Efficiency of hand-rim propulsion

Lenton, John Paul

Efficiency of hand-rim propulsion:

Synchronous vs. Asynchronous push strategies

John P. Lenton

Efficiency of hand-rim propulsion:

Synchronous vs. Asynchronous push strategies

With an estimated 1% of the total population wheelchair dependent and despite the low mechanical efficiency associated with hand-rim wheelchair propulsion, hand rim propulsion continues to be the most common mode of propulsion in daily life and wheelchair sports.

Numerous factors make up the wheelchair-user combination and are suggested to contribute to wheelchair propulsion performance. Factors that can be easily manipulated by individuals are important starting points into the understanding of hand-rim wheelchair propulsion and the optimisation thereof, in particular the physiological aspects and mechanical efficiency.

The present thesis investigates the efficiency of synchronous and asynchronous hand-rim wheelchair propulsion strategies. The results provide a platform for the both theoretical as well as practical significance in the context of propulsion. Generating information on optimum conditions for cyclic arm work in rehabilitation and wheelchair sports is important for wheelchair performance and efficiency of functioning.

Efficiency of hand-rim propulsion: Synchronous vs. Asynchronous push strategies

John Paul Lenton

Propositions (Stellingen)

Accompanying the thesis

Efficiency of hand-rim propulsion: Synchronous vs. Asynchronous push strategies

John P. Lenton, 24th October 2012

1. Efficiency of hand-rim propulsion in synchronous and asynchronous push strategies remains relatively low in comparison with other upper-body exercise modalities.

2. Push (arm) frequency is the predominant component of push strategy selection in hand-rim wheelchair propulsion to optimise mechanical efficiency.

3. Practice is a key element to improved mechanical efficiency.

4. Propulsion practice should not be aimed at feedback based optimisation of the effective propulsion force because this may be less efficient and more straining for individuals.

5. Synchronous vs. Asynchronous propulsion: So many questions, yet so few answers.

6. Hand-rim propulsion is here to stay; the search for optimal conditions in all environments is far from complete and must continue.

7. In the search for optimal conditions thought should be given to both physiological and biomechanical aspects of hand-rim propulsion.

8. If I was to summarise my PhD journey and research work in just three simple words I would have to say “it goes on.”

9. “Insanity is doing the same thing, over and over again, but expecting different results.” (Albert Einstein).

10. “The saddest aspect of life right now is that science gathers knowledge faster than society gathers wisdom.” (Isaac Asimov).

11. “I may not have gone where I intended to go, but I think I have ended up where I needed to be.” (Douglas Adams).

12. “It does not do to dwell on dreams and forget to live.” (J.K. Rowling).

The studies described in this thesis have been conducted at the Manchester Metropolitan University, Exercise and Sport Science Department. All studies were funded by Manchester Metropolitan University.
www.mmu.ac.uk

The printing of this thesis was financially supported by:

www.rug.nl

www.rug.nl/umcg

Peter Harrison Centre for Disability Sport

www.peterharrisoncentre.org

www.rgklife.com

www.bromakin.co.uk

ISBN: 978-90-367-5772-0

Layout: John P Lenton
Cover Design: Harvinder Rai, RGK & Darren Langham, twelve20 design
Printed by: GVO drukkers & vormgevers B.V. | Ponsen & Looijen, www.p-l.nl

RIJKSUNIVERSITEIT GRONINGEN

Efficiency of hand-rim propulsion: Synchronous vs. Asynchronous push strategies

Proefschrift

ter verkrijging van het doctoraat in de
Medische Wetenschappen
aan de Rijksuniversiteit Groningen
op gezag van de
Rector Magnificus, dr. E. Sterken,
in het openbaar te verdedigen op
woensdag 24 oktober 2012
om 16.15 uur

door

John Paul Lenton

geboren op 15 augustus 1980
te Whiston, Engeland

Promotores:	Prof. dr. L.H.V. van der Woude Prof. dr. N.E. Fowler
Copromotor:	Dr. V.L. Tolfrey
Beoordelingscommissie:	Prof. dr. K. Postema Prof. dr. Y. Vanlandewijck Prof. dr. H.E.J. Veeger

ISBN: 978-90-367-5772-0

Contents

Chapter 1

General Introduction

Hand-rim wheelchair propulsion

Hand-rim wheelchair propulsion is a necessity in the daily activities of many people with a spinal cord injury or other lower limb impairment. It is estimated that 1% of the total population are wheelchair dependent (www.newdisability.com). Hence in 2010 there were in the region of 8.1 million wheelchair users throughout Europe and approximately 68.5 million worldwide. Despite the low mechanical efficiency associated with hand-rim wheelchair propulsion, it is estimated that 90% of all wheelchairs are hand-rim propelled and this continues to be used as the most common mode of propulsion in daily life and wheelchair sports [47]. The last few decades have seen researchers contribute significantly to the understanding of wheelchair propulsion during rehabilitation, daily activity and sports performance. Research is becoming increasingly important in the effort for the optimisation of propulsion to help reduce the physical strain [67], and mechanical load placed upon the upper extremity [119]. Nevertheless, despite the general acceptance of the low mechanical efficiency and high mechanical load, relatively few studies have attempted to explain and understand this low mechanical efficiency and consequently the limited wheelchair propulsion performance.

Researchers have employed a variety of methods to investigate a wide range of questions. These questions can be categorised into performance associated issues (e.g. power production, propulsion technique and mechanical efficiency), disability related issues (e.g. human capacity, skill and injury risks) and the ergonomics of wheelchair design (e.g. wheel size, seat height). Van der Woude and colleagues [130, 134] suggested that three basic qualities of the wheelchair-user combination are crucial to determine the final performance in wheelchair propulsion. First, there is the user, who produces the energy and work for propulsion; secondly, the design and technical characteristics of the wheelchair; finally the interaction of the wheelchair and user which determine the efficiency of the energy transfer from the user to the wheelchair. To fully understand the low mechanical efficiency of wheelchair propulsion would require studies that cover a wide range of topics including mechanical, physiological, health related consequences and biomechanical aspects of wheelchair propulsion.

There are numerous factors that can have an effect on wheelchair propulsion performance and/or efficiency and any conceptual model needs to incorporate these using an interdisciplinary approach **(Figure 1.1)**. Research into mechanical efficiency and performance needs to include a focus on the propulsion technique and modes of propulsion; i.e. push strategies adopted by individuals. Through practice and training, individuals often learn to adopt different push strategies that meet their needs and the different conditions of their chosen sport or daily activity. Push strategy is a very general term and can be broken down into two more specific terms. When using the term 'push strategy' in the present thesis, the term comprises of push frequency (the number of pushes or total number of left and right arm movements performed per minute) and propulsion mode, i.e. whether the hands contact the hand rim together (synchronous) or alternately (asynchronous). Synchronous propulsion is the movement pattern most commonly seen during straight line wheelchair propulsion and is characterised by both hands contacting the hand-rim at the same time. Whereas in the asynchronous propulsion the hands contact the hand-rim alternatively with the left and right arm movements approximately 180º out of phase.

Little has been reported on the efficiency of different propulsion modes or mode / push-frequency combinations (push strategies). The limited evidence available suggests that lower push frequencies and longer simultaneous push strokes are more efficient and potentially reduce the risk of injury to the upper extremity [9]. Early studies demonstrate that mechanical efficiency is affected by changes in push frequency for both able-bodied inexperienced individuals and experienced wheelchair users [46, 135]. The majority of research has focussed on synchronous propulsion, with only a few studies investigating the asynchronous mode [43, 48]. The predominance of studies focused on synchronous propulsion is to be expected as this is the most common mode of propulsion in most sporting situations and activities of daily living. However, increased interest and observations in wheelchair sports such as basketball and tennis reveal that asynchronous propulsion is used extensively in these activities. It is therefore important to explore this alternative means of propulsion. It would appear that the asynchronous propulsion mode involves a different range of motion to that of the synchronous mode and thus will present different performance demands.

Previous research has demonstrated asynchronous force application to be as good as, or superior to, the synchronous mode in terms of oxygen cost [43]. It was suggested that the greater continuity of hand-rim force application during asynchronous propulsion reduced fluctuations in hand-rim velocity, and thereby decreased the acceleration and work requirement of each stroke. Goosey-Tolfrey & Kirk [48] also indicated that the asynchronous mode was preferred at higher push frequencies. Research suggests that unilateral movements are advantageous over bilateral movements as they take advantage of inherent neural pathways for the reciprocal stimulation of the contralateral muscle groups for improved performance [31]. There is the suggestion that deficits in bilateral force can be large enough to be functionally important and could well account for the 20% deficit reported by van Soest and colleagues [103] in two-legged jump height vs. one-legged jump height. Research by Vandervoort et al. [117] showed that the bilateral deficit increases with movement velocity, which may explain some of the reduction in gross efficiency associated with increased push frequency in wheelchair propulsion. Synchronous and asynchronous research has generated interest in other forms of upper-body exercise, handcycling [1, 25, 27, 127, 132] and arm-cranking [64, 83]. However, the aforementioned literature presents conflicting results with the synchronous mode more efficient in handcycling whereas in arm-cranking the asynchronous is either more efficient or reports no advantage of either mode.

The developing interests in wheelchair sports which utilise an asynchronous movement pattern make investigation of such a propulsion mode timely. There is a general paucity of research investigating the mechanics of this propulsion mode and so it is difficult for coaches, rehabilitation professionals and wheelchair manufacturers to know what is best to adapt, the technique or chair configuration to achieve optimal results. Since wheelchair users are able to choose which propulsion strategy they wish to adopt, it is important that any investigation of the asynchronous propulsion mode compares performance measures with those of the alternative and predominantly utilised synchronous propulsion mode to allow meaningful evaluation. Examining of the efficacy of the asynchronous movement pattern may also provide further insight into the relatively low gross efficiency reported for wheelchair propulsion.

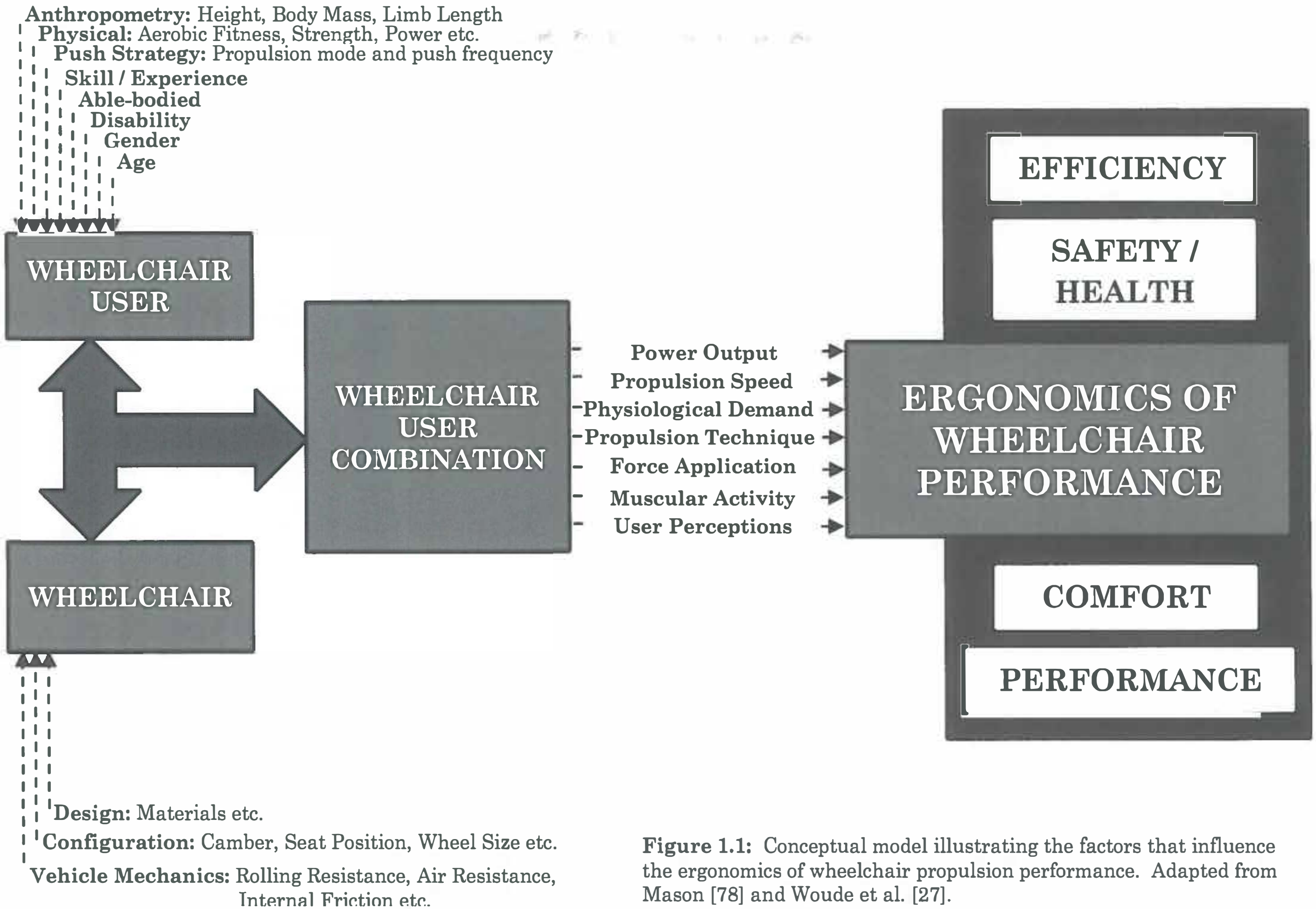


Figure 1.1: Conceptual model illustrating the factors that influence the ergonomics of wheelchair propulsion performance. Adapted from Mason [78] and Woude et al. [27].

Methodology

Previous studies have highlighted a number of methodological considerations when designing investigations that study wheelchair propulsion. There are issues relating to the nature of the task including the choice of over-ground or ergometer based propulsion, the wheelchair configuration, and relative or absolute work. In addition there are concerns relating to the sample population to be used including whether to use habitual wheelchair users, who normally have some form of musculoskeletal or neuromuscular impairment, or individuals with no disability. Level of experience in wheelchair propulsion is also worthy of consideration. In addition there are a number of questions relating to measurement techniques and determination of key performance variables. The following section will seek to outline critical methodological issues relating to each of these areas.

Experimental set-up

The most ecologically valid way to assess wheelchair propulsion would be to use over-ground propulsion as this is the task that performers are required to complete in their day-to-day locomotion and in sport. However, assessing over-ground propulsion presents a range of challenges to the investigator and is the least standardised. The nature of the floor surface, its hardness and friction characteristics have a direct impact upon the rolling resistance and thus the work requirements of the propulsion task. Investigations should control and/or report these characteristics. At present there is no agreed standard for 'normal' floor conditions to allow comparison between studies. In addition to the rolling resistance, the use of over-ground propulsion would introduce an element of aerodynamic drag proportional to the relative air speed and the size and shape of the wheelchair and user. Such factors make the determination and control of the work associated with over-ground propulsion difficult to standardise, compromising the ability to make comparisons between experimental conditions.

To address the problems of controlling and determining work in over-ground propulsion, research has employed the motor driven treadmill with researchers suggesting that this is the most mechanically realistic simulation of wheelchair propulsion [5, 35, 109, 113, 118, 128]. However, wheelchair ergometers have also been used and there are three types. Firstly, is the earliest type which is an extension of the popular Monark bicycle ergometer [12, 42, 43, 69]. Secondly are computerised stationary wheelchair simulators in which wheelchair characteristics are kept equal for all individuals [54-57, 75, 84, 104, 121]. Finally the use of a wheelchair roller ergometer (WERG) has been common [8, 9, 21, 32, 48, 49, 100, 103, 116, 133]. These wheelchair ergometers are typically constructed with either a single or split roller, attached via a fixed chain to a flywheel **(Figure 1.2A)**. The inertial characteristics of the wheelchair and roller are set such as to approximate the typical work requirements of over-ground propulsion. The work requirements of the WERG can be calculated from the product of the roller resistance and velocity [32, 116, 133], assuming the resistance to be constant it is thus possible to control or vary the work by monitoring the propulsion velocity. Although ergometers do not reproduce identical performance demands to over-ground propulsion, for example there is no influence of air resistance and neither is there a requirement to maintain the chair in a linear path, the capacity to control work has made them by far the most prevalent tool in wheelchair research [8, 9, 21, 32, 48, 49, 101, 104, 117, 134]. The different measurement systems have their advantages and disadvantages in terms of validity and reliability, however, the comparability of results and applicability of the existing knowledge base remains somewhat limited without the standardisation of measurement equipment and methodology [66, 127, 134].

Wheelchair roller ergometers provide a useful tool for determining and controlling work, but the selection of an appropriate level of work remains a challenge. A wide variety of different workloads, hence exercise intensity levels have been utilised in the literature and as a consequence the comparison between studies is sometimes not possible. In designing a study it is necessary to identify an ecologically relevant level of work, i.e. one that represents the equivalent demand of performing the task over-ground. Where studies seek to compare either within or between groups across a range of performance conditions or time points, it is essential to determine whether the comparison should be between the absolute or the relative work. For different individuals performance of the same external work will elicit a different degree of physiological strain. As the physiological responses do not change in a linear fashion with intensity of demand changes it is necessary to consider using tasks that present a similar level of relative demand, i.e. a similar proportion of the maximum work capacity [62, 63].

There are a considerable number of components that define the wheelchair-user configuration, these are summarised in **Figure 1.1**. Various investigations have shown that alterations to any of these components can result in changes to the physiological demand of the task e.g. seat height and position [65, 73, 81, 95, 107, 124, 128, 136], hand-rim size [41, 138], wheel size [80] and wheel camber [14, 79]. In the absence of an accepted optimal model for wheelchair configuration it is important that standardised settings are used for both within and between subject comparisons **(Figure 1.2B)**.

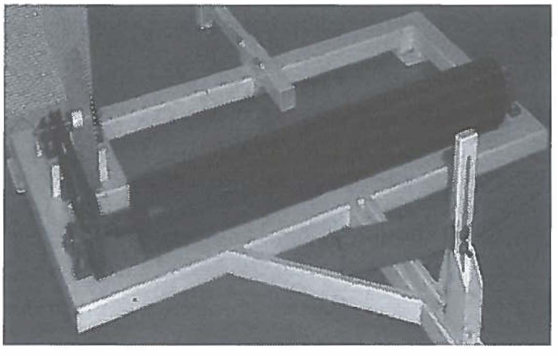


Figure 1.2A: Wheelchair Ergometer (roller length 1.143 m; diameter 0.15 m; circumference 0.479 m; mass 38.5 kg).

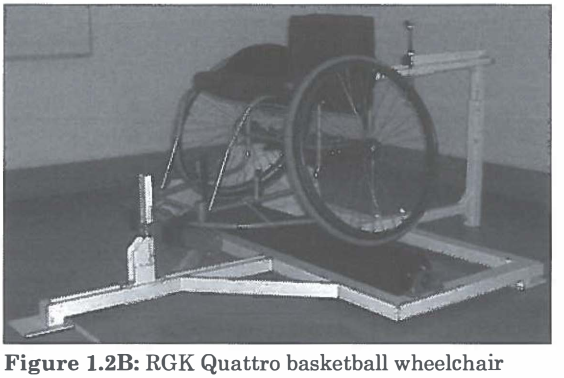


Figure 1.2B: RGK Quattro basketball wheelchair (Serial No: SQ989-02) attached to WERG.

Sample Population

The variability in the assessment of the physiological response to wheelchair propulsion is not exclusively influenced by the nature of the task and its constraints (wheelchair configuration, propulsion surface etc.), there is also an impact of the intra and inter participant variability. Habitual wheelchair users typically are affected by some form of musculoskeletal or neuromuscular deficit which impairs their locomotion. It is not uncommon for the underlying pathology to also affect other aspects of the physiological system and thus the responses to exercise. There are many different reasons that lead to individuals becoming wheelchair users and it is a mistake to consider all such users as a single homogenous group.

One method to overcome the inherent problem of the heterogeneity of participants, who are wheelchair users as a result of physical disabilities, is to study 'able-bodied' non-wheelchair users. The use of able-bodied populations for the study of wheelchair propulsion has been widespread [6, 12, 13, 27, 28, 43, 48, 49, 51, 54-58, 62, 63, 129, 130, 133] as it can be reasonably assumed that these participants should respond in a more homogenous manner and demonstrate similar physiological responses to exercise as seen in other sport and exercise activities. A number of wheelchair propulsion studies have demonstrated such similarities with overall trends in physiology and technique matching that of wheelchair users, whilst acknowledging the absolute differences [28, 63, 89, 129, 130, 135]. Differences identified through manipulation of constraints can more easily be attributed to such changes in constraint and do not risk conflating aspects of impairment with task changes.

