnitude of peak *Fres*, mean *Fres*, *Ftan* and *Flat* ($P < 0.0005$) were all shown to be significantly greater during FOR than REV at all speeds (Table 2). Peak and mean *Frad* and max *Fy* were all significantly greater during FOR at 6 km·h^{-1} and 8 km·h^{-1} ($P \leq 0.006$). Alternatively min *Fy* was significantly greater during REV across all speeds ($P \leq 0.001$), which was the result of an upwards force component displayed at the beginning of the push phase (Figure 3). Direction of propulsion had a significant main effect on *FEF* ($P < 0.0005$), with a significantly higher *FEF* demonstrated during REV at 6 km·h^{-1} and 8 km·h^{-1} ($P < 0.0005$). The rate of force development was also influenced by propulsion direction ($P = 0.006$). Rates of force development were shown to be significantly greater during REV at 4 km·h^{-1} ($P = 0.021$), 6 km·h^{-1} ($P = 0.014$) and 8 km·h^{-1} ($P = 0.013$). Subjective examinations of the *Mz* traces demonstrated that a more pronounced negative dip occurred at the beginning of the push phase during REV compared to that observed in FOR (Figure 4).

INSERT TABLE 2 HERE

INSERT FIGURE 3 HERE

INSERT FIGURE 4 HERE

Propulsion kinematics were also influenced by the direction of propulsion (Table 2). Push angles and push times ($P < 0.0005$) were significantly greater during REV across all speeds ($P \leq 0.001$). However, push frequency was not significantly affected by the direction of propulsion ($P = 0.151$).

All physiological and biomechanical variables with the exception of *FEF* ($P = 0.438$) were shown to increase in magnitude as a function of speed of propulsion.

Discussion

The results of the current study confirmed the hypothesis that reverse wheelchair propulsion increases physiological demand at fixed speeds. Physiological demand only appeared to be influenced by the direction of propulsion at higher speeds (6 and 8 km·h^{-1}) since no significant effect was observed for $\dot{V}O_2$ or HR at 4 km·h^{-1}. However, HR became elevated during REV at 6 km·h^{-1} and both $\dot{V}O_2$ and HR were greater at 8 km·h^{-1} compared to FOR.

The physiological results revealed by the current investigation were more in agreement with the work of Salvi et al.[11], who also revealed an increase in the physiological cost of reverse wheelchair propulsion, as opposed to that of Linden et al.[10]. Linden et al.[10] reported a reduction in physiological demand during reverse wheelchair propulsion, which may be the result of methodological flaws. As mentioned previously, Linden et al.[10] did not utilise a manual wheelchair for their study and instead incorporated a stool placed between two independent wheels to simulate wheelchair propulsion. This set-up fails to accurately replicate a number of the key features of a manual wheelchair. For example, in a conventional wheelchair a backrest is present, which can inhibit the amount of trunk extension possible, which may be particularly relevant during REV. Subsequently, the set-up adopted by Linden et al.[10] may have enabled participants to effectively utilise the larger trunk extensors, which may have accounted for the reduction in physiological demand observed during REV. Even though the physiological results of the current study were akin to those reported by Salvi et al.[11], subtle differences still existed between these studies. Salvi et al.[11] identified an increase in physiological demand during REV, yet also observed a reduction in push frequency. This contradicts previous research, whereby lower push frequencies have been associated with improved pushing economy.[4] Subsequently, the absence of any biomechanical analyses made it difficult to interpret the physiological results reported by Salvi et al.[11].

