Hand-Rim Forces and Gross Mechanical Efficiency in Asynchronous and Synchronous Wheelchair Propulsion: A Comparison

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Abstract

To compare the force application characteristics at various push frequencies of asynchronous (ASY) and synchronous (SYN) hand-rim propulsion, 8 able-bodied participants performed a separate sub-maximal exercise test on a wheelchair roller ergometer for each propulsion mode. Each test consisted of a series of 5, 4-min exercise blocks at 1.8 m·s⁻¹—initially at their freely chosen frequency (FCF), followed by four counter-balanced trials at 60, 80, 120 and 140% FCF. Kinetic data was obtained using a SMART Wheel, measuring forces and moments. The gross efficiency (GE) was determined as the ratio of external work done and the total energy expended. The ASY propulsion produced higher force measures for FRES, FTAN, rate of force development & FEF (P < 0.05), while there was no difference in GE values (P = 0.518). In pair-matched push frequencies (ASY80:SYN60, ASY100:SYN80, ASY120:SYN100 and ASY140:SYN120), ASY propulsion forces remained significantly higher (FRES, FTAN, rate of force development & FEF P < 0.05), and there was no significant effect on GE (P = 0.456). Both ASY and SYN propulsion demonstrate similar trends: changes in push frequency are accompanied by changes in absolute force even without changes in the gross pattern/trend of force application, FEF or GE. Matched push frequencies continue to produce significant differences in force measures but not GE. This suggests ASY propulsion is the predominant factor in force application differences. The ASY would appear to offer a kinetic disadvantage to SYN propulsion and no physiological advantage under current testing conditions.

Introduction

It has been shown that the efficiency of alternate, asynchronous (ASY) and simultaneous, synchronous (SYN) arm movements in hand-rim wheelchair propulsion are not significantly different, at least in inexperienced able-bodied individuals [19], although Glaser and colleagues did report a preference towards the ASY propulsion when examining the ratings of perceived exertion [10]. While the SYN mode is the more traditional method adopted by wheelchair users for activities of daily living, the ASY mode is used by a substantial number of experienced wheelchair sportsmen [19]. It has been suggested that the ASY mode of propulsion may be advantageous as it allows greater continuity of the hand-rim force application, reducing fluctuations in the velocity profile and therefore, the acceleration with each stroke is reduced [10]. Interestingly, ASY limb movement patterns are employed in other, more efficient, modes of locomotion (e.g. walking and bicycling) and may take advantage of inherent neural pathways for the reciprocal stimulation of the contralateral muscle groups [9]. Despite there being no clear benefit reported in terms of gross efficiency (GE) with ASY propulsion, this technique continues to be adopted in everyday use and more so in sporting environments of wheelchair tennis and basketball. The ASY mode appears to require a different range of motion and stability from the trunk in hand-rim wheelchair propulsion [19,20] and during handcycling [1]. The greater postural stability associated with ASY propulsion has been noted to be seemingly [missing word] due to trunk rotation over the pelvis during reciprocal arm swing allowing easier maintenance of balance than the forward and back trunk motion used during SYN propulsion in able-bodied individuals [10]. Both arm-cranking and handcycling have also investigated the physiological responses to SYN and ASY cyclic arm exercise, and there are some inconsistent findings. Research studies in handcycling indicate better efficiency in SYN move-
ment pattern [1,31], whereas in arm-cranking it is the ASY movement pattern [11,23]. The conflicting findings could well be the consequence of the combined effects of individual participant groups and different experimental set-ups. In particular the difference between the 2 modalities, whereby hand-cycling performance incorporates a steering element and arm-cranking is a stationary set-up.