Where aspects of either the propulsion technique or wheelchair configuration are to be altered, the employment of experienced users does introduce an element of learning and habituation that may skew results towards the most familiar, synchronous mode of propulsion [12, 69, 89, 135]. The employment of relative novice participants, usually able-bodied individuals, presents an opportunity to manipulate the task constraints without the interference of exposure bias. Propulsion experience evidently influences energy cost, mechanical efficiency and technique of wheelchair propulsion [12, 89]. Studies have investigated the differences in mechanical efficiency between experienced wheelchair dependent individuals and non-experienced able-bodied individuals [135]. The results suggest that experience produces significantly higher gross efficiency in comparison to inexperienced users.

Learning studies are limited in the wheelchair propulsion literature [3, 54-57, 72, 94]. However, studies have demonstrated that, through practice and implicit learning; individuals become more efficient [12, 89, 135]. Sparrow [114] stated that with practice, the movement pattern will be refined to approximate more closely that pattern which is mechanically and physiologically optimal within the constraints of the task.

Measurement Techniques

Mechanical efficiency

Mechanical efficiency represents the ratio between the energy cost and work done for a task. This is easy to understand and applied for simple machines but becomes more complex when related to whole body movement and the interaction of the human user with a mechanical device such as a wheelchair. Throughout the literature many different approaches to quantifying efficiency have been employed and these are addressed in some detail by Cavanagh & Kram [17, 18]. The most common definition used for evaluation of wheelchair propulsion is that of gross efficiency. Gross efficiency is defined as the ratio of the task related external work accomplished to the metabolic energy expended to perform that work (i.e. Gross efficiency = External Work / Metabolic cost). Typical gross efficiency values in wheelchair propulsion have been shown to vary between 2 and 11% under conditions common to every-day activities [62, 63, 121, 131, 135], see **Table 1.1**. However, in sporting situations values can be as high as 12% [45, 118] dependent on the propulsion velocity and population studied. The range of mechanical efficiency values reported in the literature reinforces the importance of accurate reporting and control of the experimental environment to allow the underlying mechanisms for such differences to be explained. It is essential that the work and metabolic demand can each be accurately determined. On the other hand the gross efficiency of hand-rim wheelchair propulsion in comparison with alternate forms of upper body-body exercise remains substantially lower to that of handcycling 12-15% [25, 122, 123, 130] and arm-cranking 14-20% [50, 76, 91, 125] dependent on exercise conditions.

Although the majority of studies in wheelchair propulsion and the other modes of upper body exercise have focused upon gross efficiency [12, 46, 54-57, 108, 118, 126, 130, 136] there are other indices which can be used. Net efficiency, work efficiency and delta efficiency all differ in terms of base-line subtraction from the metabolic energy expenditure [39, 126]. These indices are considered to be more meaningful estimations of the true muscular efficiency since they account for the unmeasured internal work done. The use of work efficiency is particularly difficult by the challenges of creating a representative 'zero-load' condition to set as a baseline. Regardless of definition, all efficiency indices require the determination of the metabolic cost for the work done. This is most conveniently done by estimating the calorific equivalence from expired air, the product of $\dot{V}O_2$ and the oxygen energetic equivalent by using the associated measurements of the respiratory exchange ratio (RER) and standard conversion tables [90]. Utilisation of $\dot{V}O_2$ data to estimate energy expenditure is predicated on the assumption that the dominant source of metabolism is aerobic. At higher relative exercise intensities this assumption becomes challenged as a greater proportion of energy is derived from anaerobic sources. It is therefore essential that, when determining the efficiency of wheelchair propulsion, the exercise intensity is set at a level whereby all participants can complete all tasks and maintain a steady state sub-maximal, predominantly aerobic level of exertion.

Table 1.1: Mechanical efficiency in hand-rim wheelchair propulsion

Reference	Participants	Speed ($m \cdot s^{-1}$)	Power Output (W)	Efficiency (%)
TREADMILL				
van der Woude et al.[130]	WS (n = 8)	0.55 – 1.39	5.0 – 77.5	GE 2.1 – 11.0
van der Woude et al.[137]	WS (n = 8)	0.83 – 3.33		GE 4.5 – 7.9
van der Woude et al.[134]	WS (n = 6) AB (n = 6)	0.55 – 1.39	20.4 – 50.3 18.5 – 30.5	GE 8.5 – 10.4 GE 6.1 – 7.5
van der Woude et al.[135]	WS (n = 9)	0.55 – 1.39	14.1 – 36.4	GE 6.6 – 8.8
Vanlandewijck et al. [117]	WS (n = 40)	1.11 – 2.22	60 & 80% $\dot{V}O_2$ peak	GE 7.6 – 11.1
Dallmeijer et al. [27]	WD (n = 9) AB (n = 10)	1.25 1.08	25 – 35	GE 9.0 – 10.2 GE 8.0 – 8.2
de Groot et al. [53]	WD (n = 92)	0.83 - 1.11	6.5 – 17.0	GE 3.1 – 7.2
de Groot et al. [59]	AB (n = 10)	1.11	10.3 – 24.8	GE 4.2 – 6.9
WHEELCHAIR ERGOMETER				
Knowlton et al. [69]	WD (n = 5) AB (n = 5)	30rpm	20.5 / 31.5 / 47.6 28.8 / 34.0 / 39.5	NE 12.9 – 15.7 NE 10.1 – 11.4
Brown et al. [12]	WS (n = 5) AB (n = 5)		12.8 – 40.6	NE 10.0 – 19.5 NE 7.0 – 11.5
WHEELCHAIR ROLLER ERGOMETER				
van der Woude et al. [133]	AB (n = 10)	1.39	6.4 – 40.1	GE 3.0 – 9.1
Goosey et al. 1998 [	WS (n = 18)	4.70 6.58		GE 8.0 – 12.1 GE 10.5
Goosey et al. [46]	WS (n = 8)	6.58	50	GE 9.3 – 10.1
Hintzy et al. [62]	AB (n = 15)	1.11	22.4 36.8 51.2	GE 6.5 – 8.8 NE 9.9 – 11.1 WE 13.8 – 16.8
Hintzy & Tordi [61]	AB (n = 18)	1.11	22.7 37.5	GE 6.5 – 8.0 NE 9.9 – 11.1
Goosey-Tolfrey & Lenton [49]	AB (n =8)	1.70	27	GE 5.5 – 5.9
STATIONARY WHEELCHAIR ERGOMETER				
Veeger et al. [120]	AB (n = 9)	0.83 – 1.67	0.25 $W \cdot Kg^{-1}$ 0.50 $W \cdot Kg^{-1}$	GE 6.0 – 8.2 GE 8.5 – 10.4
Linden et al. [74]	AB (n = 6)	1.11 – 1.67	16.9 – 26.5	GE 6.1 – 7.1
de Groot et al. [54]	AB (n = 10) AB (n = 10)	1.11 1.11	14.2 / 23.2 / 36.9 13.9 / 23.4 / 38.2	GE 5.5 – 8.5 GE 5.9 – 9.9
de Groot et al. [55]	AB (n = 10) * 2	1.11	0.15 $W \cdot Kg^{-1}$ 0.25 $W \cdot Kg^{-1}$	GE 5.5 – 8.1
de Groot et al. [56]	AB (n = 9)	1.11	0.25 $W \cdot Kg^{-1}$ 22.5	GE 7.5
van der Woude et al. [129]	AB (n = 10)	1.11	12.2 / 29.2 / 40.7	GE 5.3 – 9.1
de Groot et al. [58]	AB (n = 13) AB (n = 11)	1.11 1.39	22 – 23 31.3 – 33.5	GE 6.7 – 7.1 GE 7.0 – 7.6
de Groot et al. [59]	AB (n = 10)	1.11	13.8 – 23.5	GE 5.6 – 8.1

Key: AB = Able-bodied; WS = Wheelchair sportsperson; WD = Wheelchair dependent; GE = gross efficiency; NE = net efficiency; WE = work efficiency

Push/cycle frequency

The effect of pedal cadence (frequency) and the proposed mechanisms responsible for an optimal cadence has received widespread attention in the cycling literature [7, 19, 20, 38, 39, 60, 61, 77]. Hand-rim wheelchair propulsion is somewhat similar to cycling, primarily because of the repetitive and cyclic nature of both activities; the upper-body equivalent to this is handcycling and arm-cranking which has seen research into cadence as well as mode (synchronous and asynchronous). However, there is a paucity of research exploring push frequency during wheelchair propulsion [46, 135]. These studies have shown the existence of an optimal push frequency in relation to oxygen uptake and mechanical efficiency, at the freely chosen push frequency in both inexperienced and experienced participants. It has been suggested that, at higher frequencies, this could be attributed to the faster movement of the arms and increasing the recruitment of fast twitch fibres [24, 115], which are believed to exhibit lower metabolic efficiency. At lower frequencies, an increased force/work for each arm stroke may well increase the oxygen cost as a result of the changes in the force-velocity and length-tension relationships of the contracting muscles. Intramuscular pressure at low frequencies may well be reduced along with a reduced oxygen transportation improving efficiency. These suggestions for changes in efficiency as a consequence of changes in push frequency draw heavily on assumptions about the application of force to the hand-rim. To be able to properly evaluate these assumptions it is important that hand-rim forces are investigated under a range of propulsion modes and frequencies.

To date, studies on push frequency have compared the relative frequency measured as some percentage of the freely chosen frequency [46, 135]. There has also been examination of the absolute frequency used for wheelchair propulsion [48, 49]. Studies of the absolute propulsion have shown that in general athletes or individuals who adopt a lower freely chosen frequency demonstrate a higher efficiency/better economy [40, 44-46, 68]. It is therefore important to consider both the absolute and the relative frequency used when seeking to investigate the effects of push frequency on wheelchair propulsion.

Force Application

During wheelchair propulsion the push cycle consists of two distinct phases, the push phase and the recovery phase. It is in the push phase that the hands make contact with the hand-rims and forces are applied. Only the component of the force acting tangential to the hand-rim fully contributes to propulsion [8, 54, 106, 121] although other components may be necessary to create the contact forces necessary to allow the effective transfer of force between the hand and the rim [11, 54, 105]. The velocity of the wheelchair is dependent upon the torque impulse (the product of the tangential force, radius of the hand-rim and contact time) or the work done during hand contact (the product of the tangential force, radius of the hand-rim and angular displacement).

For a given intensity of exercise, changing the push frequency requires a change in the amount of work per cycle although this may not be evident by any major changes in the movement patterns of the arm segments [121]. On the other hand literature has suggested that improvements in mechanical efficiency are due to modifications in technique that consequently improve the force generation [105]. A study, based on the provision of feedback to aid the learning of a more tangential force direction, demonstrated that whilst novice individuals were able to improve the effectiveness of the force application towards a tangential direction [54] there was no positive effect on mechanical efficiency. Therefore, the fraction of effective force can be changed based on feedback up to and beyond 100%, yet is then requiring more energy. Not all studies have shown the force effectiveness to be trainable; Kotajarvi et al. [72] also recently demonstrated little utility of feedback in improving the force effectiveness of wheelchair propulsion in experienced wheelchair users. This could be a result of experienced individuals having already optimised their stroke in a manner that optimises mechanical efficiency. Other variables, such as stroke length and frequency may be more amenable to visual biofeedback and improved efficiency. Richter and colleagues [99] suggest that wheelchair users adapt their stroke pattern to accommodate their propulsion environment. This area of research requires hand-rim kinetic information to investigate how individuals orientate forces to the hand-rims with the changes in push frequency and or propulsion mode. Such studies remain scarce in the literature; however, significant contributions on force production have been made by groups led by van der Woude & Veeger in the Netherlands, from the 1980s onwards and Cooper & Boninger in the USA from the 1990s onwards. More recent studies on force application have been conducted by researchers such as Goosey-Tolfrey et al. [51], Kotajarvi et al. [72, 73], Koontz et al. [70, 71], Richter et al. [96, 98, 99] and Rice et al. [94].

Understanding the magnitude and direction of the forces applied and the period of the cycle for which they act, is an essential element in seeking to understand the mechanical efficiency of wheelchair propulsion. Tangential forces have been shown to differ between inexperienced and experienced wheelchair users [100]. Robertson and colleagues [100] stated that the experienced wheelchair users: 1) had a longer contact period with the hand-rim, 2) reduced peak forces, 3) peaked later in push phase, and 4) the cycle was maintained for longer time periods. There remains the debate as to whether magnitudes of forces are related to propulsion experience and improved skills/technique because of the lack of evidence suggests otherwise. However, more recently Rozendaal et al. [106] provided a simulation study on force direction, which suggested that experienced wheelchair users optimise the force pattern by balancing the mechanical effect as well as musculoskeletal cost. It is clear that in order to offer insight into the adaptive responses to changes in wheelchair propulsion mode and frequency, knowledge of the hand-rim forces is essential.

To investigate propulsion forces an instrumented force-sensing hand-rim is required e.g. the SMART^{Wheel} **(Figure 1.3)**. This has been used extensively to investigate kinetic data during wheelchair propulsion [2, 8, 21, 22, 70-73, 94, 95, 100, 110]. The SMART^{Wheel} is a modified wheel that measures three dimensional forces and moments applied to the hand-rim [4, 21]. Measurement of the contact forces in all three dimensions also allows the calculation of the fraction of effective force. Veeger and colleagues, [121] defined the fraction of effective force as the ratio between the tangential force and the total force or the fraction of effective force. The concept of the fraction of effective force has been used on a number of occasions to investigate wheelchair propulsion [2, 11, 26, 29, 54-57, 59, 70, 73, 92, 121, 128] although there have been questions raised about its meaningfulness. Particular concern has been expressed about the assumption that only the tangential force is useful or effective [54, 72]. It can be argued that some degree of force is necessary in the radial and medio-lateral directions to facilitate the frictional contact force necessary for the transmission of the tangential component necessary. It is clear that to properly understand wheelchair propulsion examination of all the force components is necessary.

Figure 1.3: SMART^{Wheel} attached to a wheelchair on the WERG

Ratings of perceived exertion

Psycho-physiological measures have seen rating scales become the most prevalent tool in the study of perceived exertion and the most widely utilised scale for quantifying the rating of perceived exertion is the Borg 15-point scale [10]. This scale has been shown to have a high degree of validity and reliability [33, 36, 102, 111]. The rating of perceived exertion correlates highly with physical indicators of effort such as heart rate, oxygen consumption, blood lactate and ventilation rate [87]. Research has studied the physiological determinants of perceived exertion [15, 16, 82, 85, 86, 101] based on the theory of central and local or peripheral factors [34]. Central factors correspond to sensations from the cardio-respiratory system (for example heart rate and oxygen uptake) whereas local or peripheral factors relate to feelings of strain in the exercising muscles or joints (for example local muscle fatigue). The dominant influence on perceived exertion comes from a combination of local sensations [101, 123].

The mechanisms that control the selection of push strategies are not well understood. The cycling literature suggests that peripheral cues from active muscles are important determinants for cadence selection [34, 93]. However, this type of subjective reporting of perceived exertion is an area that has received very little attention in the wheelchair propulsion literature. Of the work that is available, ratings of perceived exertion has been examined in relation to hand-rim size and propulsion velocity [41], propulsion strategy-frequency combination [48] and the degree of co-ordination between breathing and rhythmic arm movements [37]. Extending this work to include a comparison of the central and peripheral perceived exertion in experienced and in-experienced wheelchair users may provide a further insight into the mechanisms that control push strategy selection [86].

Rating of perceived exertion scores have been shown to have a curvilinear relationship with push frequency [46] and is minimised at the self-selected frequency. The RPE appears to mirror the trend seen for oxygen uptake and or mechanical efficiency with push frequency. In contrast Fabre et al. [37] demonstrated an increase in rating of perceived exertion scores with increased push frequency but no difference with decreased push frequency. Consequently the relationship of perceived exertion and frequency remains unclear, although literature strongly suggests that peripheral cues from active muscles are important determinants for cadence selection [34, 88, 93]. It is proposed that the feedback from these cues influences an individual's rating of perceived exertion score therefore, perception of effort mediated by the peripheral feedback sources could well be important in push frequency selection during wheelchair propulsion. The distinct lack of perceived exertion data in the wheelchair literature does not allow conclusions to be drawn on the relationships that the rating of perceived exertion scores could have with push frequency and propulsion mode [37, 46]. Currently findings are taken from cycling and arm-cranking and the theory applied to wheelchair propulsion. It is presumed that ratings of perceived exertion would not only be a useful tool in providing information of the relationship with push strategy but importantly the differentiated scores could offer insight into whether the central or local factors contribute more so to changes seen in mechanical efficiency. An opportunity exists to demonstrate the trends and relationships of perceived exertion with push strategy and propulsion experience in wheelchair propulsion.

Aim of this thesis

Our understanding of wheelchair propulsion is constantly evolving as research into rehabilitation and wheelchair sport develops. Clearly research directed towards an understanding of the physiological aspects of propulsion and mechanical efficiency would be of both a theoretical as well as a practical significance in the context of propulsion performance. However, there remains a need for sustained and systematic research into the relative efficacy of different propulsion modes and frequencies (push strategies). Such work needs to consider the mechanisms underpinning such relationships and the theoretical basis for optimal performance.

It is very evident from the literature that wheelchair propulsion is relatively inefficient physiologically in comparison to other forms of locomotion, i.e. walking, running, cycling and handcycling/arm-cranking. Accept for handcycling these modalities tend to be asynchronous in their nature prompting the question as to whether wheelchair propulsion could be better if performed asynchronously. In light of the interests from daily wheelchair users and wheelchair sports which are beginning to utilise an asynchronous movement pattern makes investigation of such a propulsion mode appropriate. Therefore, the thesis main aim seeks to explore if an asynchronous propulsion mode can be more efficient than the synchronous propulsion mode. To help answer this question a number of experimental chapters will compare both synchronous and asynchronous propulsion modes. Mechanical efficiency measures, physiological variables, psycho-physiological markers propulsion practice and kinetic measures will all be employed to help address the research question. We hypothesise that asynchronous propulsion will improve the mechanical efficiency of wheelchair propulsion and be more advantageous to that of the traditional synchronous propulsion.

Outline of thesis

This thesis comprises of six experimental chapters **(Chapters 2 - 7)** aimed to address the research aim documented previously. **Chapter 2** determines the separate contributions of push frequency and the mode of propulsion on the internal work during sub-maximal propulsion. The findings provide information of the different indices of mechanical efficiency that help to understand and realise the role of internal and external work production with different push strategies. **Chapter 3** focuses on determining the mechanical efficiency of propulsion at different push frequencies during both synchronous and asynchronous propulsion modes. The findings provide information about the relationship between mechanical efficiency and the push frequency of arm movements. **Chapter 4** is an extension of **chapter 3**, examining the role of wheelchair propulsion experience on mechanical efficiency. The incorporation of differentiated ratings of perceived exertion (central and peripheral) allows the psycho-physiological relationships to be investigated for both push frequency and propulsion mode. The findings identify the trends in physiological responses of experienced wheelchair sportsmen compared with those of able-bodied individuals. The differentiated ratings of perceived exertion aim to provide support for the relationships and trends observed in physiological and mechanical efficiency data, as a result of experience, push frequency and propulsion mode. **Chapter 5** investigates the effects of practice on mechanical efficiency and timing parameters associated with propulsion strategy. Identifying how both paced and unpaced practice affect mechanical efficiency and the relationship with push frequency changes. **Chapters 6 and 7** investigate force production and effectiveness of force application at a range of push frequencies for both propulsion modes to help understand the changes seen in mechanical efficiency. The results provide important information as to the relationship of force application from both a push strategy and mechanical efficiency perspective. **Chapter 8** discusses the overall findings of this thesis in the context of theoretical, clinical and practical understanding of cyclic arm work, as well as the limitations of the research approach taken.

References

1 Abel T, Kroner M, Rojas Vega S, Peters C, Klose C, Platen, P. Energy expenditure in wheelchair racing and handbiking – a basis for prevention of cardiovascular diseases in those with disabilities. Eur J Cardiovasc Prev Rehabil 2003; 10: 371-376.