The current investigation was the first study to incorporate a comprehensive biomechanical examination of reverse wheelchair propulsion. It was clear from the kinetic analysis that no differences in push frequency were observed and the magnitude of force application was greater during FOR, which rejects the original hypothesis. It was hypothesised that a larger magnitude of force would be required during REV, resulting from the reduced push frequency also hypothesised, in order to maintain the test speeds and that this would ultimately account for the greater physiological demand observed. Since this was not the case, it was proposed that the greater physiological demand during REV was alternatively due to insufficient force being generated around the wheel. Subsequently it could be suggested that participants were required to adapt kinematic aspects of their propulsion technique to maintain the desired test speeds during REV. It was apparent that although push frequencies were similar between conditions, push times were significantly greater during REV, meaning that recovery times would have been shorter, which may also have contributed to the greater physiological demand during REV. In addition to increased push times, participants were also shown to be in contact with the hand-rim over a larger push angle. Although no three-dimensional upper body kinematic analysis was conducted, it was likely that a larger range of trunk motion was necessary in order to contact the wheel over the larger push angle, which could again account for the greater physiological demand of REV. During the current investigation it was noticeable that two distinct propulsion techniques were employed during the push phase of FOR and REV. During FOR, participants were able to accelerate their hands at a greater rate and appeared to contact the hand-rim without gripping. During REV participants appeared unable to couple the wheel as effectively and subsequently had to ‘grasp’ the wheel when pulling backwards. The slower, longer ‘grasping’ technique during REV was exemplified by the M_z traces at the highest test speed (Figure 4), where a more pronounced braking force was applied at the beginning of the push phase, which is the likely result of insufficient hand speed.[29,30] This technique was also reinforced by the vertical forces (F_y) observed during REV, which began in an upwards direction as participants pulled up and back, before shifting to a downwards F_y, which was not as large in magnitude compared to FOR. This ‘grasping’ technique may have accounted for the improvement in the direction of force application, as indicated by the higher *FEF* and reduced *Flat*, suggesting that less force was wasted during REV. However, it was clear that the mechanically effective force application of REV did not correspond with physiological efficiency, confirming what has previously been reported.[31]

It is likely that the inability to generate sufficient force, the adaptations in propulsion technique at initial hand contact and the subsequent increase in physiological demand during REV were all related to the configuration of the wheelchair. For instance, the seat of a sports wheelchair is positioned and configured in a way to optimise aspects of forwards propulsion. This is not to suggest that changes in wheelchair configuration need to be explored in order to optimise reverse wheelchair propulsion, since it is only considered a minor movement in the context of wheelchair sports competition.[12] It is just a likely rationale for the differences observed.

Although the magnitude of force application was lower during REV, the rate of force development was greater. Greater rates of force development have previously been associated with increased risk of injury.[32] However further research is required to determine whether the values observed during REV in the current study are substantial enough to be deemed a serious risk factor. Given that the antagonist muscles used during forwards propulsion become actively engaged during reverse wheelchair propulsion, it could also be argued until further research has been conducted that the omission of reverse propulsion from wheelchair court sports training programmes would potentially place athletes at a greater risk of injury by helping to prevent muscle imbalance. As mentioned earlier, rowing and weight training programmes have been shown to be more effective in recruiting scapular retractor muscle activity than reverse wheelchair propulsion.[16] However, given the greater sports specificity of reverse wheelchair propulsion, its inclusion in training programmes for wheelchair athletes appears warranted.

Previous research into reverse wheelchair propulsion has focused on establishing whether it was a more efficient form of ambulation.[10,11] Reducing physiological demand is often the objective of such studies concerned with daily life wheelchair propulsion. However for wheelchair athletes, stressing the cardiovascular system is a prerequisite with exercise prescription. Subsequently, the increased physiological demand associated with REV during the current investigation further advocates that reverse wheelchair propulsion should be a fundamental component of on court training programmes for athletes competing in the wheelchair court sports. Future research should be aimed at developing guidelines about the frequency, intensity and duration of new and existing reverse wheelchair propulsion drills.[17-19] The speeds and durations selected by the current investigation provided a sub-maximal comparison between the physiological and biomechanical demands of forwards and reverse wheelchair propulsion. However, the speeds at which athletes perform reverse wheelchair propulsion during wheelchair court sport competition as well as the duration are likely to differ widely to these. Therefore, further detailed match analysis of the wheelchair court sports would be required to establish a more accurate understanding of the sports before more sport specific training programmes can be devised.

Limitations and future recommendations

Although the current study did not experience any significant differences in PO between FOR and REV, it was acknowledged that these differences did approach statistical significance. The mean PO during FOR was slightly higher than during REV at all speeds, which appeared to be related to the slightly, yet not significantly higher rolling resistance during FOR. These slight changes were thought to be due to the configuration of the WERG used in the current set-up. The wheelchair is more rigidly attached to the WERG at the front than it is at the rear. It is possible that this type of attachment may have acted as a slight confounding factor towards the resistance experienced in each direction. Although this may have been construed as a limitation, it must be emphasised that the differences in resistance and PO were not statistically significant and even though both were marginally higher during FOR, it did not appear to affect the results as physiological demand was still higher during REV.