Early research suggested that the low mechanical efficiency reported for wheelchair propulsion could be attributed to what can be described as ineffective propulsion technique whereby the direction of the propulsive force is non-optimal. This gave rise to the concept of the fraction of effective force (FEF), which is the ratio between the magnitude of the tangentially directed force and the total force applied to the hand-rim [29]. The hypothesis that increasing FEF would improve efficiency has however, been disputed [6,12,32]. Previous research comparing propulsion modes has manipulated the freely chosen frequency when investigating push frequency [19–21]. With the exception of one research study by Lenton and colleagues [18] there has never been any emphasis placed on the comparison of ASY and SYN propulsion with matched push frequencies (total number of left and right arm movements). It would be pertinent to introduce pair-matched frequency conditions when comparing the propulsion forces of asynchronous and synchronous propulsion modes.

To our knowledge there is no literature that has attempted to investigate force production in ASY hand-rim propulsion and compare it with the traditional SYN propulsion. Therefore, the purpose of this study was threefold: 1) to describe the force application profiles of ASY propulsion at a range of push frequencies, 2) to compare the hand-rim force application between the push frequencies in ASY and SYN propulsion, and 3) to compare it with the traditional SYN propulsion. We hypothesise that: 1) the effects of push frequency would be similar in both propulsion modes but absolute values for force parameters would be reduced in ASY propulsion; 2) no significant differences in force parameters and GE are expected when push frequency is matched in ASY and SYN propulsion modes.

Material and Methods

Eight able-bodied male participants volunteered for this study and gave written informed consent prior to participation following a detailed explanation of all testing procedures. Participant physical characteristics are given in Table 1. Approval for the study procedures was obtained from the University Research Ethics Committee and was conducted in accordance with the Declaration of Helsinki and Ethical Standards in Sport and Exercise Science Research [14]. Participants had prior experimental experience in wheelchair exercise, but were not specifically trained in upper body sports activities or hand-rim wheelchair propulsion.

Table 1

<table>
<thead>
<tr>
<th>Participant</th>
<th>Age (years)</th>
<th>Height (m)</th>
<th>Seated Height (m)</th>
<th>Body Mass (Kg)</th>
<th>Mean PO (W)</th>
<th>Total Resistance (N)</th>
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</thead>
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<td>Mean</td>
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<td>1.81</td>
<td>1.41</td>
<td>85.5</td>
<td>54</td>
<td>30.2</td>
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<tr>
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<td>4</td>
<td>0.06</td>
<td>0.02</td>
<td>12.3</td>
<td>6</td>
<td>3.4</td>
</tr>
</tbody>
</table>

Instrumentation

For the wheelchair trials, all participants were tested in the same 15° cambered hand-rim basketball wheelchair (Quattro, RGK, Burntwood, Staffordshire, England), featuring typical characteristics of a sports wheelchair used during the early stages of skill acquisition. The wheelchair was configured with a force sensing SMARTWheel [3 (Rivers Holdings, Mesa, AZ)] to collect kinetic data, characteristics and properties of the SMARTWheel are described elsewhere [7,27]. Wheels were fitted with the standard solid tyres provided by the SMARTWheel manufacturer (wheel diameter: 0.592-m and hand-rim diameter: 0.534-m). The SMARTWheel was placed on the right side of the wheelchair and its use did not change the camber, axle position or diameter of the basketball wheelchair. To ensure similar inertial properties for the left wheel a counterbalanced weight was added to the wheel. No individual adjustments relative to anthropometrics of the participants were made. The wheelchair was secured to a single roller ergometer (Bromakin; cylinder length, 1.14-m; circumference, 0.48-m). Although velocity was derived from the SMARTWheel, a flywheel sensor was connected to the roller and interfaced to a laptop computer (Compaq Armada 1520, Series 2920A), which was able to calculate and display the wheelchair velocity during trials for participants. Mean power output (Po) was determined from the SMARTWheel and calculated from the torque applied to the wheel axis (Mz) and their angular velocity (ω) [24].

\[
\text{Mean Po (W)} = (\frac{1}{\text{Samples}} \sum (Mz \text{(N} \cdot \text{m) } \cdot \omega (\degree \cdot \text{s}^{-1}))) \cdot 2
\]

As the SMARTWheel measures unilaterally, symmetry was assumed and thus to determine Po the values were multiplied by two prior to time averaging to account for work done on the contralateral wheel. The recovery phase was accounted for with Mz (being zero throughout) and the angular velocity of the wheel, time averaged from the onset of the first push to the completion of the final push.