2 Ambrosio F, Boninger ML, Souza AL, Fitzgerald SG, Koontz AM, Cooper RA. Biomechanics and strength of manual wheelchair users. J Spinal Cord Med 2005; 28(5): 407-414.

3 Amazeen PG, Amazeen EL, Beek PJ. Coupling of breathing and movement during manual wheelchair propulsion. J Exp Psychol Hum Percept Perform 2001; 27: 1243-1259.

4 Asato KT, Cooper RA, Robertson RN, Ster, JF. SMART^{Wheel}: development and testing of a system for measuring manual wheelchair propulsion dynamics. IEEE Trans Biomed Eng 1993; 40: 1320-1324.

5 Bennedik K, Engel P, Hildebrandt G. Der Rollstuhl [The wheelchair]. Internationale Schriftenreihe her Rehabilitationsforschung 15. Rheinstettten, Schindele Verlag, 1978.

6 van den Berg R, de Groot S, Swart KM, van der Woude LH. Physical capacity after 7 weeks of low-intensity wheelchair training. Disabil Rehabil 2010; 32(26): 2244-52.

7 Böning D, Gonen Y, Maassen N. Relationship between work load, pedal frequency and physical fitness. Int J Sports Med 1984; 5: 92-97.

8 Boninger ML, Cooper RA, Robertson RN, Shimada SD. Three dimensional pushrim forces during two speeds of wheelchair propulsion. Am J Physical Med Rehab 1997; 76(5): 420-426.

9 Boninger ML, Souza AL, Cooper RA, Fitzgerald SG, Koontz AM, Fay BT. Propulsion patterns and pushrim biomechanics in manual wheelchair propulsion. Am J Phys Med Rehab 2002; 76: 420-426.

10 Borg G. Perceived exertion as an indicator of somatic stress. Scand. J. Rehabil Med 1970; 2: 92-98.
11 Bregman DJJ, van Drongelen S, Veeger HEJ. Is effective force application in handrim wheelchair propulsion also efficient? Clin Biomech 2009; 24: 13-19.

12 Brown DD, Knowlton RG, Hamill J, Schneider TL, Hetzler RK. Physiological and biomechanical differences between wheelchair-dependent and able-bodied subjects during wheelchair ergometry. Eur J Appl Physiol 1990; 60: 179–182.

13 Brubaker CE, McClay IS, McLaurin CA. Effect of seat position on wheelchair propulsion efficiency. In Proceedings of 2nd International Conference on Rehabilitation Engineering 1984; 12-14. Ottawa: Canadian Medical and Biological Engineering Society.

14 Buckley SM & Bhambhani YN. The effects of wheelchair camber on physiological and perceptual responses in younger and older men. Adapted Physical Activity Quarterly 1998; 15: 15-24.

15 Cafarelli E. Peripheral and central inputs to the effort sense during cycling exercise. Eur J Appl Physiol 1977; 37: 181-189.

16 Carton RL & Rhodes RC. A critical review of the literature on ratings scales for perceived exertion. Sports Med 1985; 2: 198-222.

17 Cavanagh PR & Kram R. The efficiency of human movement – a statement of the problem. Med Sci Sports Exerc 1985a; 17(3): 304-308.

18 Cavanagh PR & Kram R. Mechanical and muscular factors affecting the efficiency of human movement. Med Sci Sports Exerc 1985b; 17(3), 326-331.

19 Chavarren J & Calbet JAL. Cycling efficiency and pedalling frequency in road cyclists. Eur J Appl Physiol 1999; 80: 555-563.

20 Coast JR &Welch HG. Linear increase in pedal rate with increased power output in cycle ergometry. Eur J Appl Physiol 1985; 53: 339-342.

21 Cooper RA, Robertson RN, van Sickle DP, Boninger ML. Methods for determining three-dimensional wheelchair pushrim forces and moments: a technical note. J Rehab Res Dev 1997; 34: 162-170.

22 Cowan RE, Boninger ML, Sawatzky BJ, Mazoyer BD, Cooper RA. Preliminary outcomes of the SmartWheel Users' Group database: a proposed framework for clinicians to objectively evaluate manual wheelchair propulsion. Arch Phys Med Rehabil 2008; 89(2): 260-8.

23 Cowan RE, Nash MS, Collinger JL, Koontz AM, Boninger ML. Impact of surface type, wheelchair weight, and axle position on wheelchair propulsion by novice older adults. Arch Phys Med Rehabil 2009; 90(7): 1076-83.

24 Coyle EF, Sidossis LS, Horowitz JF, Beltz JD. Cycling efficiency is related to the percentage of Type I muscle fibers. Med Sci Sports Exerc 1992; 24: 782-788.

25 Dallmeijer AJ, Ottjes L, de Waardt E, van der Woude LHV. A physiological comparison of synchronous and asynchronous hand cycling. Int J Sports Med 2004a; 25: 1–5.

26 Dallmeijer AJ, Woude LHV van der, Veeger HEJ, Hollander AP. Effectiveness of force application in manual wheelchair propulsion in persons with spinal cord injuries. Am J Phys Med Rehab 1998; 77: 213-221.

27 Dallmeijer AJ, Zentgraaff ID, Zijp NI, Woude LHV van der. Sub-maximal physical strain and peak performance in handcycling versus hand-rim wheelchair propulsion. Spinal Cord 2004b; 42: 91–98.

28 Davis GM & Shephard RJ. Strength training for wheelchair users. Br J Sports Med 1990; 24(1): 25-30.

29 Desroches G, Aissaoui R, Bourbonnais D. The effect of resultant force at the pushrim on shoulder kinetics during manual wheelchair propulsion: a simulation study. IEEE Trans Biomed Eng 2008a; 55(4): 1423-31.

30 Desroches G, Aissaoui R, Bourbonnais D. Relationship between resultant force at the pushrim and the net shoulder joint moments during manual wheelchair propulsion in elderly persons. Arch Phys Med Rehabil 2008b; 89(6): 1155-61.

31 Van Dieen JH, Ogita F, de Haan A. Reduced neural drive in bilateral exertions: a performance-limiting factor? Med Sci Sports Exerc 2003; 35(1), 111-118.

32 DiGiovine CP, Cooper RA, Boninger ML. Dynamic calibration of a wheelchair dynamometer. J Rehabil Res Dev 2001; 38(1): 41-55.

33 Dunbar CC, Robertson RJ, Baun R, Blandin MF, Metz K, Burdett R, Goss FL. The validity of regulating exercise intensity by ratings of perceived exertion. Med Sci Sports Exerc 1992; 24(1): 94-99.

34 Ekblom B & Goldbarg AN. The influence of physical training and other factors on the subjective rating of perceived exertion. Acta Physiol Scand 1971; 83: 399–406.

35 Engel P, Neikes M, Bennedik K, Hildebrandt G, Rode FW. Work physiological studies performed to optimate the lever propulsion and the seat position of a lever propelled wheelchair. Rehabil 1976; 15(4): 217-218.

36 Eston RG & Williams JG. Reliability of ratings of perceived effort regulation of exercise intensity. B J Sports Med 1988; 22(4): 153-155.

37 Fabre N, Perrey S, Arbez L, Ruiz J, Tordi N, Rouillon JD. Degree of coordination between breathing and rhythmic arm movements during hand rim wheelchair propulsion. Int. J. Sports Med 2006; 27: 67–74.

38 Faria IE. Energy expenditure, aerodynamics and medical problems in cycling. Sports Med 1982; 14: 43-63.

39 Gaesser GA, Brooks GA. Muscular efficiency during steady-rate exercise: effects of speed and work rate. J Appl Physiol 1975; 38: 1132–1139.

40 Gaines RF, Zomlefer MR, Zhao W. Armstroke patterns of spinal cord injured wheelchair users. Archives of Physical Medicine Rehabilitation 1984; 65: 618.

41 Gayle GW, Pohlman RL, Glaser RM. Cardiorespiratory and perceptual responses to arm crank and wheelchair exercise using various hand-rims in male paraplegics. Res Q Exerc Sport 1990; 61(3): 224-232.

42 Glaser RM, Sawka MN, Young RE, Suryaprasad AG. Metabolic and cardiopulmonary responses to wheelchair and bicycle ergometry. J Appl Physiol 1979; 46: 1066-1070

43 Glaser RM, Sawka MN, Young RE, Suryaprasad AG. Applied physiology for wheelchair design. J Physiol 1980; 48: 41–44.

44 Goosey VL, Campbell IG. Pushing economy and wheelchair propulsion technique at three speeds. Adapt Phys Activ Q 1998a; 15: 36–50.

45 Goosey VL, Campbell IG, Fowler NE. The relationship between three-dimensional wheelchair propulsion techniques and pushing economy. J Appl Biomech 1998b; 14: 412–427.

46 Goosey VL, Campbell IG, Fowler NE. Effect of push frequency on the economy of wheelchair racers. Med Sci Sports Exerc 2000; 32: 174–181.

47 Goosey-Tolfrey. Wheelchair Sport: A Complete Guide for Athletes, Coaches and Teachers. Leeds: Human Kinetics 2010; preface.

48 Goosey-Tolfrey VL, Kirk JH. Effect of push frequency and strategy variations on economy and perceived exertion during wheelchair propulsion. Eur J Appl Physiol 2003; 90: 153–158.

49 Goosey-Tolfrey VL, Lenton JP. A comparison between intermittent and constant wheelchair propulsion strategies. Ergonomics 2006; 49(11): 1111-1120.

50 Goosey-Tolfrey VL & Sindall P. The effects of arm crank strategy on physiological responses and mechanical efficiency during sub-maximal exercise. J Sports Sci 2007; 25(4): 453-460.

51 Goosey-Tolfrey VL, West M, Lenton JP, Tolfrey K. Influence of varied tempo music on wheelchair mechanical efficiency following 3-week practice. Int J Sports Med 2011; 32(2): 126-31.

52 de Groot S, de Bruin M, Noomen SP, van der Woude LHV. Mechanical efficiency and propulsion technique after 7 weeks of low-intensity wheelchair training. Clin Biomech 2008; 23: 434-441.

53 de Groot S, Dallmeijer AJ, Kilkens OJ, van Asbeck FW, Nene AV, Angenot EL, Post MW and van der Woude LHV. Course of gross mechanical efficiency in handrim wheelchair propulsion during rehabilitation of people with spinal cord injury: a prospective cohort study. Arch Phys Med Rehab 2005; 86(7): 1452-1460.

54 de Groot S, Veeger HEJ, Hollander AP, van der Woude LHV. Consequence of feedback-based learning of an effective hand rim wheelchair force production on mechanical efficiency. Clin Biomech 2002a; 17: 219-226.

55 de Groot S, Veeger DHEV, Hollander AP, van der Woude LHV. Wheelchair propulsion technique and mechanical efficiency after 3 wk of practice. Med Sci Sports Exerc 2002b; 34: 756–766.

56 de Groot S, Veeger DHEV, Hollander AP, van der Woude LHV. Adaptations in physiology and propulsion technique during the initial phase of learning manual wheelchair propulsion. Am J Phys Med Rehab 2003a; 82(7): 504-510.

57 de Groot S, Veeger DHEV, Hollander AP, van der Woude LHV. Short- term adaptations in co-ordination during the initial phase of learning manual wheelchair propulsion. J. Electromyogr. Kinesiol 2003b; 13: 217–228.

58 de Groot S, Veeger HEJ, Hollander AP, van der Woude LHV. Effect of wheelchair stroke pattern on mechanical efficiency. Am J Phys Med Rehab 2004; 83: 640-649.

59 de Groot S, Veeger DHEV, Hollander AP, van der Woude LHV. Influence of task complexity on mechanical efficiency and propulsion technique during learning of hand rim wheelchair propulsion. Med Eng Phys 2005; 27(1): 41-49.

60 Hagberg JM, Mullin JP, Giese MD, Spitznagel E. Effect of pedalling rate on submaximal exercise responses of competitive cyclists. J Appl Physiol 1981; 51: 447-451.

61 Hansen EA, Andersen JL, Nielsen JS, Sjogaard G. Muscle fibre type, efficiency, and mechanical optima affect freely chosen pedal rate during cycling. Acta Physiologica Scandinavica 2002; 176(3): 185-194.

62 Hintzy F, Tordi N. Mechanical efficiency during hand-rim wheelchair propulsion: effects of base-line subtraction and power output. Clin Biomech 2004; 19: 343–349..

63 Hintzy F, Tordi N, Perrey S. Muscular efficiency during arm cranking and wheelchair exercise: A comparison. Int J Sports Med 2002; 23: 408–414.

64 Hopman MTE, Teeffelen WM, Brouwer J van, Houtman S, Binkhorst RA. Physiological responses to asynchronous and synchronous arm-cranking exercise. Eur J Appl Physiol 1995; 72: 111–114.

65 Hughes CJ, Weimar WH, Sheth PN, Brubaker CE. Biomechanics of wheelchair propulsion as a function of seat position and user-to-chair interface. Arch Phys Med Rehab 1992; 73(3): 263-269.

66 Hutzler Y. Anaerobic fitness testing of wheelchair users. Sports Med 1998; 25(2): 101-13.

67 Janssen TW, Oers CA, van der Woude LHV and Hollander AP. Physical strain in daily life of wheelchair users with spinal cord injuries. Med Sci Sport Exerc 1994; 26(6): 661-670.

68 Jones D, Baldini F, Cooper RA, Robertson R, Widman L. Economical aspects of wheelchair propulsion. Med Sci Sport Exerc 1992; 24: S32.

69 Knowlton RG, Fitzgerald PI, Sedlock DA. The mechanical efficiency of wheelchair dependent women during wheelchair ergometry. Can J Appl Sports Sci 1981: 6(4): 187-190.

70 Koontz AM, Cooper RA, Boninger ML, Souza AL, Fay BT. Shoulder kinematics and kinetics during two speeds of wheelchair propulsion. J Rehabil Res Dev 2002; 39(6): 635-649.

71 Koontz AM, Yang Y, Price R, Tolerico ML, DiGiovine CP, Sisto SA, Cooper RA, Boninger ML. Multisite comparison of wheelchair propulsion kinetics in persons with paraplegia. J Rehabil Res Dev 2007; 44(3): 449-58.

72 Kotajarvi, BR, Basford JR, An KN, Morrow DA, Kaufman KR. The effect of visual biofeedback on the propulsion effectiveness of experienced wheelchair users. Arch Phys Med Rehab 2006; 87: 510-515.

73 Kotajarvi BR, Sabick MB, An KN, Zhao KD, Kaufman KR, Basford JR. The effect of seat position on wheelchair propulsion biomechanics. J Rehab Res Dev 2004; 41(3B): 403-414.

74 Linden ML van der, Valent L, Veeger HEJ, Woude LHV van der. The effect of wheelchair handrim tube diameter on propulsion efficiency and force application (tube diameter and efficiency in wheelchairs). IEEE Trans Rehab Eng 1996; 4(3): 123 – 132.

75 McLaurin CA, Brubaker CE. Biomechanics and the wheelchair. Prosthetics and Orthotics International 1991; 15(1): 24-37.

76 Marais G, Dupont L, Maillet M, Weisslans T, Vanvelcenaher J, Pelayo P. Cardiorespiratory and efficiency responses during arm and leg exercises with spontaneously chosen crank and pedal rates. Ergonomics 2002; 45: 631-639.

77 Marsh AP, Martin PE, Foley KO. Effect of cadence, cycling experience, and aerobic power on delta efficiency during cycling. Med Sci Sports Exerc 2000; 32(9): 1630-1634.

78 Mason B. The ergonomics of wheelchair configuration for optimal sport performance. PhD Thesis, Loughborough University, Loughborough, Leicestershire, UK, May 2011.

79 Mason B, Woude L van der, Groot S de, Goosey-Tolfrey V. Effects of camber on the ergonomics of propulsion in wheelchair athletes. Med Sci Sports Exerc 2011a; 43(2): 319-26.

80 Mason B, Woude L van der, Tolfrey K, Lenton J, Goosey-Tolfrey V. Effects of wheel and hand-rim size on submaximal propulsion in wheelchair athletes. Med Sci Sports Exerc 2011b; Epub ahead of print PMID: 21701409.

81 Masse LC, Lamontagne M, O'Riain MD. Biomechanical analysis of wheelchair propulsion for various seating positions. J Rehab Res Dev 1992; 29(3): 12-28.

82 Mihevic PM. Sensory cues for perceived exertion: a review Med Sci Sports Exerc 1981; 13(3): 150-163.

83 Mossberg K, Willman C, Topor MA, Crook H, Patak S. Comparison of asynchronous versus synchronous arm crank ergometry. Spinal Cord 1999; 37: 569–574.

84 Niesing R, Eijskoot F, Kranse R, den Ouden AH, Storm J, Veeger HEJ, van der Woude LHV, Snijders CJ. Computer-controlled wheelchair ergometer. Med Biol Eng Comp 1990; 28(4): 329-38.

85 Pandolf KB. Influence of local and central factors in dominating rated perceived exertion during physical work. Perception and Motor Skills 1978; 46: 683-698.

86 Pandolf KB. Differentiated ratings of perceived exertion during physical exercise. Med Sci Sports Exerc 1982; 14: 397–405.

87 Pandolf KB. Advances in the study and application of perceived exertion. In Terlung (Ed.) Exerc Sports Sci Rev 1983; 11: 118-158, Franklin Institute, Philadelphia.

88 Pandolf KB & Noble BJ. The effect of pedaling speed and resistance changes on perceived exertion for equivalent power outputs on a bicycle ergometer. Med Sci Sports Exerc 1973; 5: 132-136.

89 Patterson P, Draper S. Selected comparisons between experienced and non-experienced individuals during manual wheelchair propulsion. Biomed Sci Instrum 1997; 33: 477-481.

90 Peronnet F, Massicotte D. Table of non-protein respiratory quotient: an update. Can J Sport Sci 1991; 16: 23–29.

91 Powers SK, Beadle RE, Mangum M. Exercise efficiency during arm ergometry: effects of speed and work rate. J Appl Physiol Resp Environ Exerc Physiol 1984; 56: 495-499.

92 Rankin JW, Kwarciak AM, Mark Richter W, Neptune RR. The influence of altering push force effectiveness on upper extremity demand during wheelchair propulsion. J Biomech 2010; 43(14): 2771-2779.

93 Redfield R & Hull ML. On the relation between joint moments and pedalling rates at a constant power in bicycling. J. Biomech 1986; 19: 317–329.

94 Rice I, Gagnon D, Gallagher J, Boninger M. Hand rim wheelchair propulsion training using biomechanical real-time visual feedback based on motor learning theory principles. J Spinal Cord Med. 2010; 33(1):33-42.

95 Richter WM. The effect of seat position on manual wheelchair propulsion biomechanics: a quasi-static model-based approach. Med Eng Phys 2001; 23(10): 707-712.

96 Richter WM & Axelson PW. Low-impact wheelchair propulsion: achievable and acceptable. J Rehabil Res Dev 2005; 42(3 Supplement 1): 21-33.

97 Richter WM, Kwarciak AM, Guo L, Turner JT. Effects of single-variable biofeedback on wheelchair handrim biomechanics. Arch Phys Med Rehabil 2011; 92: 572-577.

98 Richter WM, Rodriguez R, Woods KR, Axelson PW. Consequences of a cross slope on wheelchair handrim biomechanics. Arch Physical Med Rehab 2007a; 88(1): 76-80.

99 Richter WM, Rodriguez R, Woods KR, Axelson PW. Stroke pattern and handrim biomechanics for level and uphill wheelchair propulsion at self-selected speeds. Arch Physical Med Rehab 2007b; 88(1): 81-87.

100 Robertson RN, Boninger ML, Cooper RA, Shimada SD. Pushrim forces and joint kinetics during wheelchair propulsion. Archives of Physical Medicine & Rehabilitation 1996; 77: 856-864.

101 Robertson RJ, Gillespie RL, McCarthy J, Rose KD. Differentiated perceptions of exertion: Part 2. Relationship to local and central physiological responses. Perceptual and Motor Skills 1979; 49: 691-697.

102 Robertson RJ & Noble BJ. Perception of physical exertion: Methods, mediators and applications. Exerc Sports Sci Rev 1997; 25: 407-452.

103 Rodgers MN, Gayle GW, Figoni SF, Kobayashi M, Lieh J, Glaser RM. Biomechanics of wheelchair propulsion during fatigue. Arch Phys Med & Rehab 1994; 75(1): 85-93.