The inclusion of able-bodied participants may also be viewed as a limitation, since the aim of the investigation was to determine the effects of forwards and reverse propulsion in a sports wheelchair configuration, it could be argued that participants should have been wheelchair athletes. However, as this was the first study to explore this area, able-bodied participants were deemed a suitable starting point due to the homogeneity they demonstrate compared to wheelchair users. Although their physiological and biomechanical responses may differ to those of wheelchair users in absolute terms, the trends they elicit are thought to be similar.[33] Despite the justification for including experienced able-bodied participants at the current stage, it is imperative that future investigations extend this work to include wheelchair athletes during over-ground propulsion in a field based environment when attempting to establish training guidelines for both FOR and REV.

The incorporation of electromyography into future biomechanical analyses would also greatly improve our understanding of reverse wheelchair propulsion and the importance of including this movement into wheelchair athletes training programmes. Although Olenik et al.[16] established that reverse propulsion was not as effective as rowing or weight training for recruiting posterior retractor muscles, it was observed that those regularly performed this movement during training were capable of producing larger amplitudes.

Conclusions

The current study revealed that reverse wheelchair propulsion significantly increases the physiological demand of wheelchair propulsion at speeds ≥ 6 km·h^{-1}. The greater physiological demand was associated with an inability to develop sufficient force and instead required kinematic adaptations in order to maintain the desired test speeds. These changes were due to an inappropriate wheelchair configuration for reverse propulsion, although given the infrequency with which these movements are thought to be performed this is understandable. Despite the greater physiological demand of reverse wheelchair propulsion, this type of movement is strongly advocated for wheelchair court sport athletes training programmes to not only stress the cardiovascular system, but to also protect against injury by developing the antagonist muscles used during forwards wheelchair propulsion in a sports specific manner.[16]

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Figure Legends:

Figure 1. The experimental set-up illustrating the single-roller wheelchair ergometer and its interaction with the wheelchair.

Figure 2. The effect of direction and speed of propulsion on mean (±SD) physiological parameters.

Figure 3. A typical *Fy* trace from one participant during the 8 km·h^{-1} trial during a) forwards; b) reverse wheelchair propulsion.

Figure 4. A typical *Mz* trace from one participant during the 8 km·h^{-1} trial during a) forwards; b) reverse wheelchair propulsion.

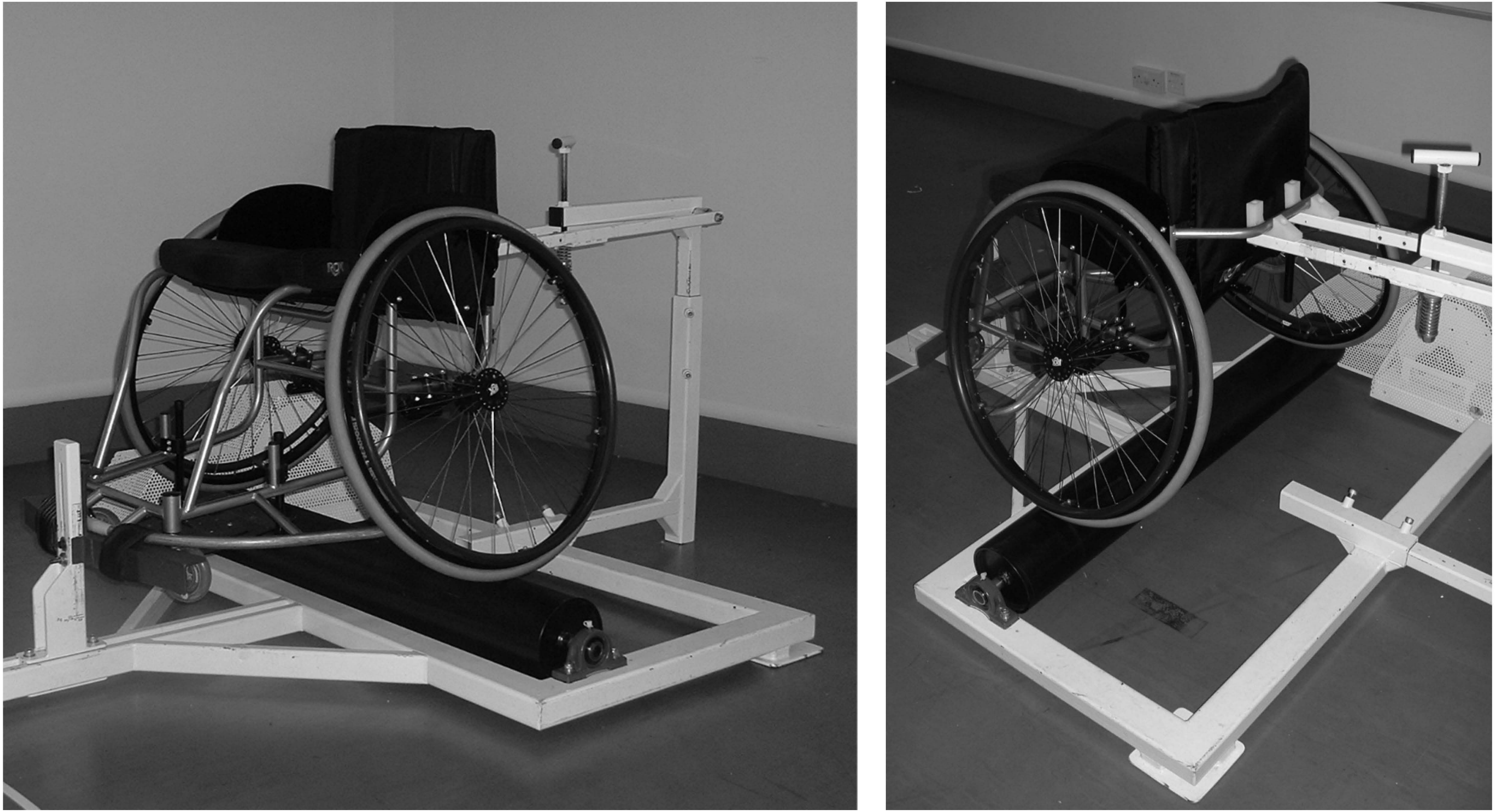
Table I. Mean (±SD) power output and speed values during forwards and reverse propulsion