Total resistance was calculated from the mean torque applied to the wheel axis (Mz) and the radius of the wheel as follows:

\[
\text{Total Resistance (N)} = \frac{\text{Mean Mz (N} \cdot \text{m)}}{\text{Wheel Radius (r) }} \cdot 2
\]

Wheelchair propulsion was performed at a constant speed hence the propulsive work done and total resistance must be equal to the resistive work done consequently; it can be assumed that the mean total resistance must be equal to the mean propulsive force calculated.
Testing procedure

The testing followed the same procedure as a previously reported experiment [22] for both ASY and SYN propulsion. Participants performed a discontinuous, sub-maximal, steady state exercise test on the roller ergometer, consisting of five exercise bouts at different push frequencies (FCF and 60%, 80%, 120% and 140% of FCF) at 1.8 m·s⁻¹. An audio-visual metronome was used to pace the push frequency requirements. Prior to performing sub-maximal push frequency conditions participants completed a 5-min warm-up, whereby HR did not exceed 130 beats·min⁻¹. After an 8-min rest period, a 1-min ‘habitation period’ was performed to allow familiarisation with the push frequency to be employed during the subsequent 4-min test period. The FCF condition was the initial 4-min exercise bout and push frequency was recorded each minute to calculate mean FCF. Subsequent exercise bouts were performed at 60, 80, 120 and 140% of the FCF in a counter-balanced order to ensure distinctly different exercise bouts were performed at 60, 80, 120 and 140% of the FCF. Recovery times (RT) were defined as the amount of time(s) that the hand exerted a positive torque around the wheel axis. Consequently, the cycle time (CT) is the summation of PT and RT (s). The push angles (PA) were also derived from and defined as the relative angle (°) over which the push occurs on the hand-rim (the hand exerting a positive moment around the hub of the wheel).

Physiological measures

Heart rate (HR) was monitored using short-range radio telemetry (PE4000 Polar Sport Tester, Kempele, Finland). Expired air samples were collected and analysed using the Douglas bag technique during the final minute of each condition. The concentrations of oxygen and carbon dioxide in the expired air samples were determined using a paramagnetic oxygen analyser (Series 1400, Servomex Ltd., Sussex, UK) and an infrared carbon dioxide analyser (Series 1400, Servomex Ltd., Sussex, UK). Expired air volumes were measured using a dry gas meter (Harvard Apparatus, Kent, UK) and corrected to standard temperature and pressure (dry). Oxygen uptake (VO₂), respiratory exchange ratio (RER), gross mechanical efficiency (GE) and HR were all calculated as an average over the final minute of each exercise condition.

Efficiency

Gross mechanical efficiency was calculated:

$$GE = \frac{W}{E} \times 100(\%) \tag{30}$$

where W is the external work done and E is the total metabolic energy expended.

External work done was determined from the Po values derived from the SMARTWheel during the hand-rim propulsion (all push frequencies). The metabolic energy expenditure was obtained from the product of VO₂ and the oxygen energetic equivalent derived from the RER and standard conversion tables [25].