104 Rodgers MM, Keyser RE, Gardner ER, Russell PJ, Gorman PH. Influence of trunk flexion on biomechanics of wheelchair propulsion. J Rehab Res Devel 2000; 37(3): 283-295.

105 Rozendaal LA & Veeger DE. Force direction in manual wheel chair propulsion: balance between effect and cost. Clin Biomech 2001; 15: Supplement 1, S39-S41.

106 Rozendaal LA, Veeger HEJ, van der Woude LHV. The push force pattern in manual wheelchair propulsion as a balance between cost and effect. J Biomech 2000; 36: 239-247.

107 Samuelsson KA, Tropp H, Nylander E, Gerdle B. The effect of rear-wheel position on seating ergonomics and mobility efficiency in wheelchair users with spinal cord injuries: a pilot study. J Rehab Res Dev 2004; 41(1): 65-74.

108 Sawka, M.N. Physiology of upper body exercise. Exerc Sports Sci Rev 1986; 14: 175-212.

109 van Ingen Schenau GJ. Cycle power: a predictive model. *Endeavour 1988; 12(1): 44-47.*

110 Shimada SD, Robertson RN, Boninger ML, Cooper RA. Kinematic characterization of wheelchair propulsion. J Rehab Res Dev 1998; 35(2): 210-218.

111 Skinner JS, Hutsler R, Bergsteinova V, Buskirk ER. Perception of effort during different types of exercise and under different environmental conditions. Med Sci Sports 1973; 5: 110-115.

112 van Soest AJ, Roebroeck ME, Bobbert MF, Huijing PA, van Ingen Schenau GJ. A comparison of one-legged and two-legged countermovement jumps. Med Sci Sports Exerc 1985; 17(6): 635-9.

113 Spaepen AJ, Vanlandewijck YC, Lysens RJ. Relationship between energy expenditure and muscular activity patterns in handrim wheelchair propulsion. J Ind Erg 1996; 17: 163-173.

114 Sparrow WA. The efficiency of skilled performance. J Motor Behaviour 1983; 15(3): 237-261.

115 Suzuki Y. Mechanical efficiency of fast- and slow-twitch fibers in man during cycling. J Appl Physiol 1979; 47: 263-267.

116 Theisen D, Francaux M, Fayt A, Sturbois X. A new procedure to determine external power output during hand-rim wheelchair propulsion on a roller ergometer: A reliability study. Int J Sports Med 1996; 17: 564–571.

117 Vandervoort AA, Sale DG, Moroz J. Comparison of motor unit activation during unilateral and bilateral leg extension. J Appl Physiol 1984; 56(1): 46-51.

118 Vanlandewijck YC, Spaepen AJ, Lysens RJ. Wheelchair propulsion efficiency: movement pattern adaptations to speed changes. Med Sci Sports Exerc 1994; 26: 1373–1381.

119 Veeger HE, Rozendaal LA, van der Helm FC. Load on the shoulder in low intensity wheelchair propulsion. Clin Biomech 2002; 17(3): 211-8.

120 Veeger HEJ, van der Woude LHV, Rozendal RH. Within-cycle characteristics of the wheelchair push in sprinting on a wheelchair ergometer. Med Sci Sports Exerc 1991; 23: 264–271.

121 Veeger HEJ, van der Woude LHV, Rozendal RH. Effect of hand-rim velocity on mechanical efficiency in wheelchair propulsion. Med Sci Sports Exerc 1992; 24: 100-107.

122 Verellen J, Theisen D, Vanlandewijck Y. Influence of crank rate in handcycling. Med Sci Sports Exerc 2004; 36: 1826–1831.

123 Watt B & Grove R. Perceived exertion: antecedents and applications. Sports Med 1993; 15(4): 225-241.

124 Wei SH, Huang S, Jiang CJ, Chiu JC. Wrist kinematic characterization of wheelchair propulsion in various seating positions: implication to wrist pain. Clin Biomech 2003; 18(6): S46-S52.

125 Weissland T, Pelayo P, Vanvelcenaher J, Marais G, Lavoie JM, Robin H. Physiological effects of variations in spontaneously chosen crank rate during incremental upper-body exercise. Eur J Appl Physiol Occup Physiol 1997; 76: 428-433.

126 Whipp BJ, Wasserman K. Efficiency of muscular work. J Appl Physiol 1969; 26: 644–648.

127 van der Woude LHV, Bosmans I, Bervoets B, Veeger HEJ. Handcycling: different modes and gear ratio. J Med Eng Tech 2000; 24: 242–249.

128 van der Woude LH, Bouw A, van Wegen J, van As H, Veeger D, de Groot S. Seat height: effects on submaximal hand rim wheelchair performance during spinal cord injury rehabilitation. J Rehab Med 2009; 41: 143-149.

129 van der Woude LHV, Formanoy M, de Groot S. Hand rim configuration: effects on physical strain and technique in unimpaired subjects? Med Eng Phys 2003; 25: 765–774.

130 van der Woude LHV, de Groot G, Hollander AP, Ingen Schenau GJ van, Rozendal RH. Wheelchair ergonomics and physiological testing of prototypes. Ergonomics 1986; 29: 1561–1573.

131 van der Woude LHV, Hendrich KMM, Veeger HEJ, van Ingen Schenau GJ, Rozendal RH, de Groot G, Hollander AP. Manual wheelchair propulsion: effects of power output on physiology and technique. Med Sci Sports Exerc 1988a; 20(1): 70-78.

132 van der Woude LHV, Horstman A, Faas P, Mechielsen S, Bafghi HA, de Koning JJ. Power output and metabolic cost of synchronous and asynchronous sub-maximal and peak level hand cycling on a motor driven treadmill in able-bodied male subjects. Med Eng Phys 2008; 30(5): 574-580.

133 van der Woude LHV, Kranen E van, Ariens G, Rozendal RH, Veeger HEJ. Physical strain and mechanical efficiency in hubcrank and handrim wheelchair propulsion. J Med Eng Tech 1995; 19(4): 123-131.

134 van der Woude LHV, Veeger HEJ, Dallmeijer AJ, Janssen TWJ, Rozendaal LA. Biomechanics and physiology in active manual wheelchair propulsion. Med Eng Physics 2001; 23: 713–733.

135 van der Woude LHV, Veeger HEJ, Rozendal RH, Sargeant AJ. Optimum cycle frequencies in hand-rim wheelchair propulsion. Wheelchair propulsion technique. Eur J Appl Physiol 1989a; 58: 625–632.

136 van der Woude LHV, Veeger HEJ, Rozendal RH, Sargeant AJ. Seat height in hand-rim wheelchair propulsion. J Rehab Res Dev 1989b; 26(4): 31-50.

137 van der Woude LHV, Veeger HEJ, Rozendal RH, Sargeant AJ. Ergonomics of wheelchair design: a prerequisite for optimum wheeling conditions. Adapted Physical Activity Quarterly 1989c; 6(2): 106-132.

138 Woude LHV van der, Veeger HEJ, Rozendal RH, Schenau GJ van Ingen, Rooth F, Nierop P van. Wheelchair racing: effects of rim diameter and speed on physiology and technique. Med Sci Sports Exerc 1988b; 20(5): 492-500.

Chapter 2

Efficiency of wheelchair propulsion and effects of strategy

John P. Lenton[1]
Neil E. Fowler[1]
Lucas HV. Van der Woude[2]
Victoria L. Goosey-Tolfrey[1]

International Journal of Sports Medicine (2008); 29(5): 384-389

1 Exercise and Sport Science, the Manchester Metropolitan University, UK.

2 Institute for Fundamental & Clinical Human Movement Sciences, Vrije Universiteit, Amsterdam, The Netherlands.

Abstract

The purpose of this study was to determine the contributions of arm frequency and propulsion mode on the internal work during submaximal wheelchair propulsion. Twelve able-bodied participants performed a $\dot{V}O_2$ peak test on a wheelchair ergometer. On a separate occasion, six (4 min) submaximal exercise conditions employing two modes of propulsion (synchronous, SYN vs. asynchronous, ASY) at arm frequencies of 40 and 80 rev·min^{-1} were performed at 1.2m·s^{-1} and 1.7m·s^{-1}. These conditions resulted in three push strategy combinations (ASY [20:20], SYN [40:40] & ASY [40:40]) at two speeds. Gross, net, work and delta efficiency were determined. The cost of unloaded exercise was significantly lower for the ASY [20:20] than both ASY and SYN [40:40] (0.49 vs. 0.58 and 0.57 L ·min^{-1}, respectively). All the efficiency indices decreased as velocity increased ($p < 0.01$). ASY [20:20] was the least efficient (gross and work) mode (4.2 ± 0.4% and 6.2 ± 0.8% respectively). Comparison of equal arm frequencies (ASY [40:40] vs. SYN [40:40]); found the efficiency to be lower for ASY propulsion ($p < 0.05$). Under the current testing conditions SYN propulsion mode offers greater efficiency during wheelchair propulsion.

Introduction

Wheelchair propulsion is often described as a cyclical, bimanual movement in which the phases repeat at intervals [17, 18]. Compared to leg exercise, this form of locomotion is extremely inefficient. Typical gross efficiency (GE) values during wheelchair propulsion activities are 2 – 10% [10, 11, 18, 19] and around 12% in studies using racing chair configurations, high speeds and trained athletes [7]. However, other forms of upper body locomotion have greater GE, e.g., arm-cranking 15% to 19% [12] and hand-cycling 14.4% [20]. The majority of studies in this topic area have only reported GE and net efficiency (NE). It is only recently, that other muscular efficiency indices; work efficiency (WE) and delta efficiency (DE), which differ in terms of base-line subtraction from the total energy expenditure [5], have been reported [10,11]. These indices (WE and DE) are considered to be better estimations of the true muscular efficiency since they account for the unmeasured work [10].

It is of interest to note that during arm cranking and hand-cycling either synchronous (SYN) or asynchronous (ASY) modes for the limb movement pattern can be adopted. Typically during wheelchair propulsion a SYN limb movement pattern is employed, this coupled with a lower push frequency has been shown to be more economical than higher frequencies [8, 9]. However, because propulsion remains relatively unconstrained, a wheelchair dependent participant could adopt either a SYN or ASY mode for propulsion. A SYN movement pattern is best described as when both hands contact the hand-rim at the same time to propel the wheelchair, whilst the ASY mode involves the hands contacting the hand-rim alternately. To date, the literature which has compared the physiological responses to SYN and ASY modes in different forms of cyclic arm exercise has been equivocal as to which is the most efficient [2, 6, 9, 16]. Goosey-Tolfrey and Kirk [9] suggested that the SYN mode of wheelchair propulsion was more economical than the ASY mode when arm frequency was lower (40 pushes·min^{-1}). In contrast, earlier work has indicated that the ASY mode provided a physiological advantage over the conventional SYN propulsion mode [6], although arm frequency was not reported.

The purpose of this study was to determine the contributions of arm movement frequency and propulsion mode on the internal work during submaximal propulsion. By using different efficiency indices a greater understanding of hand-rim wheelchair propulsion will be gained. In order to allow a direct comparison of SYN and ASY modes, the total number of arm movements is considered important, therefore, in terms of arm frequency, the following push strategy modes were selected: a) SYN [40:40], b) ASY [40:40], and c) ASY [20:20]. These ratios coupled with both SYN and ASY represent the number of movements that occur per arm (left: right). The push frequency of 40 pushes·min^{-1} was chosen to allow comparisons with previous literature [8, 9]. We hypothesised: 1) The ASY strategy is the more efficient mode of propulsion at both 1.2 and 1.7 m·s^{-1}, and 2) Higher arm frequencies [40:40] result in the lowest mechanical efficiency.

Material and Methods

Twelve able-bodied male participants with no prior experience in wheelchair exercise and were not trained in upper body sports activities gave written informed consent prior to participation. Approval for the study was obtained from the University Research Ethics Committee. Able-bodied participants were employed to reduce the impact of any pre-existing preference for either SYN or ASY propulsion. Body mass was recorded to the nearest 0.1 kg using a seated balance scale (Seca 710, Hamburg, Germany). Skinfold measurements were taken from the biceps, triceps, subscapular and suprailiac sites using Harpenden callipers (British Indicators Ltd., Luton, UK), in accordance with the procedures of Durnin and Wormersley [4]. Participant characteristics are given in **Table 2.1**.

Table 2.1: Physical characteristics of the participants which include age, body mass, body fat, peak physiological response and rolling resistance

	Mean	± SD
Age (Years)	23	2
Body mass (kg)	76.8	7.8
Body fat (%)	12.6	1.8
$\dot{V}O_2$ peak (L·min^{-1})	2.49	0.32
Peak HR (beats·min^{-1})	181	9
Peak RER	1.21	0.06
Peak power output (W)	30.8	3.6
Rolling resistance (N)	12.8	0.8

Hand-rim propulsion during push strategies and sub-maximal velocities. Values are means ± SD

Material

All participants were tested in the same basketball wheelchair (Quattro, RGK, Burntwood, Staffordshire, England) using a wheelchair ergometer (WERG) interfaced with a computer (Compaq Armada 1520, Series 2920A, Compaq Computer Corporation, Taiwan). The 12° cambered chair was fitted with 0.61m diameter wheels and 0.56-m hand-rims, with a total mass of 13.5kg. The WERG consisted of a single cylinder (length, 0.92m; circumference, 0.48m) and the rolling resistance for the study was on average 12.8N. A flywheel sensor connected to the roller and interfaced to a laptop computer calculated the wheelchair velocity. Participants performed a deceleration test **(Figure 2.1)** whereby the participant accelerated the wheelchair for 5s, then adopted a standardised, upright position with their hands placed on the knees. The roller system at this point decelerated to a complete standstill. During the deceleration period, data of time and velocity were acquired. Power output was calculated from the torque applied to the wheels and their angular velocity. The torque applied is a function of one total internal torque of 1) the WERG-wheelchair system, 2) the rotational moment of inertia of the rear wheels, 3) the one of the roller, and 4) its angular acceleration. The total internal torque reflects all internal friction forces and is determined from the deceleration test described by Theisen et al. [15].

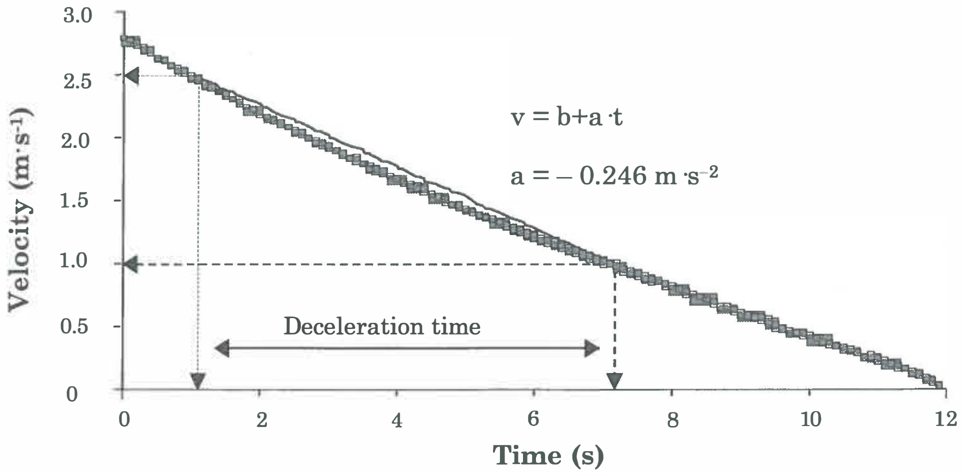


Figure 2.1: Example of deceleration trial. Velocity versus time: the linear regression was processed on the points for which the velocities performed was comprised between 2.5m $\cdot s^{-1}$ and 1.0m $\cdot s^{-1}$; the linear acceleration (– 0.246m $\cdot s^{-2}$) is given by the slope of the equation.

An incremental speed test was used to determine peak oxygen uptake ($\dot{V}O_2$ peak). The initial velocity was 1.2m·s^{-1} with 0.2m·s^{-1} increments every 2 minutes until volitional exhaustion, in accordance with the procedures described by Goosey et al. [8]. On a second visit, a discontinuous submaximal test consisting of three push modes (ASY [20:20], SYN [40:40] and ASY [40:40]) at two propulsion velocities (1.2m·s^{-1}and 1.7m·s^{-1}) was performed **(Table 2.2)**.

Table 2.2: Push strategy definition

Push strategy (propulsion mode & frequency of arm movements)	Total number of left + right arm movements	Total number of movements per arm
ASY [20:20]	40	20
SYN [40:40]	80	40
ASY [40:40]	80	40

Trunk movements were not restricted. An audio-visual metronome was used to pace the arm frequency. Participants completed a 5-minute warm-up prior to the test starting. Following an 8-minute rest period, a 1-minute "habituation period" began to allow the participant to become accustomed with the push mode followed by a 4-minute test period. An 8-minute recovery period separated each test condition and the sequence of events was repeated as shown in **Figure 2.2**. This rest period was sufficient to allow the participant's HR to return as close to their baseline HR as possible, and was consistent to previous work [8]. The order of the exercise bouts was counterbalanced to ensure that each participant performed the conditions in a distinctly different order, thus, possible effects of fatigue and/or learning were balanced out.

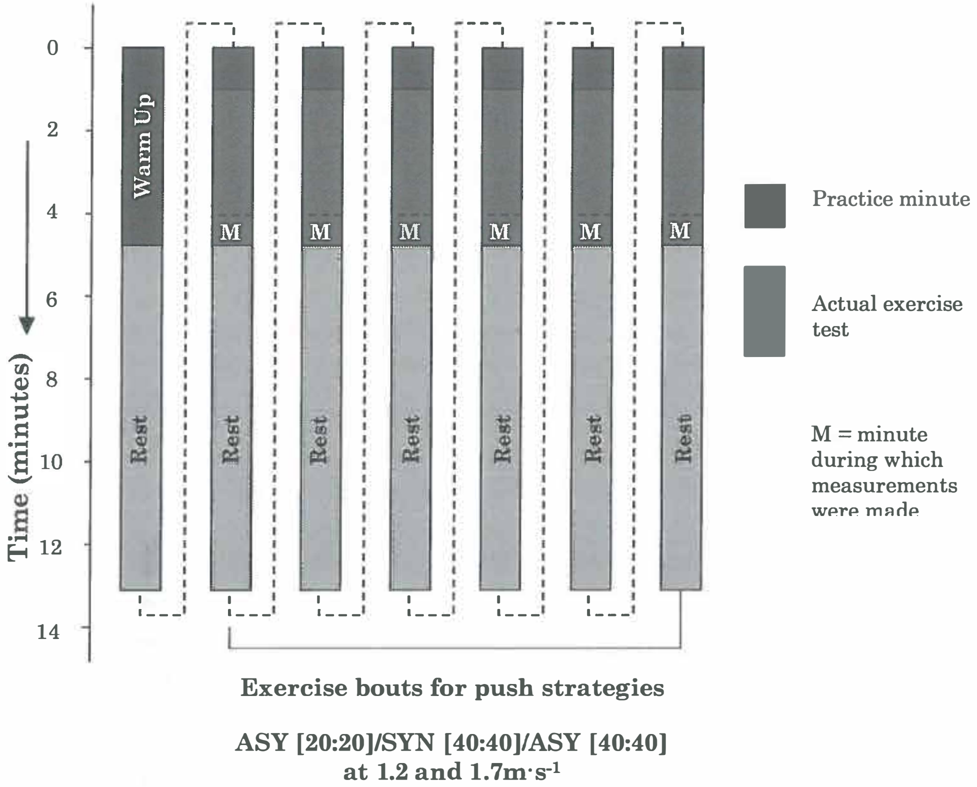


Figure 2.2: Sequence of the discontinuous exercise bouts performed by participants at different push strategies.

Physiological measurements

Throughout the test, heart rate (HR) was monitored using short range radio telemetry (PE4000 Polar Sport Tester, Kempele, Finland). Expired air samples were collected during the final steady state minute of each condition and analysed using the Douglas bag technique. The concentration of oxygen and carbon dioxide in the air samples was determined using a paramagnetic oxygen analyser (Series 1400, Servomex Ltd., Sussex, UK) and an infrared carbon dioxide analyser (Series 1400). Expired air volumes were measured using a dry gas metre (Harvard Apparatus, Kent, UK) and corrected to standard temperature and pressure (dry). Oxygen uptake ($\dot{V}O_2$), carbon dioxide output, expired minute ventilation, and respiratory exchange ratio (RER) were calculated. The analysers were calibrated with gases of known concentration before each test and the linearity of the gas metre was checked using a three-litre calibration syringe. A capillary blood sample was collected from the earlobe immediately following each condition. Blood lactate [La]b concentration was determined using an automatic analyser (YSI 1500 sport, Yellow Springs, Ohio, USA).