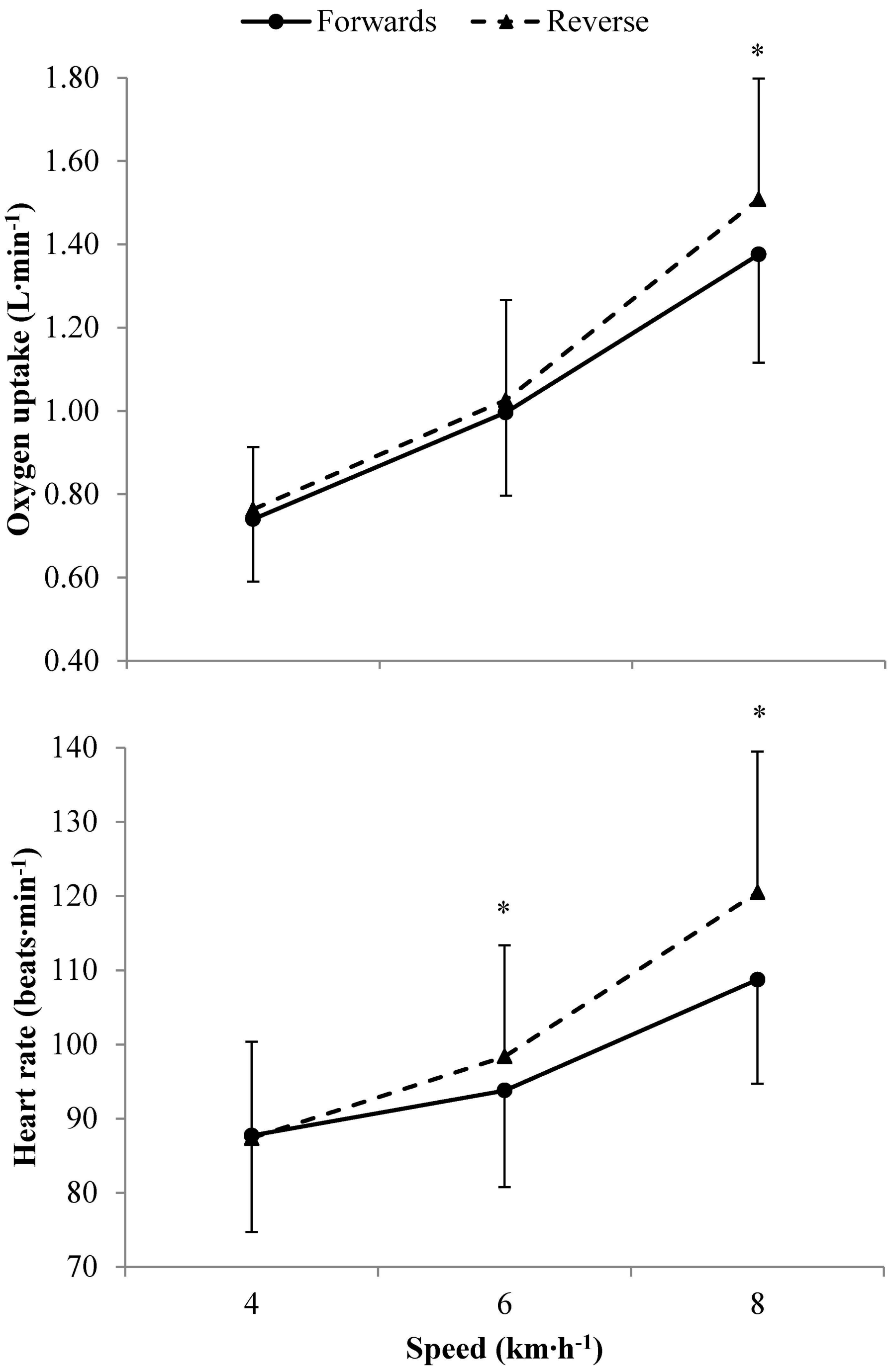
	4 km·h^{-1}			**6 km·h^{-1}**			**8 km·h^{-1}**		
	FOR	vs.	**REV**	**FOR**	vs.	**REV**	**FOR**	vs.	**REV**
Power output	17.7		16.6	27.6		26.8	38.2		37.1
(W)	(1.9)		(2.4)	(2.5)		(3.2)	(2.8)		(3.3)
Speed	4.0		4.0	5.9		6.0	8.0		8.0
(km·h^{-1})	(0.1)		(0.1)	(0.1)		(0.1)	(0.1)		(0.1)