Statistical analysis

Data were analysed using the Predictive Analytics Software (PASW SPSS for Windows Version 18; SPSS Inc., Chicago, USA). Data normality and homogeneity of variance were verified by Shapiro-Wilk and Mauchly’s test of sphericity, respectively. The degrees of freedom were adjusted for heterogeneous variances (Greenhouse-Geisser). Standard descriptive statistics (mean ± SD) were calculated for all kinetic/kinematic and physiological variables. For analysis, unmatched push frequencies were ASY₁₀₀:SYN₁₀₀, ASY₁₂₀:SYN₁₂₀, ASY₁₄₀:SYN₁₄₀. Matched push frequencies obtained from matching the absolute push frequencies in the propulsion modes were ASY₁₄₀:SYN₁₂₀, ASY₁₂₀:SYN₁₀₀, ASY₁₀₀:SYN₁₄₀, ASY₁₄₀:SYN₁₄₀. Separate one-way within measures ANOVA were used to examine the effect of the FCF manipulation on the changes in FRES from the initial contact to the Peak FRES and the changes in time between these 2 events (rate of force development) was also calculated [4]. All forces and moments were expressed as peak and mean values per push and then averaged over the total number of pushes in each 30-s data collection period.
kinetic/kinematic and physiological variables in both ASY and SYN propulsion modes. Subsequently, separate 2-way repeated measures ANOVA (propulsion mode and push frequency) were applied to all data for the unmatched and matched push frequency analyses. Bonferroni comparisons were used to identify significant pairwise differences. A probability threshold of $P \leq 0.05$ was considered to be statistically significant, and absolute standardised effect sizes (ES) are included to supplement the important findings.

**Results**

At the propulsion velocity of $1.8 \text{ m} \cdot \text{s}^{-1}$, the mean Po values for ASY propulsion conditions was $54 \pm 6$ W (range 44–62 W), and rolling resistance on average was $30.2 \pm 3.4$ N. Similarly, SYN propulsion Po was $53 \pm 6$ W (range 45–64 W), and rolling resistance was $29.7 \pm 3.5$ N. There were no significant differences during ASY and SYN propulsion for PO ($P=0.839$, ES=0.10) or total resistance ($P=0.745$, ES=0.17) (Table 1). The calculation of the metabolic energy expenditure (used in GE calculations) required RER to be $\leq 1.00$. However, the maximum energy equivalent of $5.189 \text{ kcal (21.7 KJ)}$ was used in the 2 trials where the participants RER in the 140% FCF condition exceeded unity ($1.00$). In this instance, the effect on the GE calculations was deemed to be negligible, and separate analyses revealed that removal of these data did not alter the statistical outcome.

**ASY vs. SYN propulsion mode**

The main effects of propulsion mode, push frequency and interaction of propulsion mode and frequency on force parameters are shown in Fig. 1 (a–f). GE, work per cycle, push frequency and kinematic parameters are shown in Fig. 2 (a–f). Propul-
sion modes demonstrate the same trends with respect to push frequency for Peak $F_{RES}$ ($P < 0.001$, $ES = 1.46$), Mean $F_{RES}$ ($P < 0.001$, $ES = 1.17$), Peak $F_{TAN}$ ($P < 0.001$, $ES = 1.89$), Mean $F_{TAN}$ ($P < 0.001$, $ES = 1.58$), FEF ($P < 0.001$, $ES = 1.04$) and rate of force development ($P < 0.001$, $ES = 1.05$), whereas there was no significant interaction of push frequency and propulsion mode. A significant effect for propulsion mode is found, where all the measured force variables were higher in ASY propulsion conditions ($P < 0.05$). The trend in both ASY and SYN propulsion was for FEF to decrease with increasing push frequency (74.2–71.1%, 69.1–62.6%; respectively), even though ASY FEF values were consistently higher (Fig. 1e). The mean FEF of 72.9±5.2% for ASY propulsion was significantly higher than the 66.3±7.2% for SYN propulsion ($P < 0.05$). Work per cycle was significantly affected by push frequency ($P < 0.001$, $ES = 1.00$), demonstrating a linear relationship in both propulsion modes. However, ASY values were significantly greater than SYN values ($P = 0.044$, $ES = 1.00$), resulting in increased work done per propulsion cycle throughout the push frequency manipulations. As expected, PT ($P < 0.001$, $ES = 0.97$), RT ($P < 0.001$, $ES = 0.99$) and PA ($P < 0.001$, $ES = 0.97$) all decreased significantly with increasing push frequency for ASY and SYN propulsion modes. Pairwise comparisons demonstrated significantly lower GE for push frequency conditions below the FCF in ASY propulsion (60% $P = 0.001$, $ES = 1.41$; 80% $P = 0.003$, $ES = 0.80$), whereas it was above the FCF in SYN propulsion (120% $P < 0.001$, $ES = 1.04$; 140% $P = 0.001$, $ES = 1.55$) and the lower extreme push frequency of 60% FCF ($P = 0.005$, $ES = 0.95$). Comparison of the ASY and SYN propulsion