Efficiency measurements

A resting expired air sample was taken prior to exercise; participants remained seated in the wheelchair on the WERG. Participants performed three counterbalanced, 4-minute bouts of unloaded exercise (wheelchair raised above roller) at the three different push modes. Conditions were separated by a 5-minute recovery period. Expired air samples were taken during the final minute of each exercise bout to allow $\dot{V}O_2$ rest and $\dot{V}O_2$ unload ($\dot{V}O_2$ corresponding to unloaded push strategies at 0W) to be calculated.

Mechanical efficiency (ME) was calculated as the ratio of the external work to energy expended for one minute of exercise. The work done was determined by calculating the external power output for all push modes. The energy expenditure was obtained from the product of $\dot{V}O_2$ and the oxygen energetic equivalent by using the associated measurements of RER and standard conversion tables [14]. For the calculation of efficiency indices, the following equations were used according to Whipp and Wasserman [21], Gaesser and Brooks [5] and Hintzy et al. [10, 11]:

Gross efficiency (GE) = $(W/E) \cdot 100$ (%)
Net efficiency (NE) = $(W/E - ER) \cdot 100$ (%)
Work efficiency (WE) = $(W/E - EU) \cdot 100$ (%)
Delta efficiency (DE) = $(DW/DE) \cdot 100$ (%)

where W is the external work accomplished; E is the total energy expended; ER is the energy expended at rest; EU is the energy expended during unloaded exercise; DW is the increment of work performed above previous work rate; DE is the increment of energy expended above the previous energy expended.

Statistical analyses

The Statistical Package for Social Sciences (SPSS, version 12; Chicago, IL, USA) was used for all the statistical analyses. Means and standard deviations were computed for all variables. A two-way analysis of variance (ANOVA) with repeated measurements (three push strategies at two propulsion velocities) was applied to all physiological data to study any differences. Significance was assumed at $p \leq 0.05$. A Bonferroni post hoc test was applied to further analyse significant main effects.

Results

The mean (± S.D.) $\dot{V}O_2$ peak was 2.49 ± 0.32 $L \cdot min^{-1}$. On average, the participants performed at 36 ± 5% of $\dot{V}O_2$ peak at $1.2 m \cdot s^{-1}$ and at 57 ± 7% at $1.7 m \cdot s^{-1}$. Participants performed sub-maximally, with only a few participants exceeding a RER of 1.00. In this instance, the effect on ME calculations was deemed to be negligible. The different efficiency indices (GE, NE, WE, DE), $\dot{V}O_2$, HR, [La]b concentration and RER for each bout of exercise are presented in **Table 2.3**.

$\dot{V}O_2$ rest and $\dot{V}O_2$ unload measurements are displayed in **Figure 2.3**. In the unloaded exercise, $\dot{V}O_2$ was found to be significantly higher for the SYN [40:40] ($p = 0.001$) and ASY [40:40] ($p = 0.001$) push modes than ASY [20:20]. There was an overall statistical effect on push strategies, velocity and the interaction of propulsion mode and velocity on all efficiency indicators. However, this is only evident at the velocity of $1.7 m \cdot s^{-1}$, with the exception of WE at $1.2 m \cdot s^{-1}$. At $1.7 m \cdot s^{-1}$, ASY [20:20] elicited a significantly lower GE, NE, and WE ($p = 0.001$) than SYN [40:40]. Also, significantly lower GE ($p = 0.010$), NE ($p = 0.013$) and WE ($p = 0.001$) was seen for ASY [20:20] than the ASY [40:40]. The ASY [40:40] revealed significantly lower GE ($p = 0.023$) and NE ($p = 0.017$) than SYN [40:40]. GE, NE and WE were significantly higher at $1.2 m \cdot s^{-1}$ compared with $1.7 m \cdot s^{-1}$ ($p = 0.001$). DE during ASY [20:20] was significantly lower than SYN [40:40] ($p = 0.002$) and ASY [40:40] ($p = 0.009$). GE was significantly lower than NE and WE ($p = 0.001$). DE was also significantly lower ($p < 0.01$) than all the other efficiency indices calculated (GE, NE and WE).

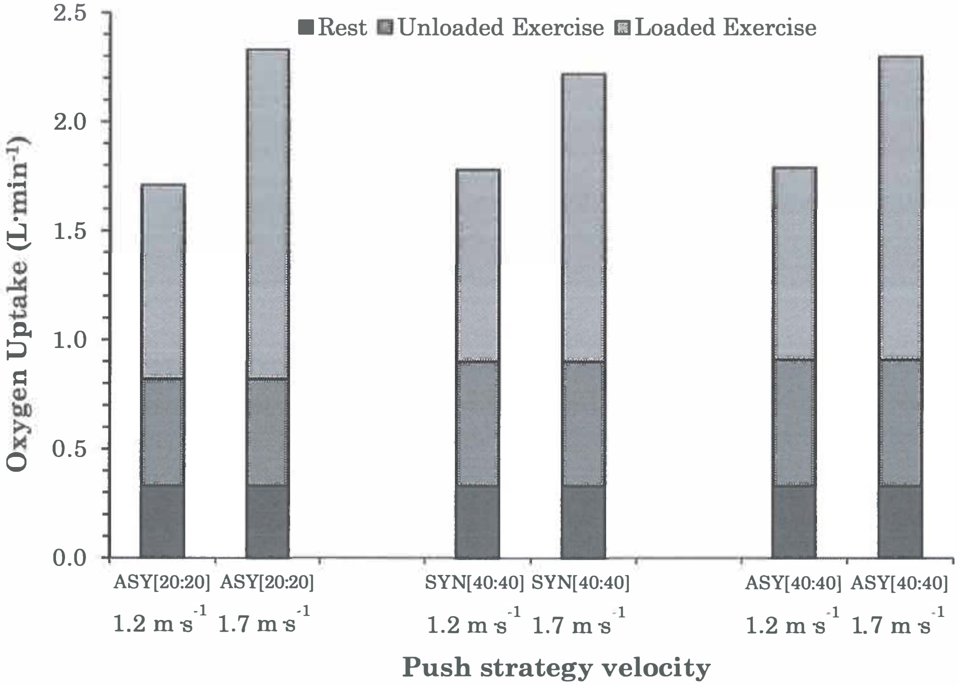


Figure 2.3: Mean oxygen uptake (n = 12) for push strategies at two submaximal propulsion velocities for rest, unloaded exercise and loaded exercise.

Table 2.3: Physiological responses and the results of statistical analysis at rest, unloaded and loaded hand-rim propulsion during push strategies and sub-maximal velocities. Values are mean ± SD

	ANOVA main effects			STRATEGY					
	Strategy	Velocity	Strategy x Velocity	ASY [20:20]		SYN [40:40]		ASY [40:40]	
				$1.2 m \cdot s^{-1}$	$1.7 m \cdot s^{-1}$	$1.2 m \cdot s^{-1}$	$1.7 m \cdot s^{-1}$	$1.2 m \cdot s^{-1}$	$1.7 m \cdot s^{-1}$
Mean Power Output (W)				16.0 (1.3)	22.5 (1.6)	16.1 (1.1)	22.6 (1.5)	15.7 (1.0)	22.3 (1.5)
Physiological Parameter									
$\dot{V}O_2$ rest ($L \cdot min^{-1}$)				0.33 (0.06)		0.33 (0.06)		0.33 (0.06)	
$\dot{V}O_2$ unload ($L \cdot min^{-1}$)	*			0.49 (0.11)[a,b]		0.57 (0.12)[a]		0.58 (0.15)[b]	
$\dot{V}O_2$ ($L \cdot min^{-1}$)	*	*	*	0.89 (0.12)	1.51 (0.11)[a,b]	0.88 (0.11)	1.32 (0.17)[a]	0.88 (0.12)	1.39 (0.18)[b]
HR ($beats \cdot min^{-1}$)	*	*		99 (16)	117 (14)[a]	95 (12)	109 (11)[a]	97 (13)	112 (13)
$[La]_b$ ($mmol \cdot L^{-1}$)	*	*		1.12 (0.56)	1.66 (0.79)[a]	1.14 (0.36)	2.13 (0.90)[a]	1.10 (0.33)	1.83 (0.68)
RER	*	*		0.90 (0.07)	0.94 (0.07)	0.94 (0.06)	0.99 (0.04)	0.90 (0.07)	0.96 (0.07)
Gross efficiency (%)	*	*	*	5.2 (0.7)[1,3]	4.2 (0.4)[a,b,1,3]	5.2 (0.6)[1,3]	4.8 (0.5)[a,c,1,3]	5.1 (0.7)[1,3]	4.5 (0.5)[b,c,1,3]
Net efficiency (%)	*	*	*	8.3 (1.4)[1,2]	5.4 (0.5)[a,b,1,2]	8.4 (1.4)[1,2]	6.4 (0.8)[a,c,1,2]	8.4 (1.7)[1,2]	5.9 (0.8)[b,c,1,2]
Work efficiency (%)	*	*	*	11.7 (2.1)[a,b,2,3]	6.2 (0.8)[a,b,2,3]	14.8 (3.1)[a,2,3]	8.4 (1.5)[a,2,3]	16.3 (5.3)[b,2,3]	7.9 (1.7)[b,2,3]
Delta efficiency (%)	*		*	3.0 (0.5)[a,b]		4.2 (0.9)[a]		3.7 (0.8)[b]	

Discussion

Results show a combination of different phenomena: 1) the effect of SYN versus ASY; 2) the effect of propulsion velocity for all push modes; 3) the shift in overall magnitude for the different efficiency indices as a consequence of the different correction factors for internal work. These phenomena are discussed below. For inexperienced, able-bodied participants using a velocity based protocol at low power output levels, the GE values across conditions averaged 4.2 to 5.2%. These values are in line with previous studies examining efficiency at similar power outputs [3, 10]. It is evident in the literature that ME is affected by velocity, mode and arm frequency [2, 10, 11, 18, 19].

Gross, net, work and delta efficiency show significant changes with both the frequency [20:20] vs. [40:40] **(Table 2.3)**, and propulsion mode (SYN vs. ASY). **Table 2.3** indicates a disadvantage for GE, NE and WE with a lower arm frequency (ASY [20:20] vs. SYN [40:40] and ASY [40:40]) at $1.7 m \cdot s^{-1}$. This is in contrast with $\dot{V}O_2$ unload (internal work) that shows a significantly lower value at [20: 20] compared to [40:40]. The lower internal work at [20:20] unloaded is overruled by the task requirements of ASY [20: 20] at $1.7 m \cdot s^{-1}$, as indicated by the lower GE and WE. Although no significant differences were found for $1.2 m \cdot s^{-1}$ for $\dot{V}O_2$ and GE, the change in $\dot{V}O_2$ for ASY [20:20] is higher than the [40:40] conditions as a consequence of the lower $\dot{V}O_2$ unload in the ASY [20:20] condition. This is expressed in the significant difference found in the WE. Thus, the lower arm frequency introduces a higher internal workload, as expressed in the lower GE and WE values. This seems to be associated to the higher amount of external work per arm per push that needs to be generated to maintain a constant velocity. Similar findings were seen in van der Woude et al. [18] for the lower frequency range in submaximal wheelchair propulsion at a constant power output in both able-bodied and wheelchair dependent individuals and in handcycling at different gear ratios [16]. The higher work per push introduces a shift in the force-velocity characteristic of the active muscles and changes in the stabilisation requirement of the trunk. There could also be changes in the force-length characteristics of the muscle through changes in stroke angle and kinematics due to the need for greater work per push. When comparing conditions with the same number of arm movements [40:40], the SYN mode appears preferential. The SYN vs. ASY propulsion mode at the equal number of arm movements [40:40] at $1.7 m \cdot s^{-1}$

demonstrated an efficiency advantage with the SYN mode. Previous literature that has investigated SYN vs. ASY in different forms of cyclic arm exercise has reported equivocal findings as to which is the most efficient in upper body arm work [2, 6, 9, 16]. Once again with no significant difference being observed for $\dot{V}O_2$ unload of SYN [40:40] and ASY [40:40], yet there was a difference in the loaded $\dot{V}O_2$ ($p = 0.07$, 1.32 vs. 1.39 $L \cdot min^{-1}$, respectively). This helps explain the differences noted in GE. The implication being that during the ASY mode there is an increased "active" internal workload, perhaps as a result of the task complexity, and as such follows the findings in ASY vs. SYN hand cycling [2,16] and lever propulsion [17]. The different movement pattern and simultaneously stabilising role of the trunk and its different, more complex involvement in unilateral external force production contribute to increased energy expenditure at the same propulsion velocity. Mechanical efficiency indices (GE, NE, WE) were all dependent upon velocity of propulsion, and significant reduction in efficiency was found at the higher velocity. This may be explained by the internal work involved. The proportion of unmeasured work in the total energy expenditure changes significantly and cannot be measured in the unloaded condition. Consequently, the ratio between work done and the energy expended is increased, decreasing efficiency. Increased velocity increases the demands of, for example push forces and coupling of the hand-rim [19]. The effect of the velocity increase could also be attributed to the constraint of arm frequency in the push modes employed. It is therefore apparent that physiological responses and ME indices are influenced by a combination of propulsion mode, frequency and velocity.

Important points for discussion relate to methodological considerations. Able-bodied inexperienced wheelchair participants were employed for two main reasons. Firstly, to avoid any influence of disability and the probable effects of limited arm or trunk function; secondly, to avoid the possible effects of training in wheelchair users at given propulsion modes and frequency of arm movements. Therefore, a homogenous participant group (training, propulsion experience; no pathology) was created. Although its use is open to debate [13], literature has continually reported responses in able-bodied non-wheelchair user groups to comply with the overall trends in physiology as shown by wheelchair users [1, 2, 11, 18]. The counterbalanced order of the six experimental conditions separated by rest periods allowed us to minimise both the effects of learning and fatigue. A standardised chair configuration eliminated effects of chair designs/setups on physiological measurements. The wheelchair ergometer with a fixed chain using a single roller allowed the wheelchair to be fixed in a stationary position. This allowed the effects of push strategy to be investigated because there are no effects of coasting direction of the wheelchair, and thus the external work requirements. More importantly, the power output in both the SYN and ASY mode is equal during propulsion.

In conclusion, the energy expenditure of unloaded arm movements decreases with a lower arm frequency but is overruled by the task complexity requirements of propulsion at the higher arm frequency. Under the current testing conditions, SYN propulsion mode offers greater efficiency during wheelchair propulsion.

Acknowledgements

The authors would like to acknowledge the support provided by RGK Wheelchairs for the loan of the Quattro basketball wheelchair. They would also like to thank the participants for their commitment to the investigation.

References

1 Brown DD, Knowlton RG, Hamill J, Schneider TL, Hetzler RK. Physiological and biomechanical differences between wheelchair-dependent and able-bodied subjects during wheelchair ergometry. Eur J Appl Physiol 1990; 60: 179–182.

2 Dallmeijer AJ, Zentgraaff ID, Zijp NI, van der Woude LHV. Sub-maximal physical strain and peak performance in handcycling versus hand-rim wheelchair propulsion. Spinal Cord 2004; 42: 91–98.

3 Groot S de, Veeger DHEV, Hollander AP, van der Woude LHV. Wheelchair propulsion technique and mechanical efficiency after 3 wk. of practice. Med Sci Sports Exerc 2002; 34: 756–766.

4 Durnin JV, Womersley J. Body fat assessed from total body density and its estimation from skinfold thickness: measurements on 481 men and women aged from 16 to 72 years. Br J Nutr 1974; 32: 77–97.

5 Gaesser GA, Brooks GA. Muscular efficiency during steady-rate exercise: effects of speed and work rate. J Appl Physiol 1975; 38: 1132–1139.

6 Glaser RM, Sawka MN, Young RE, Suryaprasad AG. Applied physiology for wheelchair design. J Physiol 1980; 48: 41–44.

7 Goosey VL, Campbell IG, Fowler NE. The relationship between three-dimensional wheelchair propulsion techniques and pushing economy. J Appl Biomech 1998; 14: 412–427.

8 Goosey VL, Campbell IG, Fowler NE. Effect of push frequency on the economy of wheelchair racers. Med Sci Sports Exerc 2000; 32: 174–181.

9 Goosey-Tolfrey VL, Kirk JH. Effect of push frequency and strategy variations on economy and perceived exertion during wheelchair propulsion. Eur J Appl Physiol 2003; 90: 153–158.

10 Hintzy F, Tordi N. Mechanical efficiency during hand-rim wheelchair propulsion: effects of base-line subtraction and power output. Clin Biomech 2004; 19: 343–349.

11 Hintzy F, Tordi N, Perrey S. Muscular efficiency during arm cranking and wheelchair exercise: a comparison. Int J Sports Med 2002; 23: 408–414.

12 Marais G, Dupont L, Maillet M, Weisslans T, Vanvelcenaher J, Pelayo P. Cardiorespiratory and efficiency responses during arm and leg exercises with spontaneously chosen crank and pedal rates. Ergonomics 2002; 45: 631–639.

13 Patterson P, Draper S. Selected comparisons between experienced and non-experienced individuals during manual wheelchair propulsion. Biomed Sci Instrum 1997; 33: 477-481.

14 Peronnet F, Massicotte D. Table of non-protein respiratory quotient: an update. Can J Sport Sci 1991; 16: 23–29.

15 Theisen D, Francaux M, Fayt A, Sturbois X. A new procedure to determine external power output during hand-rim wheelchair propulsion on a roller ergometer: a reliability study. Int J Sports Med 1996; 17: 564–571.

16 van der Woude LHV, Bosmans I, Bervoets B, Veeger HEJ. Handcycling: different modes and gear ratios. J Med Eng Tech 2000; 24: 242–249.

17 van der Woude LHV, Veeger HEJ, Dallmeijer AJ, Janssen TWJ, Rozendaal LA. Biomechanics and physiology in active manual wheelchair propulsion. Med Eng Physics 2001; 23: 713–733.

18 van der Woude LHV, Veeger HEJ, Rozendal RH, Sargeant AJ. Optimum cycle frequencies in hand-rim wheelchair propulsion. Wheelchair propulsion technique. Eur J Appl Physiol 1989; 58: 625–632.

19 Veeger HEJ, van der Woude LHV, Rozendal RH. Effect of hand-rim velocity on mechanical efficiency in wheelchair propulsion. Med Sci Sports Exerc 1992; 24: 100–107.

20 Verellen J, Theisen D, Vanlandewijck Y. Influence of crank rate in handcycling. Med Sci Sports Exerc 2004; 36: 1826–1831.

21 Whipp BJ, Wasserman K. Efficiency of muscular work. J Appl Physiol 1969; 26: 644–648.

Chapter 3

Effects of arm frequency during synchronous and asynchronous wheelchair propulsion on efficiency

John P. Lenton[1,2]
Lucas HV. Van der Woude[3]
Neil E. Fowler[1]
Victoria L. Goosey-Tolfrey[1,2]

International Journal of Sports Medicine (2009); 30(4): 233-239

[1] Department of Exercise & Sport Science, the Manchester Metropolitan University, UK.

[2] School of Sport & Exercise Sciences, Loughborough University, UK.

[3] Faculty of Human Movement Sciences, VU University Amsterdam, the Netherlands.

Abstract

To further understand the possible underlying mechanisms of the low efficiencies in hand-rim wheelchair propulsion, this study examined efficiency indices at different arm frequencies during two propulsion modes (synchronous and asynchronous). Fourteen male able-bodied participants performed $\dot{V}O_2$ PEAK tests for both propulsion modes. Subsequently two sub-maximal exercise tests examining synchronous and asynchronous propulsion were completed at an individualised velocity (60 % of $\dot{V}O_2$ PEAK). The freely chosen arm frequency (FCF), followed by four counter-balanced trials at 60, 80, 120, and 140 % of FCF were performed. Gross, net, and work efficiency were determined. Gross efficiency was significantly lower ($p < 0.05$) at arm frequencies > 100 % and participants were more efficient between 60 to 100 % FCF. These arm frequencies corresponded to 76 ± 22 to 126 ± 36 and 70 ± 18 to 116 ± 30 pushes·min^{-1} (synchronous and asynchronous respectively). Trends in $\dot{V}O_2$, gross and work efficiency suggest that 80 % of FCF produced the best economy and efficiency during both propulsion modes (non-significant). Gross and work efficiency at 80 % FCF were 6.8 ± 0.7 % and 13.0 ± 4.6 % for synchronous and 7.0 ± 0.8 % and 11.5 ± 1.6 % for asynchronous respectively. The results suggest that during both modes of propulsion the FCF is not necessarily the most efficient.