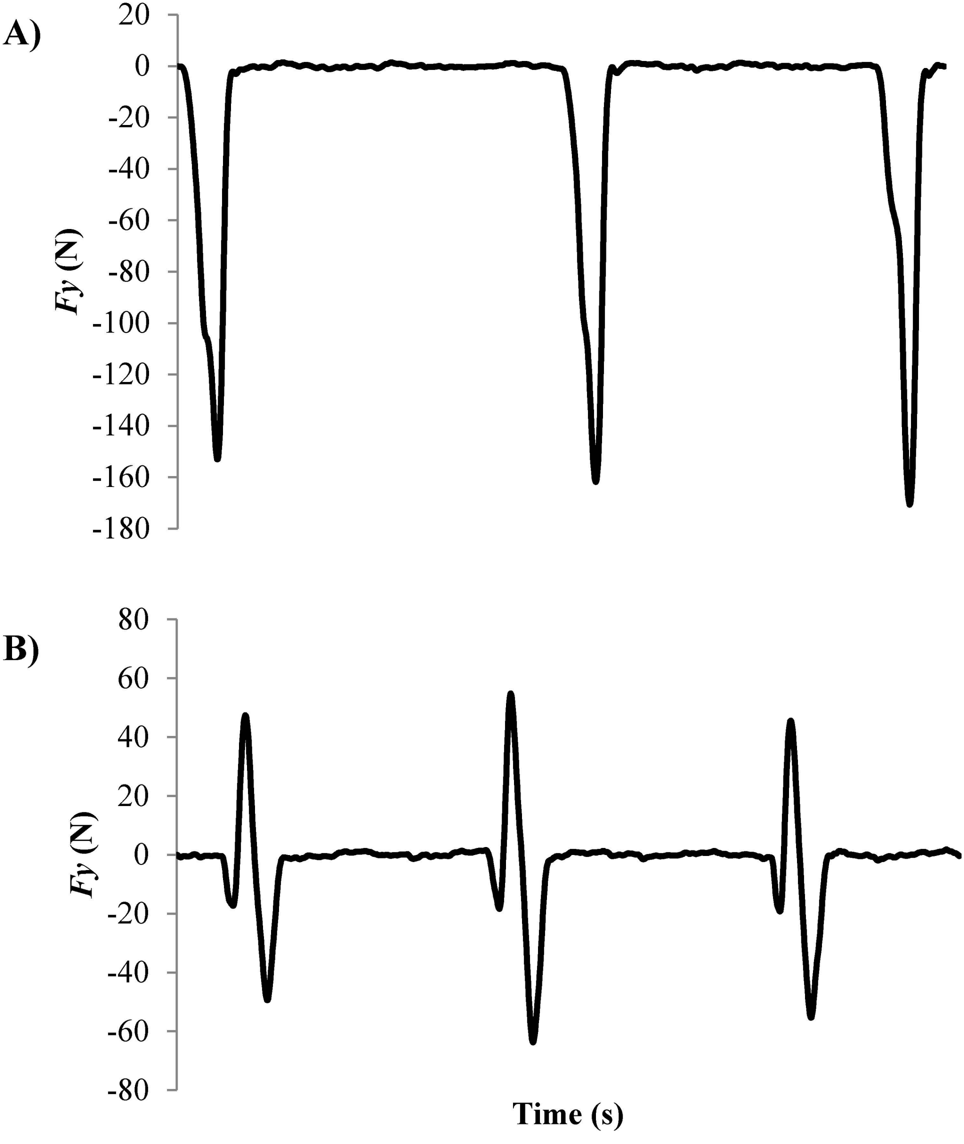
Table II. Mean (±SD) biomechanical measures during forwards and reverse propulsion across different speeds.