![Fig. 2 Unmatched push frequencies: Mean values ± SD for efficiency and timing parameters in synchronous (SYN) and asynchronous (ASY) hand-rim propulsion across range of push frequencies.](image)

a work per cycle, b push time, c gross efficiency, d recovery time, e push frequency and f push angle. *Significant main effect mode (ASY vs. SYN). † Significant main effect frequency. ‡ Significant main effect mode*frequency ($P \leq 0.05$).
modes at the push frequencies of 60, 80, 100, 120 & 140% While FCF only produced significant differences at 140% FCF (P=0.039, ES=1.14), at 120% FCF the significance was borderline with a large effect suggesting it was probably meaningful (P=0.079, ES=0.95).

Matched push frequency

The experimental protocol allowed for the comparison of propulsion modes, where the unilateral push frequency was very similar, see Fig. 2e. Analysis of the matched push frequencies resulted in non-significant differences in push frequency with small effects: ASY60:SYN60 (P=0.502, ES=0.35), ASY100:SYN100 (P=1.000, ES=0.06), ASY120:SYN100 (P=0.704, ES=0.19) and ASY140:SYN120 (P=0.345, ES=0.49). The ASY propulsion produced significantly greater force parameter values for peak and mean FRES (P=0.026, ES=0.82; P=0.030, ES=0.60), FEF (P=0.020, ES=1.19; P=0.011, ES=0.99) and rate of force development (P=0.016, ES=1.34). However, GE (P=0.456, ES=0.20), work per cycle (P=0.789, ES=0.10) and recovery time (P=0.418, ES=0.29) differences were not significant (Fig. 3) between propulsion modes, and the effects were small. Peak efficiency was found when operating in the push strategy range of SYN80:ASY100 and SYN100:ASY120 (Fig. 3a). Both these
SYN:ASY combinations produced an average push frequency of 48–59 pushes·min⁻¹ at 1.8 m·s⁻¹.

Discussion

To the authors’ knowledge, this study is the first to describe the forces applied during ASY hand-rim wheelchair propulsion. In summary the data show: 1) a significant effect of push frequency on force parameters (ASY and SYN); 2) ASY propulsion produces significantly greater force values; 3) in ASY and SYN propulsion pair-matched push frequencies report no significant interaction (propulsion mode*push frequency) for force parameters. In light of these findings we reject both hypotheses: 1) the effects of push frequency are similar in both propulsion modes but absolute values for force parameters are greater in ASY propulsion; 2) no significant differences in force parameters and GE are expected when push frequency is matched in ASY and SYN propulsion.