Introduction

Previous research investigating the manipulation of arm frequency and or propulsion mode is limited [7, 8, 10, 14, 25] and the effects of arm frequency are not well understood in terms of energy cost or efficiency of propulsion. Hand-rim propulsion is a guided movement that is regulated highly by the rim curvature and its speed and direction of movement. Within these constraints participants are free to adopt different arm frequencies, propulsion modes or both in such a way that suits their requirements at a given wheelchair propulsion velocity or task. In terms of arm frequency, a considerable degree of inter-individual variations is seen at a given speed and/ or resistance level [8, 25]. Despite this, hand-rim propulsion remains relatively inefficient with reported gross efficiency values up to 10 % during everyday activities [24, 28] and 12 % in studies using trained wheelchair racing athletes (7).

Typically most studies have employed the synchronous (SYN) mode of propulsion. This arm movement pattern is best described as when both hands contact the wheels at the same time to propel the wheelchair. On the other hand an asynchronous (ASY) movement pattern is when the hands contact the wheel alternately [14]. Recent observations have shown the ASY propulsion mode to have emerged during everyday use and sporting situations (wheelchair tennis and basketball). However, for this propulsion mode the question arises as to whether participants can indeed adopt this strategy, and at what energy cost. The ASY mode appears to require a different range of motion and stability from the trunk as well as muscle function in comparison to the SYN mode. Adopting the ASY mode therefore, could require different levels of active and passive work to stabilise the trunk and accelerate the arms, resulting in changes to energy cost, hence improved or reduced efficiency of propulsion. Comparing these different propulsion modes could further help understand the low wheelchair propulsion efficiencies reported. The manipulation of arm frequency and its role in efficiency of propulsion is also an important factor to be considered in parallel with propulsion mode.

When considering the physiological responses to SYN and ASY cyclic arm exercise there are some inconsistent findings with research studies indicating better efficiency in SYN movement pattern [3, 10, 14, 22] and others the ASY movement pattern [6, 15]. Findings are unclear as to which is the most efficient in upper body arm work, Goosey-Tolfrey and Kirk [10] suggested that SYN propulsion was more economical than ASY when the frequency of arm movements were lower (40 pushes·min^{-1}), however, at 70 pushes·min^{-1} ASY propulsion was preferred despite no statistical difference to the SYN propulsion. In contrast, earlier work has indicated that the ASY technique provided a physiological advantage over the conventional SYN technique [6]. More recent work from our laboratory has found the SYN mode to offer improved efficiency during hand-rim propulsion [14].

We know from previous work that operating at the freely chosen frequency (FCF) is the most optimal with respect to the gross efficiency [7, 8]. However, study of the combined influence of arm frequency and propulsion mode (SYN & ASY) is needed to further our understanding in this area. The purpose of this study was to determine the effect of different arm frequencies on the indices of efficiency during high-level sub-maximal hand-rim wheelchair propulsion on a roller ergometer in able-bodied participants for both SYN and ASY propulsion modes. We hypothesised: 1) That efficiency would be highest and optimised at the FCF; 2) Higher arm frequencies would result in the lowest efficiency; 3) The SYN strategy would be the more efficient mode of propulsion in able-bodied participants.

Material and Methods

Fourteen male able-bodied participants volunteered for this study and gave written informed consent prior to participation. Approval for the study procedures was obtained from the University Research Ethics Committee. Participants had no prior experience in wheelchair exercise and were not trained in upper body sports activities to limit the impact of any pre-existing preference for either propulsion mode. Body mass was recorded to the nearest 0.1 Kg using a seated balance scale (Seca 710, Hamburg, Germany). Participant characteristics are given in **Table 3.1**.

Table 3.1: Physical characteristics of the participants which include age, body mass, peak physiological responses and rolling resistance for both synchronous (SYN) and asynchronous (ASY) propulsion

	Mean	± SD		
age (yr)	20	2		
body mass (kg)	77.6	12.9		
	SYN		ASY	
	Mean	± SD	Mean	± SD
$\dot{V}O_2$ PEAK ($L{\cdot}min^{-1}$)	2.55	0.43	2.47	0.37
Peak HR ($beats{\cdot}min^{-1}$)	183	7	183	9
Peak $[La]_b$ ($mmol{\cdot}L^{-1}$)	4.68	0.61	4.65	0.67
Peak RER	1.17	0.06	1.16	0.06
Peak power output (W)	47.4	6.8	47.8	4.3
Rolling resistance (N)	18.7	1.4	18.7	1.3

Values are mean ± SD

Material

All participants were tested in the same hand-rim basketball wheelchair (Quattro, RGK, Burntwood, Staffordshire, England) using the wheelchair ergometer interfaced with a computer (Compaq Armada 1520, Series 2920A). The 15° cambered chair was fitted with 0.66-m diameter wheels and 0.61-m hand-rims, with a total mass of 12.9 kg. Rear wheel tyre pressure was standardised to 758 KPa (7.58 bar). No individual adjustments relative to anthropometrics of the participants were made. The wheelchair ergometer consisted of a single roller (length, 1.14-m; circumference, 0.48-m) and the rolling resistance for the study was on average 18.7 N. A flywheel sensor connected to the roller and interfaced to a laptop computer calculated and displayed the wheelchair velocity.

Each participant performed a deceleration test and power output was calculated using the principles described by Theisen et al. [19]. The deceleration test was repeated for both testing sessions as participants performed SYN and ASY propulsion on two separate test days. For each deceleration trial the participant was asked to accelerate the roller to the appropriate speed (2.5 $m{\cdot}s^{-1}$) and to then stop pushing. During the deceleration they sat stationary in the chair as if in the position to perform the next push. The velocity was recorded as the chair slowed and the average acceleration calculated from the slope of this velocity time data, resistance was then calculated from this acceleration [14, 19]. Power output was calculated from the torque applied to the wheels and their angular velocity. The torque applied is a function of one total internal torque of 1) the wheelchair ergometer-wheelchair system, 2) the rotational moment of inertia of the rear wheels, 3) the one of the roller, and 4) its angular acceleration. The total internal torque reflects all internal friction forces and is determined from the deceleration test. For further details of this procedure please refer to Theisen et al. [19].

Testing procedure

The SYN and ASY tests were performed on separate days in a counter-balanced order. Each test day was divided into two distinct sessions, separated by a two hour rest period, to allow a full recovery.

Session one – Peak exercise capacity

Prior to exercise participants remained seated quietly in the wheelchair on the wheelchair ergometer for a period of twenty minutes following which a two minute pre-exercise sample of expired air ($\dot{V}O_2$ REST) was collected. Each participant then completed an incremental sub-maximal exercise test comprising five or six, four minute stages. The initial speed was determined following a self-selected warm-up period of five minutes where heart rate (HR) was approximately 100 beats$\cdot$min^{-1}, subsequently each exercise stage was a 0.2m$\cdot$s^{-1} increment of the previous stage. Following a fifteen minute rest period an incremental speed test was used to determine the peak oxygen uptake ($\dot{V}O_2$ PEAK) as previously described by Goosey-Tolfrey et al. [9]. These tests provided a familiarisation with both propulsion modes; however, its main objective was to establish participant's individual velocity at 60 % $\dot{V}O_2$ PEAK.

Session two – Arm frequency manipulations

A discontinuous sub-maximal test consisting of five different arm frequencies (freely chosen frequency (FCF – 100%) and 60%, 80%, 120% and 140% of FCF) at the velocity calculated in session one was performed. The experimental design was similar to that previously reported by Woude et al. [26] and Goosey et al. [8]. An audio-visual metronome was used to pace the arm frequency.

Participants completed a 5-min warm-up prior to the test starting at a FCF and propulsion velocity which was guided with HR not exceeding 130 beats·min^{-1}. Following an 8-min rest period, a 1-min 'habituation period' allowed the participant to become accustomed to the arm frequency followed by a 4-min test period. The FCF was the initial 4-min exercise condition and arm frequency (defined as the total number of left and right arm movements) was recorded each minute and then averaged. Subsequent exercise bouts were performed at the manipulated arm frequencies. An 8-min recovery period separated each test condition and the sequence of events was repeated as shown in **Figure 3.1**. This rest period was sufficient to allow participant's HR to return as close to their baseline HR as possible. The order of these four exercise bouts was counter-balanced to ensure each participant performed the conditions in a distinctly different order, thus, possible effects of fatigue and / or learning were balanced out. On completion of loaded exercise conditions, five counter-balanced, 4-min bouts of unloaded exercise (wheelchair raised above roller) followed at five different arm frequencies. Conditions were separated by a 5-min recovery period. Expired air samples were taken during the final-minute to allow $\dot{V}O_2$ UNLOAD (the $\dot{V}O_2$ corresponding to unloaded arm frequencies at 0 W) to be calculated.

Physiological measurements

Throughout the test, 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 concentration of oxygen and carbon dioxide in the expired air samples was 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 ($\dot{V}O_2$), carbon dioxide output, expired minute ventilation, and respiratory exchange ratio (RER) were calculated.

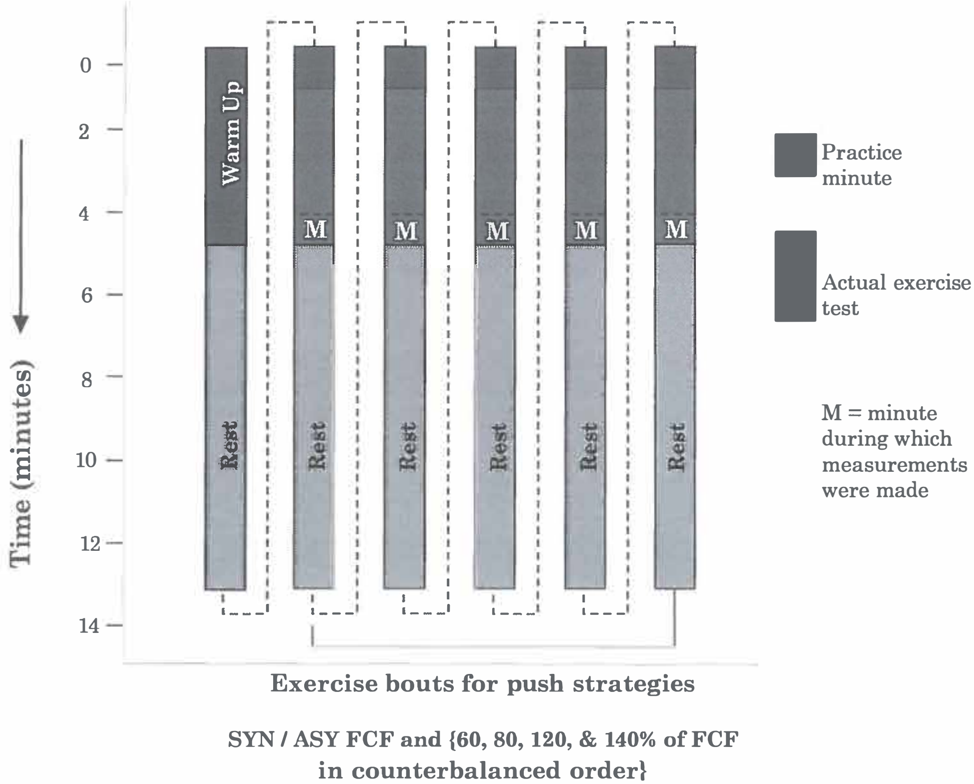


Figure 3.1: Sequence of the discontinuous exercise bouts performed by participants during different push frequencies for both synchronous (SYN) and asynchronous (ASY) propulsion modes.

Efficiency measurements

Propulsion efficiency was calculated as the ratio of the external work to energy expended for one minute of exercise. The work accomplished was determined by calculating the work done against the ergometer during hand-rim wheelchair propulsion for all arm frequencies. The energy expenditure was obtained from the product of $\dot{V}O_2$ and the oxygen energetic equivalent by using the associated measurements of RER and standard conversion tables [16]. For the calculation of efficiency indices, the following equations were used according to Whipp and Wasserman [29], Gaesser and Brooks [5] and Hintzy et al. [12, 13]:

Gross efficiency (GE) = (W / E) · 100(%)
Net efficiency (NE) = (W / (E – ER)) · 100(%)
Work efficiency (WE) = (W / (E – EU)) · 100(%)

where W is the external work accomplished; E is the total metabolic energy expended; ER is the metabolic energy expended at rest; EU is the metabolic energy expended during unloaded exercise.

Statistical analyses

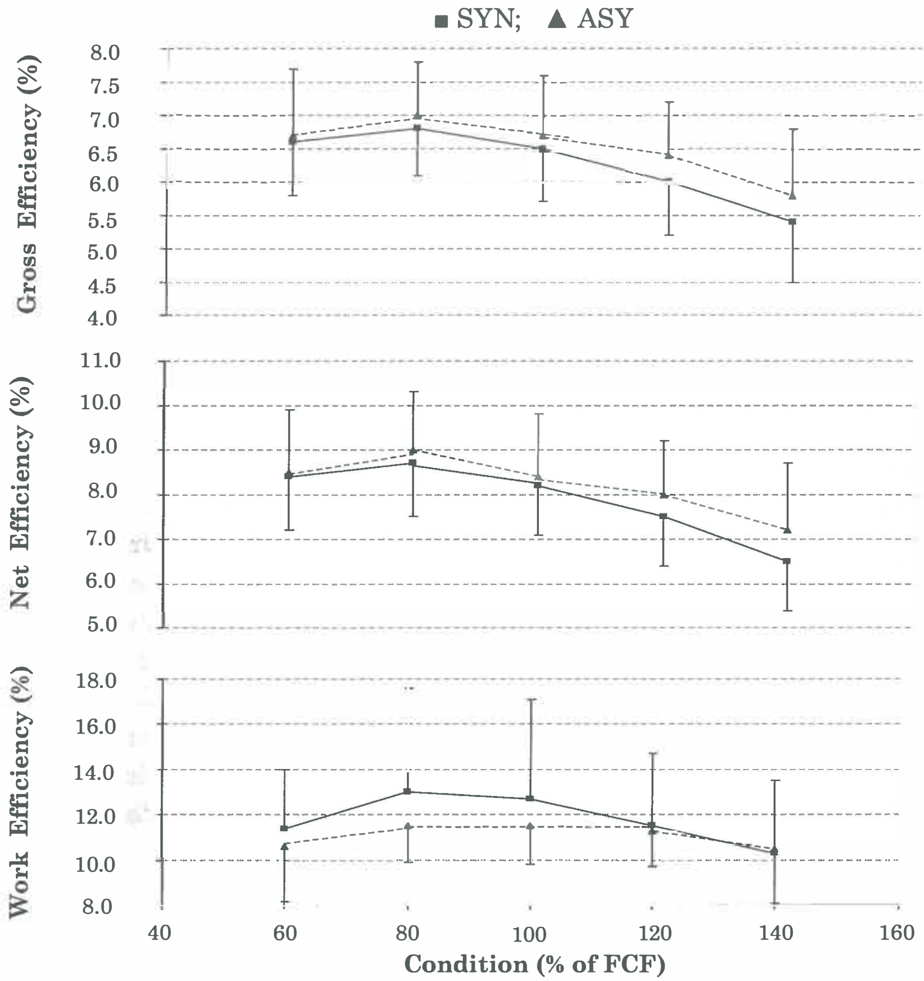
The Statistical Package for Social Sciences (SPSS, version 12.0; Chicago, IL, USA) was used for all the statistical analyses. Means and standard deviations were computed for all variables. Separate paired Student's t-tests were used to analyse the peak physiological responses obtained during SYN and ASY propulsion modes. A two-way ANOVA with repeated measurements (five arm frequencies at two propulsion modes) was applied to all physiological data. Significance for all tests was assumed at $p \leq 0.05$. A Bonferroni post hoc test was applied to further analyse significant main effects.

Results

The mean power output during sub-maximal SYN exercise (at 60 % $\dot{V}O_2$ PEAK) was 36.1 ± 4.4 W, ranging from 29.6 to 47.1 W and for the ASY mode 35.5 ± 3.4 W, ranging from 29.7 to 43.4 W ($p = 0.319$). Participants performed sub-maximally, with only a few participants exceeding a RER of 1.00 at the 140 % FCF exercise condition. In this instance, the effect on efficiency calculations was deemed to be negligible. Max RER values were only 1.01 and separate analysis revealed that removal of these data did not alter the outcome. The $\dot{V}O_2$, HR, RER and arm frequency for each bout of exercise are presented in **Table 3.2**. The indices of efficiency (gross, net, work) are displayed in **Figure 3.2**. To determine whether the order of conditions would influence the results an ANOVA was performed. This revealed no order effect [F (2.5, 32.8) = 1.2, $P = 0.31$ and F (2.2, 28.8) = 1.64, $P = 0.21$ for SYN and ASY] and any differences can be attributed to arm frequency or propulsion mode, not test order.

Table 3.1 presents SYN and ASY propulsion for $\dot{V}O_2$ PEAK measurements. The $\dot{V}O_2$ PEAK values ranged from 1.73 to 3.56 L·min^{-1}, with average values of 2.55 and 2.47 $L \cdot min^{-1}$ during SYN and ASY propulsion respectively ($P = 0.329$). All individual propulsion velocities when calculated as 60 % $\dot{V}O_2$ PEAK were 1.86 ± 0.15$m \cdot s^{-1}$ (SYN) and 1.87 ± 0.11$m \cdot s^{-1}$ (ASY). The propulsion of the wheelchair at the FCF and sub-maximal velocities corresponded to 61 ± 4 % of $\dot{V}O_2$ PEAK for SYN propulsion and 61 ± 3 % of $\dot{V}O_2$ PEAK for ASY propulsion. However, the differences between the FCF of the SYN and ASY propulsion modes was non-significant **(Table 3.2)**.

Arm frequency had significant effects on both $\dot{V}O_2$ UNLOAD and loaded $\dot{V}O_2$ which was particularly evident when the arm frequency was increased beyond the FCF (120% and 140%) **(Table 3.2)**. In all cases the energy cost of unloaded propulsion rose with the increases in arm frequency hence an indication of greater metabolic demand. The $\dot{V}O_2$ UNLOAD represented on average 43.2 % (± 3.4 %) of the loaded $\dot{V}O_2$, with the proportion remaining more-or-less constant across the range of arm frequencies. Consequently, due to the metabolic cost of unloaded arm movements the work efficiency values were significantly ($P = 0.001$) greater than the gross efficiency values recoded. The results identified no significant differences between FCF and the lower arm frequencies of 60 % and 80 % FCF. Therefore, the FCF cannot be reported as the most efficient arm frequency under the current testing conditions. Trends in the data suggest that an 80 % FCF yielded non-significant, yet improved economy and efficiency for both propulsion modes. On the other hand propulsion mode had no significant effect on efficiency nor were there any significant interactions between mode and arm frequency **(Figure 3.2)**.



[a] denotes significant difference ($P < 0.05$) from 60% FCF,
[b] 80% FCF, [c] FCF 100%, [d] 120% FCF, [e] 140% FCF

Figure 3.2: Mean values and standard deviation for gross efficiency, net efficiency and work efficiency for synchronous (SYN) and asynchronous (ASY) propulsion across the range of arm frequencies.

Table 3.2: Physiological responses and the results of statistical analysis at rest, unloaded and loaded hand-rim propulsion during different propulsion mode and arm frequencies.