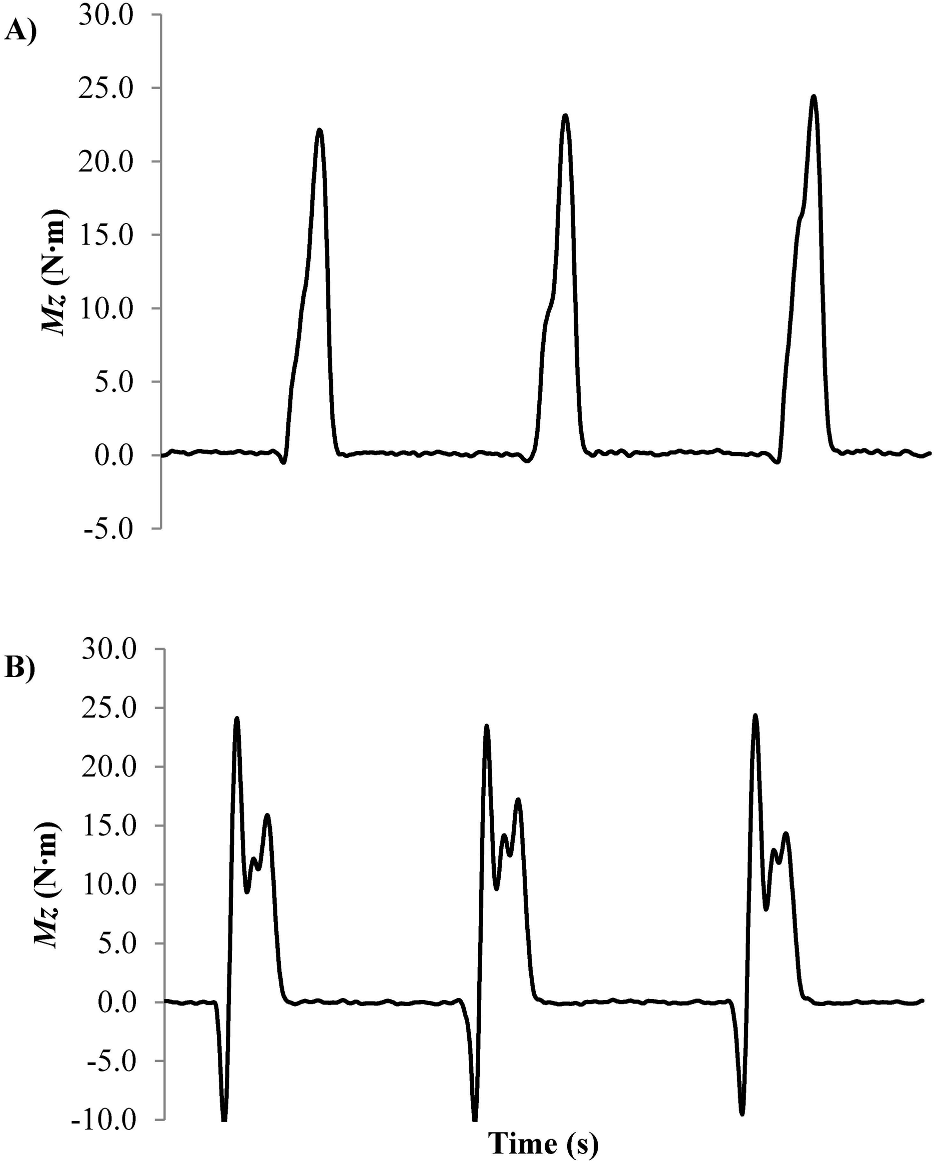
	4 km·h^{-1}			**6 km·h^{-1}**			**8 km·h^{-1}**		
	FOR	vs.	**REV**	**FOR**	vs.	**REV**	**FOR**	vs.	**REV**
Work (J)	48.8		43.9	68.2		64.9	77.9		70.7
	(17.5)		(16.4)	(26.3)		(28.5)	(22.4)		(28.1)
Peak *Fres* (N)	102.0	*	83.1	148.5	*	108.9	172.4	*	110.6
	(30.6)		(27.1)	(38.5)		(29.0)	(30.8)		(23.7)
Mean *Fres* (N)	66.7	*	49.2	90.7	*	65.3	102.5	*	68.7
	(19.5)		(10.3)	(21.9)		(18.6)	(17.6)		(13.5)
Mean *Ftan* (N)	47.7	*	37.0	61.8	*	53.1	66.3	*	54.3
	(14.4)		(13.3)	(17.8)		(18.9)	(14.0)		(14.2)
Peak *Frad* (N)	57.4		54.6	85.7	*	68.3	108.2	*	70.3
	(19.3)		(12.5)	(18.8)		(22.3)	(19.9)		(19.7)
Mean *Frad* (N)	38.0		29.2	53.3	*	32.5	63.0	*	36.0
	(13.3)		(7.2)	(12.7)		(10.1)	(11.8)		(9.8)
Mean Max *Fy* (N)	-68.2		-59.0	-114.0	*	-78.3	-141.5	*	-80.9
	(22.5)		(16.4)	(30.9)		(28.2)	(25.2)		(26.8)
Mean Min *Fy* (N)	-5.8	*	-30.8	-5.8	*	-51.3	-6.5	*	-61.7
	(5.5)		(30.4)	(5.1)		(41.6)	(3.0)		(37.6)
Mean *Flat* (N)	23.0	*	9.6	33.3	*	9.1	39.2	*	10.6
	(10.0)		(4.9)	(15.7)		(5.1)	(14.2)		(7.4)