ASY vs. SYN propulsion mode

The Peak/Maximal F_RES and F_TAN displayed identical trends with respect to push frequency for both modes of propulsion. As push frequency increased (60–140% FCF), both the F_RES and F_TAN decreased, although ASY propulsion produced significantly higher values at each push frequency. This finding is the result of increased push frequency (60–140% FCF) and the requirement for participants to maintain a constant velocity, hence work during each condition. With an increased number of hand contacts it was possible to reduce the force per push necessary to achieve the required work. The greater absolute values of ASY propulsion are a consequence of the lower absolute frequencies used. FEF remained more or less constant across push frequencies with reciprocal changes in F_RES and F_TAN. However, there was a tendency for FEF to be slightly lower as the push frequency increased, although significant differences are only observed at extreme push frequencies (60% and 140% FCF). On the other hand, the ASY propulsion showed a significantly superior F_TAN to F_RES ratio. Despite this difference in FEF there was no association between the FEF and GE, hence FEF cannot be used as an indicator for efficient propulsion in the ASY mode. This is supportive to recent work in the area suggesting that the most efficient propulsion technique from a kinetic viewpoint is not necessarily the most efficient from the physiological perspective [6,12,16,22,28]. The relatively stable nature of FEF could possibly be linked to the guided movement of the push phase and no geometric changes to the wheelchair/user interface. Consequently the magnitudes of F_RES and F_TAN are simply altered without the ratio between the 2 changing significantly. The magnitude of the required force is being controlled predominantly by the push frequency and work required per stroke to meet the conditions of propulsion at a constant Po. The ASY and SYN FEF values are comparable to those found in the literature albeit gathered under different testing conditions and the inclusion of ASY propulsion [6,8,16,32].

Matched push frequencies

For matched absolute push frequencies the rate of force development was significantly greater during ASY propulsion, which may well be the consequence of the significant difference in PA and PT to that of the SYN propulsion. With a significantly reduced PA and PT in the ASY propulsion and the unilateral nature of this technique, participants are required to apply a greater F_RES but more importantly at a greater rate of force development to maintain the same external workload. Therefore, as both propulsion mode and push frequency (push strategy) are manipulated, the participants adopt a somewhat consistent and stable model to satisfy the movement requirements under the given geometric and performance task boundaries of each condition [28]. Increased push frequency causes the rate of force development to increase as does the use of ASY technique since both changes reduce the period over which active work can be done on the hand-rim. Despite this study not investigating risk of injury, Boninger and colleagues [3–5] suggest that increased cadence, force magnitudes and rate of force development are linked to risk of injury. The findings of our study for rate of force development suggest that wheelchair users should maybe adopt the SYN style of propulsion at lower push frequencies if we consider reductions in the magnitude of forces and the rate of force development to be important. As the rate of force development remained significantly higher in ASY propulsion, coaches and rehabilitation practitioners looking to utilise this mode of propulsion should be aware of the relationship (and combined effect of push frequency) for the potential relation to risk of injury in wheelchair users. However, GE suggests different decisions would be taken should the objective be to optimise the efficiency of propulsion since there is no direct link between GE values and propulsion force data.

Force changes are seemingly controlled by the task geometry and movement frequency. The findings suggest that SYN propulsion is a better option for the ASY propulsion because the total force and rate of force development remain lower even with the matched push frequencies. The unilateral application of the force in the ASY mode seems to require the production of greater forces and rate of force development to maintain the same work (propulsion velocity). The theory of van Dienen and colleagues [9] with better performance in unilateral movement being the result of the inherent neural pathways for the reciprocal stimulation of the contra-lateral muscle groups does not appear to be applicable to hand-rim wheelchair propulsion under the current test conditions. The suggestion by Bregman et al. [6] that propulsion technique is mainly determined by the geometrical boundaries of the musculoskeletal system would appear to offer a plausible reason for the difference observed between ASY and SYN propulsion. In that context, FEF is suggested to be an invariant characteristic of the biological system that only changes with extreme geometric changes or with continued learning and training where detailed fine tuning is critical and will lead to small long term shifts in FEF [6,12,13,16]. Our data support the notion that adaptation to push strategy (frequency and mode) involves a regulation of the force magnitude and movement velocity, but does not involve a fundamental shift in coordination strategy of either propulsion mode in this cyclic movement. Understanding how individuals apply forces to the hand-rim together with the effects of propulsion mode and push frequency is important for determining strategies for implementing in activities of daily life and sporting situations. Particular attention should be paid to reducing the levels of force exerted on the upper extremity during prescription purposes when working with a wheelchair user and his or her physical capacity.