Physiological Parameter	FCF (%)				
	60	80	100	120	140
SYNCHRONOUS PROPULSION					
$\dot{V}O_{2\ REST}$ ($L \cdot min^{-1}$)			0.32 (0.04)		
$\dot{V}O_{2\ UNLOAD}$ ($L \cdot min^{-1}$)	0.64 (0.16)	0.68 (0.20)	0.72 (0.21)	0.79 (0.24)[a,b,c]	0.87 (0.24)[a,b,c,d]
$\dot{V}O_2$ ($L \cdot min^{-1}$)	1.56 (0.29)	1.53 (0.32)	1.55 (0.24)	1.69 (0.32)[b,c,e]	1.90 (0.41)[a,b,c]
HR ($beats \cdot min^{-1}$)	129 (13)	128 (12)	129 (15)	136 (17)[a,b,c,e]	147 (18)[a,b,c,d]
RER	0.91 (0.05)	0.91 (0.06)	0.96 (0.04)[a,b]	0.98 (0.03)[a,b]	0.99 (0.03)[a,b]
RER_{UNLOAD}	0.64 (0.16)	0.68 (0.20)	0.72 (0.21)	0.79 (0.24)[a,b,c]	0.87 (0.24)[a,b,c,d]
Arm Frequency	76 (22)	100 (28)	126 (36)	152 (44)	176 (50)
ASYNCHRONOUS PROPULSION					
$\dot{V}O_{2\ REST}$ ($L \cdot min^{-1}$)			0.31 (0.04)		
$\dot{V}O_{2\ UNLOAD}$ ($L \cdot min^{-1}$)	0.55 (0.15)	0.57 (0.17)	0.64 (0.18)[a,b]	0.71 (0.20)[a,b,c,e]	0.78 (0.20)[a,b,c,d]
$\dot{V}O_2$ ($L \cdot min^{-1}$)	1.52 (0.27)	1.45 (0.25)	1.50 (0.23)	1.58 (0.27)[b,e]	1.75 (0.44)[b,c,d]
HR ($beats \cdot min^{-1}$)	127 (9)	126 (12)	128 (12)	133 (14)[b]	143 (17)[a,b,c]
RER	0.94 (0.05)	0.94 (0.06)	0.96 (0.04)[a]	0.97 (0.03)	0.99 (0.05)[a,b,c]
RER_{UNLOAD}	0.55 (0.15)	0.57 (0.17)	0.64 (0.18)	0.71 (0.20)	0.78 (0.20)
Arm Frequency	70 (18)	94 (22)	116 (30)	140 (36)	160 (40)

Values are Mean ± SD. Significant main effect ($P < 0.01$) for arm frequency
[a] denotes significant difference ($P < 0.05$) from 60 % FCF / [b] denotes significant difference ($P < 0.05$) from 80 % FCF / denotes significant difference ($P < 0.05$) from 100 % FCF / [d] denotes significant difference ($P < 0.05$) from 120 % FCF / [e] denotes significant difference ($P < 0.05$) from 140 % FCF

Discussion

The efficiency data and other physiological measures show: 1) the significant effect of arm frequency above FCF; 2) the non-significant effect of arm frequency below FCF; 3) the non-significant effect of SYN vs. ASY propulsion modes. These are discussed below.

When considering the conditions of the present study the gross efficiency values across the exercise conditions averaged 5.4–7%, which are in agreement with previous studies at similar power output levels [13, 26]. Reporting gross and work efficiency indices helps us to begin to understand the role of the different elements of hand-rim propulsion with different push strategies [14] since the former includes a composite measure of the energy cost of both moving the arms, stabilising the body and accelerating the wheel and the latter off -sets the cost of the arm movements and stabilisation associated with unloaded exercise. In the present study, arm frequency has a significant effect on all these indices when the frequency exceeds the FCF **(Figure 3.2).**

Effect of arm movement frequency

The decrease in gross and work efficiency as arm frequency increases beyond the FCF (120% and 140%) is in agreement with previous studies of both able-bodied [26] and wheelchair sportsmen [8, 26] . Interestingly in contrast to previous research examining the effect of arm frequency manipulation [8, 26], when the arm frequency was reduced (< 100 % FCF) there were no significant changes in gross efficiency, net efficiency, $\dot{V}O_2$ or HR. An unexpected finding because both work by Woude and colleagues [26] and Goosey et al. [8] report 100% FCF to be more efficient and economical.

The paced arm frequencies in the current study affect timing, kinematics, dynamics, and the work per cycle without affecting the mean external power production, since this is inherently the same for all frequency conditions. Consequently this will impact the way in which the work is performed and thus affect energy cost and efficiency. For example cyclic timing changes result in 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. Different paced arm frequencies therefore, affect the force-length and length tension of the contracting muscles, thus influencing the energy required for the contraction and production of work done against the hand-rim. Differences in energy cost at the different frequencies will be attributable to some combination of different efficiency of the propulsive element and different efficiency of the arm movements. These would not contribute to external power output, which is fixed, but to a change in the metabolic work of the muscles and hence efficiency [22]. Thus the reduction in efficiency for the frequencies beyond 80 % FCF could be attributed to increased energy expenditure, elicited from the increased work to move the arms, as seen in both the results of $\dot{V}O_2$ UNLOAD **(Table 3.2)** and the efficiency indices **(Figure 3.2)**. The result of increases in the loaded energy cost would explain this because the unloaded energy cost proportion remained more or less constant (% of total energy cost) across the range of arm frequencies. In turn this would help explain the significantly higher work efficiency values calculated for both AB and WS. Work efficiency shows a similar effect for arm frequency, even with the correction for increased energy cost of $\dot{V}O_2$ UNLOAD, therefore this stresses that the loaded exercise condition brings in factors other than more arm movements which further increase work done. Coupling and uncoupling of the hand-rim is inherently complex and associated with short bursts of negative work [25, 28] at the start and end of the push phase. Higher arm frequencies will increase the number of couplings and un-couplings hence the negative forces increase and consequently increase energy losses.

Increased arm frequency was accompanied with increasing RER and significant differences were observed between the arm frequencies, which has also been evident during arm crank ergometry [19]. There are a number of speculative suggestions that could, in part, contribute to this observed rise in RER. Firstly, it is possible that increased arm frequency may lead to an improvement of ventilation and an increased breathing rate at any given exercise intensity, with an observed link between movement and respiratory frequency previously reported [2]. This would serve to further reduce efficiency and result in a greater metabolic production of CO_2. Secondly arm movement speed increases and therefore could lead to an earlier and increased number of activated type II fibres resulting in a greater accumulation of lactate [1]. Finally, the increases in arm frequency increased the work done due to muscular friction.

The absence of significant differences at the lower range of arm frequencies (60 – 100% FCF) occurs in spite of the relatively linear change in $\dot{V}O_2$ UNLOAD with increasing arm frequency **(Table 3.2)**. This may possibly imply the existence of counteracting phenomena between the loaded and unloaded conditions, whereby lower arm frequencies benefit from factors that reduce the total amount of work associated with moving the arms at loaded exercise conditions. Lower arm frequencies will essentially lead to lower hand and segment velocities over the larger part of the trajectory. This could allow a more secure, effective coupling and the need for a less controlled transfer of muscle forces through the sequence of contractions, as well as reduced (stabilizing) co-contractions. A reduction of linear velocity at the same power output indeed improves the efficiency in hand-rim propulsion [27]. In addition, changes in arm frequency may affect the suggested coupling between arm motion and breathing pattern [2]. This higher form of co-ordination may possibly be disturbed at the non-preferred higher arm frequencies and be closer to the metabolic optimal at the lower range of arm frequencies.

In cycling studies optimal pedalling force-velocity relationships at given power output levels have demonstrated reductions in $\dot{V}O_2$, suggesting that they are individual-specific as a result of differences in muscle fibre composition and recruitment patterns [5, 17]. Consequently the non-significant differences observed in physiological responses between 60% and 100% arm frequencies could imply that the muscle mechanics are not changed significantly to affect force-velocity relationships, however, arm frequencies > 100 % were sufficient to elicit changes great enough to reduce efficiency. The current results at 60 – 100 % are in contrast to findings of Woude et al. [26] and Goosey et al. [8], whereby significant changes are reported. An explanation for this may be as a result of the average FCF. The current FCF reports no differences in average arm movement frequency for SYN 126 and ASY 116 ($P = 0.213$). In comparison Woude et al. [26] reported the FCF to be 106 at comparable power outputs, which is significantly lower ($p \leq 0.05$). As a result the inverted U curvi-linear relationship seen previously [26] indicates a clear optimal efficient arm frequency at a given workload. The significant difference of freely chosen frequencies generates a different range of frequencies to those studied here; however, when the data are combined it exemplifies a shift to the right of this shaped curve. Therefore, arm frequencies below 100 % FCF in this study fall into a different range not low enough to report a similar trend and relationship. A consequence of this will be the impact on the position in the force-velocity relationship of the various muscles involved in the task of propulsion. With increased arm frequency the forces exerted in each push decrease, whereas the velocities of contractions increase, increasing the metabolic demand.

Alternatively with decreased arm frequency the forces exerted increase but consequently the velocity of contractions will decrease. However, the range of arm frequencies between the 60 – 100 % conditions may not have been sufficient to have significant effect on metabolic costs and efficiency. Therefore, the suggestion is that the intact human biological system can counteract changes in arm frequency within a range whereby the metabolic costs are very similar for the same external workload. Through a combination of changes that may occur (i.e. improved technique at lower arm frequency, amount of work per push, acceleration / deceleration changes, muscle activity etc.), the energy costs balance one another to avoid significant changes in efficiency within the specified range.

Effect of propulsion mode (SYN vs. ASY)

No significant effect of propulsion mode was statistically evident in the current study although ASY propulsion displayed lower physiological responses and increased gross and net efficiency. This is similar to the findings of Glaser et al. [6] whereby ASY propulsion demonstrated reduced physiological responses and increased efficiency, although it remains unclear as to why. One suggestion could point towards the FCF being significantly different; however, this was not evident **(Table 3.2)**. Other explanations could include 1) differences in muscle activity, however, this remains an unknown requiring further research. 2) ASY propulsion allows greater continuity of the hand-rim force application, reducing fluctuations in the velocity profile and therefore, the inertial forces overcome with each stroke are reduced. 3) ASY limb movement patterns are employed in other more efficient modes of locomotion (e.g. walking, bicycling, rowing) and may take advantage of inherent neural pathways for the reciprocal stimulation of the contra-lateral muscle groups [20]. In addition Glaser et al. [6] indicated through subjective evaluation that the ASY mode provided greater stability as a consequence of the trunk rotation over the forward and back motion of the SYN mode. This suggests that maybe decreased muscle activity is required for stability and therefore, a reduced $\dot{V}O_2$ response and improved efficiency. This hypothesis warrants further evaluation.

Limitations

The impact of using able-bodied, inexperienced wheelchair participants with a standardised chair configuration and the identical wheelchair ergometer have been discussed previously in Lenton et al. [14] and elsewhere. Whilst this may have influenced the absolute efficiency of propulsion, due to the participants having a less well developed technique, the aim of this study was to evaluate the impact of changing arm frequency and propulsion mode and so it was important to eliminate any bias caused by habitual use. Propulsion velocity was calculated to correspond with 60% $\dot{V}O_2$ PEAK at the FCF in an attempt to maintain similar exercise intensity for all participants. In a small number of cases the RER exceeded 1.00 and may imply that the effort was no longer predominantly aerobic and participants may also have not reached a steady state. This may have impacted the metabolic cost calculated for these individuals. Removal of these cases from the analysis did not result in any change in outcome. The imposed arm frequencies (60, 80, 120 and 140% of FCF) ensured that the participant's FCF was manipulated at the same relative levels although the absolute arm frequencies were different.

Conclusion

In accordance with existing literature [4, 8, 26] a curvilinear association of efficiency with arm frequency is observed. A shift in the work required to move the arms at a higher frequency seems to be responsible. Continued studies combining physiological and biomechanical analyses are required to draw attention to the relevant biomechanical mechanisms involved, especially for the absence of any statistical significance in the lower arm frequencies (60 – 100%). In contrast to previous findings gross efficiency and $\dot{V}O_2$ are not optimised at the FCF. The unloaded work was similar for both modes under the current task constraints despite different movement patterns.

Acknowledgements

The authors would like to greatly acknowledge RGK Wheelchair manufacturers for the loan of the Quattro basketball wheelchair.

References

1 Ahlquist LE, Bassett DR, Sufi t R, Nagle FJ, Thomas DP. The effect of pedalling frequency on glycogen depletion rates in type I and type II quadriceps muscle fibers during sub-maximal cycling exercise. Eur J Appl Physiol 1992; 65: 360-364.

2 Amazeen PG, Amazeen EL, Beek PJ. Coupling of breathing and movement during manual wheelchair propulsion. J Exp Psychol Hum Percept Perform 2001; 27: 1243-1259.

3 Dallmeijer AJ, Ottjes L, de Waardt E, van der Woude LHV. A physiological comparison of synchronous and asynchronous hand cycling. Int J Sports Med 2004; 25: 1–5.

4 Fabre N, Perrey S, Arbez L, Ruiz J, Tordi N, Rouillon JD. Degree of coordination between breathing and rhythmic arm movements during hand rim wheelchair propulsion. Int J Sports Med 2006; 27: 67–74.

5 Gaesser GA, Brooks GA. Muscular efficiency during steady-rate exercise: effects of speed and work rate. J Appl Physiol 1975; 38: 1132–1139.

6 Glaser RM, Sawka MN, Young RE, Suryaprasad AG. Applied physiology for wheelchair design. J Physiol 1980; 48: 41–44.

7 Goosey VL, Campbell IG. Pushing economy and wheelchair propulsion technique at three speeds. Adapt Phys Activ Q 1998; 15: 36–50.

8 Goosey VL, Campbell IG, Fowler NE. Effect of push frequency on the economy of wheelchair racers. Med Sci Sports Exerc 2000; 32: 174–181.

9 Goosey-Tolfrey VL, Batterham AM, Tolfrey K. Scaling behaviour of peak in trained wheelchair athletes. Med Sci Sports Exerc 2003; 35: 2106–2211.

10 Goosey-Tolfrey VL, Kirk JH. Effect of push frequency and strategy variations on economy and perceived exertion during wheelchair propulsion. Eur J Appl Physiol 2003; 90: 153–158.

11 Hopman MTE, Teeffelen WM, Brouwer J van, Houtman S, Binkhorst RA. Physiological responses to asynchronous and synchronous arm-cranking exercise. Eur J Appl Physiol 1995; 72: 111–114.

12 Hintzy F, Tordi N. Mechanical efficiency during hand-rim wheelchair propulsion: effects of base-line subtraction and power output. Clin Biomech 2004; 19: 343–349.

13 Hintzy F, Tordi N, Perrey S. Muscular efficiency during arm cranking and wheelchair exercise: A comparison. Int J Sports Med 2002; 23: 408–414.

14 Lenton JP, Fowler N, Woude L van der, Goosey-Tolfrey VL. Efficiency of wheelchair propulsion and effects of strategy. Int J Sports Med 2007; 28: 1–6.

15 Mossberg K, Willman C, Topor MA, Crook H, Patak S. Comparison of asynchronous versus synchronous arm crank ergometry. Spinal Cord 1999; 37: 569–574.

16 Peronnet F, Massicotte D. Table of non-protein respiratory quotient: an update. Can J Sport Sci 1991; 16: 23–29.

17 Seabury JJ, Adams WC, Ramey MR. Influence of pedalling rate and power output on energy expenditure during bicycle ergometry. Ergonomics 1977; 20: 491–498.

18 Smith PM, Doherty M, Price MJ. The effect of crank rate on physiological responses and exercise efficiency using a range of submaximal workloads during arm crank ergometry. Int J Sports Med 2006; 27: 199–204.

19 Theisen D, Francaux M, Fayt A, Sturbois X. A new procedure to determine external power output during hand-rim wheelchair propulsion on a roller ergometer: A reliability study. Int J Sports Med 1996; 17: 564–571.

20 Van Dieen JH, Ogita F, De Haan A. Reduced neural drive in bilateral exertions: a performance-limiting factor? Med Sci Sports Exerc 2003; 35: 111–118.

21 Vanlandewijck YC, Spaepen AJ, Lysens RJ. Wheelchair propulsion efficiency: movement pattern adaptations to speed changes. Med Sci Sports Exerc 1994; 26: 1373–1381.

22 Woude LHV van der, Bosmans I, Bervoets B, Veeger HEJ. Handcycling: different modes and gear ratio. J Med Eng Tech 2000; 24: 242–249.

23 Woude LHV van der, Formanoy M, Groot S de. Hand rim configuration: effects on physical strain and technique in unimpaired subjects? Med Eng Phys 2003; 25: 765–774.

24 Woude LHV van der, Groot G de, Hollander AP, Ingen Schenau GJ van, Rozendal RH. Wheelchair ergonomics and physiological testing of prototypes. Ergonomics 1986; 29: 1561–1573.

25 Woude LHV van der , Veeger HEJ , Dallmeijer AJ , Janssen TWJ , Rozendal LA . Biomechanics and physiology in active manual wheelchair propulsion. Med Eng Phys 2001; 23: 713–733.

26 Woude LHV van der, Veeger HEJ, Rozendal RH, Sargeant AJ. Optimum cycle frequencies in hand-rim wheelchair propulsion. Wheelchair propulsion technique. Eur J Appl Physiol 1989; 58: 625–632.

27 Veeger HEJ, Woude LHV van der, Rozendal RH. Within-cycle characteristics of the wheelchair push in sprinting on a wheelchair ergometer. Med Sci Sports Exerc 1991; 23: 264–271.

28 Veeger HEJ, Woude LHV van der, Rozendal RH. Effect of hand-rim velocity on mechanical efficiency in wheelchair propulsion. Med Sci Sports Exerc 1992; 24: 100–107.

29 Whipp BJ, Wasserman K. Efficiency of muscular work. J Appl Physiol 1969; 26: 644–648.

Chapter 4

Wheelchair propulsion: effects of experience and push strategy on efficiency and perceived exertion

John P. Lenton[1]
Neil E. Fowler[1]
Lucas HV. Van der Woude[2]
Victoria L. Goosey-Tolfrey[1]

Applied Physiology, Nutrition and Metabolism (2008); 33: 870-879

1 Exercise and Sport Science, the Manchester Metropolitan University, United Kingdom.

2 Institute for Fundamental and Clinical Human Movement Sciences, Vrije Universiteit, Amsterdam, The Netherlands.

Abstract

The purpose of this study was to examine the role of wheeling experience on efficiency, metabolic cost, and differentiated ratings of perceived exertion (RPEs) during synchronous and asynchronous hand-rim propulsion with varying arm frequencies. Fourteen able-bodied (AB) male participants and 8 male wheelchair sportsmen (WS) performed tests of peak oxygen for both propulsion modes. Subsequently, 2 series of five, 4-min sub-maximal exercise bouts were completed at an individualized velocity (60% of peak oxygen consumption). Arm frequencies consisted of the freely chosen frequency (FCF), followed by 4 counter-balanced paced trials pushing at 60%, 80%, 120%, and 140% of the FCF. Efficiency indices (gross, GE; work, WE) were determined and peripheral (RPE-P), central (RPE-C), and overall (RPE-O) RPEs were recorded. The GE (6.4% vs. 8.4%) and WE (11.3% vs. 15.1%) were significantly higher in WS than in AB (p = 0.001). Trends in the oxygen consumption, GE, and WE data were similar in both groups, propulsion mode, and arm frequency. Data suggest that 80% FCF resulted in improved efficiency for both propulsion mode and group, although the differences between those arm frequencies immediately above and below were non-significant. Lower RPE scores corresponded with higher efficiency values. Regardless of group there were significant differences (p = 0.001) between the differentiated RPE measures, whereby RPE-P was on average always the highest score (13.1) and RPE-C the lowest (11.1; RPE-O was 12.2). In conclusion, despite the anticipated differences in efficiency between the WS and AB participants, this study confirmed that psycho- physiological measures produce similar trends to physiological measures with manipulations of both arm frequency and propulsion mode.