***FEF* (%)**	70.4		74.9	66.5	*	81.5	64.9	*	79.9
	(7.6)		(12.2)	(7.5)		(8.8)	(8.0)		(6.9)
Rate of force development (N·s^{-1})	272.1	*	375.0	536.0	*	831.1	893.3	*	1241.2
	(105.6)		(169.6)	(144.7)		(352.0)	(175.9)		(345.3)
Push frequency (pushes·s^{-1})	0.43		0.43	0.45		0.48	0.52		0.57
	(0.23)		(0.18)	(0.15)		(0.20)	(0.14)		(0.18)
Push angle (°)	103.4	*	129.9	110.4	*	130.9	116.9	*	137.7
	(18.5)		(19.6)	(17.8)		(22.1)	(14.3)		(20.5)
Push time (s)	0.48	*	0.59	0.34	*	0.40	0.27	*	0.32
	(0.08)		(0.09)	(0.05)		(0.05)	(0.03)		(0.04)

*represents a significant difference between FOR & REV


RGK


Forwards
Reverse
*
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
Oxygen uptake (L·min-1)
*
*
140
130
120
110
100
90
80
70
Heart rate (beats·min-1)
4
6
8
Speed (km·h-1)


A)
20
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
Fy (N)
B)
80
60
40
20
0
-20
-40
-60
-80
Fy (N)
Time (s)


A)
30.0
25.0
20.0
15.0
10.0
5.0
0.0
-5.0
Mz (N·m)
B)
30.0
25.0
20.0
15.0
10.0
5.0
0.0
-5.0
-10.0
Mz (N·m)
Time (s)