Gross efficiency

The significant differences in GE are similar to those of previous research [19–21], where reductions in the gross efficiency of hand-rim propulsion have been shown at higher push frequen-
cies (>100% FCF). Despite previous findings for ASY propulsion the current results present significant lower GE at lower push frequencies of <100% FCF (Fig. 2c). This outcome is likely to be the result of the significantly lower FCF (48 pushes·min⁻¹) in comparison to the SYN propulsion (59 pushes·min⁻¹). To examine this suggestion, ASY and SYN push frequency conditions were pair matched. The outcome subsequently produced no significant difference in the GE of ASY and SYN propulsion (Fig. 3a). As the changes in the force application for both ASY and SYN propulsion were not related to changes in GE it must be assumed that the differences in efficiency are related to changes that occur in the energy costs associated with different magnitudes of de-/accelerations of the different arm segments and trunk, as well as the different ranges in segment excursion and thus muscle lengths and tension. Push strategy (propulsion mode and push frequency) enables individuals to implement changes in the range of motion of the muscles and the force-length/velocity of the contracting muscles, thus influencing the energy required for the production of force.

The optimal GE in both propulsion modes is found in the push frequency range of 48–59 pushes·min⁻¹. It can be suggested that the choice of propulsion strategy is a trade-off between optimal efficiency in either propulsion mode and the total force applied to the hand-rim/the rate of the force development. Although lower frequencies produce greater total forces, the rate of force development is reduced. However, with increased push frequency the total forces themselves are reduced, which coincides with an increased rate of force development.

**Experimental Considerations**

The performance of able-bodied participants with limited wheelchair experience in a standardised basketball wheelchair configuration and identical wheelchair ergometer has been discussed previously by Lenton et al. [22]. Use of a standardised chair configuration eliminated any effects of different chair designs/setups. However, it is accepted that this would indeed have an effect on the relative geometry of the chair/user interface for individuals, influencing the physiological demands and propulsion mechanics. Nevertheless it is felt that the trends and relationships of the data would not change significantly. The resistance of the wheelchair/roller ergometer system is greater than documented in previous published literature with the exception of Lenton et al. [22], where it is suggested to be attributed to a number of factors. First, the camber of 15° is significantly greater in the standardised wheelchair than in propulsion studies using everyday wheelchairs. Secondly, there is the use of the standard solid tires provided by the SMARTWheel manufacturer, which have a considerable higher rolling resistance than pneumatic tires [15, 17]. Thirdly, there is the difference in roller ergometers and the use of a single roller ergometer with a much smaller roller circumference than that of the split roller ergometer with significantly greater roller circumference. The combination of these factors will have contributed to the higher rolling resistance values reported. The results of this study could be different under different testing conditions, such as for example, reduced rolling resistance and in different populations of wheelchair users.

**Conclusions**

In conclusion, push frequency changes in SYN and ASY propulsion produced identical trends for the relationship with force parameters. Increased push frequency resulted in decreased absolute force and increased rate of force development. The FEF, although consistently greater in ASY propulsion, presented no relationship with GE, thus supporting the view that FEF is overwhelmingly governed by the user/chair geometry. The ASY propulsion required significantly greater absolute forces than the SYN mode in unmatched push frequency conditions. However, with matched push frequencies the interaction of mode and frequency showed no significant differences. Despite this, propulsion mode in isolation required a significantly greater force values and rate of force development during the ASY conditions, which could all be important in relation to the risk of injury for wheelchair users. Force application differences appear to be attributable to the mode of propulsion with ASY propulsion appearing to offer a kinetic disadvantage with no physiological advantage under the current testing conditions. Future research is needed to investigate the relationship of push strategies under various propulsion velocity and Po conditions.

**Acknowledgements**

We are grateful to Prof. Martin Ferguson-Pell for the loan of the SMARTWheel (formerly ASPIRE Chair University College London) and for the support and technical assistance of Dr. Graham Nicholson whom we dedicate this work to. Graham was tragically killed in a motorcycle accident in August 2006, a dear friend and work colleague.

**References**