Résumé

Le but de cette étude est d'analyser l'effet de l'expérience en fauteuil roulant sur l'efficacité mécanique, le coût énergétique et la perception de l'effort fourni (RPE) observés au cours de séances d'exercice comportant une propulsion synchrone ou asynchrone à diverses frequencies sur le cercle propulseur de roue. Quatorze hommes valides (AB) et 8 sportifs en fauteuil roulant (WS) participent à des épreuves d'effort pour la determination du consomption d'oxygène de pointe dans les 2 modalités de propulsion. Par la suite, les sujets participent à 5 séances d'effort sous-maximal d'une durée chacune de 4 min à une intensité sollicitant 60 % du consomption d'oxygène de pointe. Les fréquences de mouvement des bras sont comme suit : fréquence librement choisie (FCF) suivie selon un ordre contrebalancé des fréquences suivantes, soit 60, 80, 120 et 140 % de la FCF. On évalue alors les efficacités brute (GE) et au travail (WE) de même que l'intensité de l'effort perçu en périphérie (RPE-P), centralement (RPE-C) et globalement (RPE-O). La GE et la WE sont significativement plus importantes chez les WS que chez les AB : GE, 6,4 % comparativement à 8,4 % et WE, 11,3 % comparativement à 15,1 % (p = 0,001). L'évolution des valeurs de consomption d'oxygène, de GE et de WE est semblable chez les 2 groupes selon les 2 modalités de propulsion et les fréquences adoptées. D'après les observations, la fréquence équivalente à 80 % de la FCF procure la meilleure efficacité chez les 2 groupes et pour les 2 modalités de propulsion, même si les différences avec les valeurs observées aux fréquences immédiatement supérieure et inférieure ne sont pas significatives. Les valeurs de RPE les plus faibles sont associées aux valeurs d'efficacité améliorée. Chez les 2 groupes, les valeurs de RPE ciblée diffèrent significativement (p = 0,001), la valeur de RPE-P étant la plus élevée (13,1) et la valeur de RPE-C, la plus basse (11,1), l'autre se situant à mi-chemin RPE-O (12,2). En guise de conclusion, et ce, malgré les hypothèses initiales concernant les valeurs d'efficacité chez WS et AB, cette étude révèle des tendances similaires des variables psychophysiologiques et des valeurs physiologiques selon les 2 modalités de propulsion et pour chacune des fréquences adoptées de mouvement.

Introduction

Manual hand-rim wheelchair propulsion is a relatively inefficient form of locomotion. Gross efficiency (GE) has been reported to range from 2% – 10% under conditions prevalent in normal daily use [14, 25, 28, 32]. However, experienced wheelchair sportsmen (WS) have achieved values of around 12% under conditions and wheelchair configurations specific to wheelchair sports [11]. Despite the various methods and experimental designs employed, it is clearly evident that experienced wheelchair users (particularly WS) exhibit much higher GE values than able-bodied (AB) participants [26]. Studies that have incorporated both AB non-wheelchair users and WS have demonstrated similar trends in the physiological responses during wheelchair exercise [2, 3, 9, 14, 25, 26, 29]. The responses in the AB non-wheelchair users fully comply with the overall trends in physiology shown by both wheelchair users and WS.

In terms of energy cost and mechanical efficiency (ME), previous hand-rim propulsion work has demonstrated that optimal push frequencies, i.e., those with the lowest energy cost, occur at an individual's freely chosen frequency (FCF) for both wheelchair users and AB participants [11, 26]. Despite these findings, the mechanisms that control arm frequency selection are not well understood. The cycling literature has suggested that peripheral cues from active muscles are important determinants for cadence selection [6, 20]. It is proposed that the feedback from these cues influences an individual's rating of perceived exertion (RPE), thus perception of effort mediated by the peripheral feedback sources could well be important in arm frequency selection. It has also been suggested in previously that RPE scores will be lower in individuals for whom it's their primary mode of training, while reporting significantly higher values of ME [12]. However, this type of subjective reporting of RPE is an area that has received very little attention in the literature on hand-rim propulsion. Of the work that is available, RPE and hand-rim propulsion have been examined in relation to hand-rim size and propulsion velocity, propulsion strategy – frequency combination, and the degree of co-ordination between breathing and rhythmic arm movements [7, 8, 10]. Further research incorporating the comparison of differentiated RPE (central, cardiopulmonary (RPE-C); peripheral, muscles and (or) joints (RPE-P)) in experienced and non-experienced wheelchair users may provide an insight into the mechanisms that control arm frequency selection [18].

Studies exploring arm frequency selection have used a synchronous (SYN) propulsion mode, as this is typically employed during hand-rim propulsion [11, 26]. However, recent observations in the sporting arena have shown asynchronous (ASY) propulsion emerging during some sporting situations such as wheelchair basketball and tennis. A SYN movement pattern can be described as both hands in contact with the wheel at the same time to propel the wheelchair. An ASY movement pattern is when the hands contact the wheel alternately (180° out–of phase). Stability of the upper body and coasting direction with the ASY movement pattern emerge as possible constraints. The question remains as to whether participants can adopt this mode, and at what cost, especially specialist wheelchair users. The comparison of SYN and ASY cyclic arm exercise has been a topic of interest in arm cranking [15, 17] and handcycling [2, 27] studies, yet has received limited attention within the hand-rim propulsion literature [9, 10, 16]. Goosey-Tolfrey and Kirk [10] found SYN propulsion to be more economical at lower push frequencies. However, they also reported a preference for the ASY mode at higher push frequencies. In contrast, Glaser et al. [9] indicated significantly lower physiological responses for ASY propulsion, suggesting that the ASY mode provided a physiological advantage over the conventional SYN mode. However, more recently, Lenton et al. [16] suggested that the SYN mode offers greater efficiency during hand-rim propulsion.

Therefore, the aim of this study was to examine the role of wheelchair propulsion experience during push strategies (arm frequency and propulsion mode) on ME and differentiated RPE. It was hypothesized that (*i*) wheelchair experience would significantly affect efficiency of propulsion regardless of arm frequency and mode of propulsion, (*ii*) similar trends with respect to arm frequency and propulsion mode are found in both physiological responses of AB and WS, (*iii*) SYN propulsion would be more efficient than ASY propulsion, (*iv*) efficiency, metabolic cost, and RPE are optimal at FCF, and (*v*) RPE relationship with frequency would follow the physiological and efficiency relationship, with the peripheral aspect as the dominant measure in rating of perceived exertion RPE (RPE-P).

Materials and methods

Fourteen AB male participants and 8 male WS volunteered for this study and gave their written informed consent prior to participation. Approval for the study procedures was obtained from the University Research Ethics Committee. The AB participants had no prior experience in wheelchair exercise and were not trained in upper-body sports activities. For this reason, the impact of any pre-existing preference for either propulsion mode was minimal. Ages ranged from 18 to 25 years. Body mass was recorded to the nearest 0.1 kg using a seated balance scale (Seca 710, seated scales, Hamburg, Germany). The WS descriptive characteristics in relation to sport, disability, daily wheelchair experience, and the sports wheelchair used are shown in **Table 4.1**. Ages ranged from 25 to 46 years. All participants were considered to be trained, having competed regularly in wheelchair basketball and tennis competitions at National level.

All participants were tested using the same wheelchair ergometer interfaced with a computer (Compaq Armada 1520, Series 2920A). The AB participants were tested in a hand-rim wheelchair designed for basketball (Quattro, RGK, England) consisting of 15° camber and was fitted with 0.66 m diameter wheels and 0.61 m hand-rims, with a total mass of 12.9 kg. The WS were tested in their sports-specific wheelchairs **(Table 4.1)**. Rear-wheel tyre pressure was standardized to 758 kPa. The wheelchair ergometer consisted of a single cylinder (length, 1.14 m; circumference, 0.48 m) and a flywheel sensor connected to the roller, interfaced to a laptop computer. The laptop computer calculated and displayed the wheelchair velocity. Each participant performed a deceleration test from which rolling resistance was determined and power output (PO) was calculated using the principles described by Theisen et al. [24]. The deceleration test was repeated for both testing sessions, as participants performed SYN and ASY propulsion on 2 separate test days. For further details of this procedure please refer to Lenton et al. [16].

Testing procedure

The SYN and ASY tests were performed on separate days in a counter-balanced order. Each test day was divided into 2 distinct sessions, separated by a 2 h rest period, to allow a full recovery.

Session 1: peak exercise capacity

Each participant completed an incremental sub-maximal exercise test comprising of five or six, 4 minute stages. The initial speed was pre-determined following a self-selected warm-up period of 5 min where heart rate (HR) was approximately 100 beats $\cdot min^{-1}$, subsequently each of the exercise stages was a 0.2 $m \cdot s^{-1}$ increment of the previous stage. After a 15 min rest period an incremental speed test was used to determine the peak oxygen uptake ($\dot{V}O_{2\ peak}$) as previously described by Goosey-Tolfrey and Kirk [10]. These tests provided a familiarization with both propulsion modes; however, their main objective was to establish each participant's individual velocity at 60% $\dot{V}O_{2\ peak}$.

Session 2: arm frequency manipulations

A discontinuous sub-maximal test consisting of 5 different arm frequencies (freely chosen (FCF) and 60%, 80%, 120%, and 140% of FCF) at the velocity calculated in session 1 was performed. The experimental design was similar to that previously reported by Van der Woude et al. [26] and Goosey-Tolfrey et al. [11]. An audio-visual metronome was used to pace the arm frequency.

Participants completed a 5 min warm-up before the test, starting at an FCF and propulsion velocity guided so as not to allow HR to exceed 130 beats $\cdot min^{-1}$. Following an 8 min rest period, a 1 min 'habituation period' began to allow the participant to become accustomed with the arm frequency, followed by a 4 min test period. The FCF was the initial 4 min exercise condition, and arm frequency (defined as the total number of left and right arm movements) was recorded each minute and then averaged. Subsequent exercise bouts were performed at the manipulated arm frequencies. An 8 min recovery period separated each test condition and the sequence of events was repeated as shown in **Figure 4.1**. This rest period was sufficient to allow the participant's HR to return to as close to their baseline HR as possible. The order of these 4 exercise bouts was counter balanced to ensure each participant performed the conditions in a distinctly different order, thus, possible effects of fatigue and (or) learning were balanced out. On completion of the loaded exercise conditions, 5 counter balanced, 4 min bouts of unloaded exercise (wheelchair raised above roller) were conducted at 5 different arm frequencies. Conditions were separated by a 5 min recovery period. Expired air samples were taken during the final minute to allow $\dot{V}O_{2\ unload}$ (the $\dot{V}O_2$ corresponding to unloaded arm frequencies at 0 W) to be calculated.

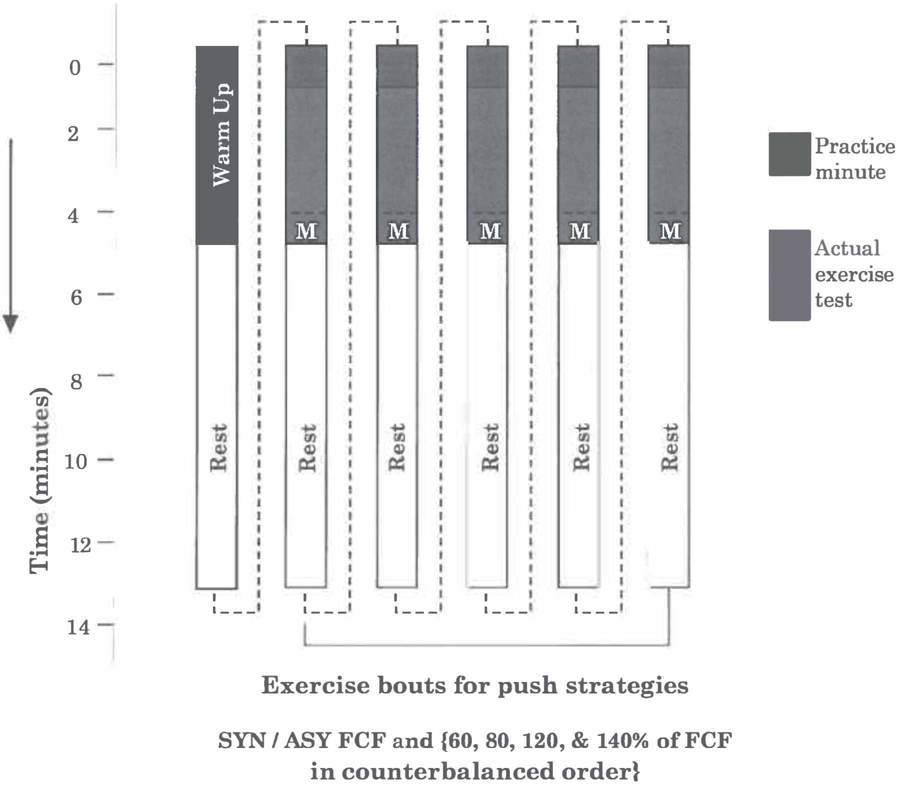


Figure 4.1: Sequence of the discontinuous exercise bouts performed by participants during different push frequencies for both synchronous (SYN) and asynchronous (ASY) propulsion modes. FCF, freely chosen frequency; M, the final minute for the 4 minute exercise bout whereby expired air was collected and other physiological responses to the exercise bout were recorded.

Table 4.2: Disability, experience, and wheelchair characteristics for wheelchair sportsmen.

Participant	1	2	3	4	5	6	7	8
Wheelchair sport	Basketball	Basketball	Basketball	Tennis	Basketball	Tennis	Basketball	Basketball
Daily manual wheelchair propulsion experience (yrs)	23	25	10	30	13	8	12	0
Wheelchair sport (yrs)	17	3	7	30	12	8	11	2
Disability	Paraplegic	Polio	Paraplegic	Spina Bifida	Paraplegic	Right Leg	Paraplegic	Nerve damage
						Amputee		
Lesion/Details	T12	-	T12, L1, L2	-	T9/T10	Transfemo ral	T12	Sciatic nerve
Wheelchair Model	RGK	RGK	RGK	Quickie	RGK	Cyclone	RGK	RGK
	Interceptor	Interceptor	Interceptor	Match Point	Interceptor		Interceptor	Interceptor
Wheel Diameter (m)	0.70	0.62	0.69	0.61	0.61	0.66	0.64	0.69
Hand-rim Diameter (m)	0.65	0.55	0.62	0.54	0.54	0.60	0.56	0.62
Degrees of camber (°)	16	20	16	20	16	20	16-18	16
Wheelchair mass (kg)	14.8	15	15.9	9.8	11.2	9.8	10.1	13.3

Physiological data

Throughout the test, 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 concentration of oxygen and carbon dioxide in the expired air samples was determined using a paramagnetic oxygen analyzer (Series 1400, Servomex Ltd., Sussex, UK) and an infrared carbon dioxide analyzer (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 ($\dot{V}O_2$), carbon dioxide output, expired minute ventilation, and respiratory exchange ratio (RER) were calculated. The analysers were calibrated with gases of known concentration before each test and the linearity of the gas meter was checked using a 3 L calibration syringe. A capillary blood sample was collected from the earlobe immediately following each condition. Blood lactate concentration ($[La]_b$) was determined using an automatic analyser (YSI 1500 Sport, Yellow Springs, Ohio). The YSI analyser was calibrated with a lactate standard of $5 mmol \cdot L^{-1}$ prior to testing.

Each participant received detailed instructions about the use of the 15 point Borg scale [1] and was given examples of how they might rate differentiated RPE. At the end of the final minute of each exercise trial, the RPE scale was presented to the participant who was then asked to state the number reflecting his perceived exertion for (*i*) a "central" rating (RPE-C; sensation of cardiorespiratory stress), (*ii*) a "peripheral" rating (RPE-P; sensation of strain from working muscles), and (*iii*) an "overall" rating (RPE-O; sensation integrating RPE-C and RPE-P).

Mechanical efficiency was calculated as the ratio of the external work to energy expended for 1 min of exercise. The work accomplished was determined by calculating the external PO during hand-rim wheelchair propulsion on the wheelchair ergometer, for all arm frequencies. The energy expenditure was obtained from the product of $\dot{V}O_2$ and the oxygen energetic equivalent by using the associated measurements of RER and standard conversion tables [19]. The ME indices (gross and work efficiency (GE and WE, respectively) were calculated in accordance with Lenton et al. [16] as follows:

GE = W/E x 100%
WE = ($W/E - E_U$) x 100%

where W is the external work accomplished, E is the total energy expended, E_U is the energy expended during unloaded exercise.

Statistical Analysis

The Statistical Package for Social Sciences (SPSS, version 12.0; Chicago, Ill.) was used for all the statistical analyses. Means and standard deviations were computed for all variables. A three-way mixed analysis of variance (ANOVA) with repeated measurements of experience, arm frequency, and propulsion mode was applied to all physiological data to study any differences. Significance for all tests was assumed at $p \leq 0.05$. A Bonferroni post-hoc test was applied to further analyse significant main effects.

Results

The data show that the 2 groups of participants were similar for the majority of the baseline physiological and anthropometric measures **(Table 4.2)**. Although the group of experienced wheelchair athletes (WS) was older (AB 20 ± 2 y vs. WS 30 ± 7 y, $p = 0.001$), they also achieved greater peak power in each of the exercise conditions (SYN $p = 0.001$; ASY $p = 0.001$). No significant differences in $\dot{V}O_{2\ peak}$ were observed between groups ($p = 0.479$). No differences were observed in mean rolling resistance between SYN and ASY protocols **(Table 4.2)**, although rolling resistance was found to be higher ($p = 0.035$) for the WS when compared with the AB individuals. The responses of the participants to the range of exercise conditions are described later in the paper; the data are described by considering each of the following effects: arm movement frequency (% FCF), propulsion mode (SYN or ASY), group (WS or AB), and then the relevant interactions between these variables.

Table 4.2: Physical characteristics of the participants, including age, body mass, seated height, peak physiological responses, and rolling resistance for both synchronous and asynchronous propulsion

	AB		WS	
Physical Characteristic	**Mean**	**±SD**	**Mean**	**±SD**
Age (y)	20	2	28	3
Body mass (kg)	77.6	12.9	79.8	14.4
Seated height (m)	1.40	0.02	1.42	0.03
SYNCHRONOUS				
$\dot{V}O_2$ Peak ($L.min^{-1}$)	2.55	0.43	2.71	0.49
Peak HR (beats·min^{-1})	183	7	185	12
Peak $[La]_b$ (mmol·L^{-1})	4.68	0.61	4.53	0.99
Peak RER				
Peak power output (W)	47.4*	6.8	69.4*	15.8
Rolling resistance (N)	18.7*	1.4	21.7*	4.6
ASYCHRONOUS				
$\dot{V}O_2$ Peak ($L.min^{-1}$)	2.47	0.37	2.84	0.49
Peak HR (beats·min^{-1})	183	9	189	9
Peak $[La]_b$ (mmol·L^{-1})	4.65*	0.67	5.28*	0.96
Peak RER				
Peak power output (W)	47.8*	4.3	68.1*	11.9
Rolling resistance (N)	18.7*	1.3	21.8*	5.6

*Significant difference between wheelchair sportsman (WS) and able-bodied (AB) individuals ($p < 0.05$)

Impact of arm movement frequency

Irrespective of experience or propulsion mode all participants demonstrated a similar response to changes in arm frequency **(Figure 4.2).** In each case, the energy cost of propulsion and associated physiological markers ($\dot{V}O_2$, $[La]_b$, HR) were lowest at the lower frequencies and rose as arm frequency increased. In each case, the graphs in **Figure 4.2** demonstrate an inflection point at 80% FCF, although the differences between markers at this frequency were not significantly different to those immediately above or below. As a consequence of the pattern of metabolic responses to changes in frequency there is an inverted U shape to the graphs for efficiency (GE and WE), with an inflexion point at 80% FCF. An exception is the ASY propulsion for the WS group, which turned at 100% FCF.

In all cases, the energy cost of unloaded propulsion rose with increases in arm frequency, indicating a greater metabolic demand as the number of total arm movements increased. The unloaded energy cost represented between 39.1% and 46.3% (43.4% ± 9.1%) of the loaded energy cost, with the proportion remaining more-or-less constant across the range of arm frequencies. As a consequence of the metabolic cost of unloaded arm movement, the values of WE were significantly ($p = 0.001$) greater than the GE values recorded.

RPEs **(Figure 4.3)** followed a trend similar to that of the physiological variables, although in each case the graphs show a plateau for the first 3 arm frequencies before rising after the 100% FCF condition. All trials demonstrated that the RPE-P was greater than both the RPE-C and overall RPE-O scores.

Impact of propulsion mode

There were no significant differences shown between the 2 modes of propulsion (SYN and ASY) for any of the measures taken. The patterns of arm frequency responses were similar for both propulsion modes and groups, with each showing greater physiological responses and lower efficiency with increasing frequency. The only difference noted between the 2 modes of propulsion was a consistently but not significantly higher HR response for the ASY mode in the WS, although this was not manifest in any of the other variables. In the SYN mode, participants made a greater total number of arm movements ($p = 0.075$) than in the ASY mode at the corresponding percentage of FCF **(Table 4.3)**, indicating that the FCF was slightly lower (ASY = 115 ± 29 AB, 122 ± 19 WS; SYN = 125 ± 36 AB, 137 ± 38 WS).

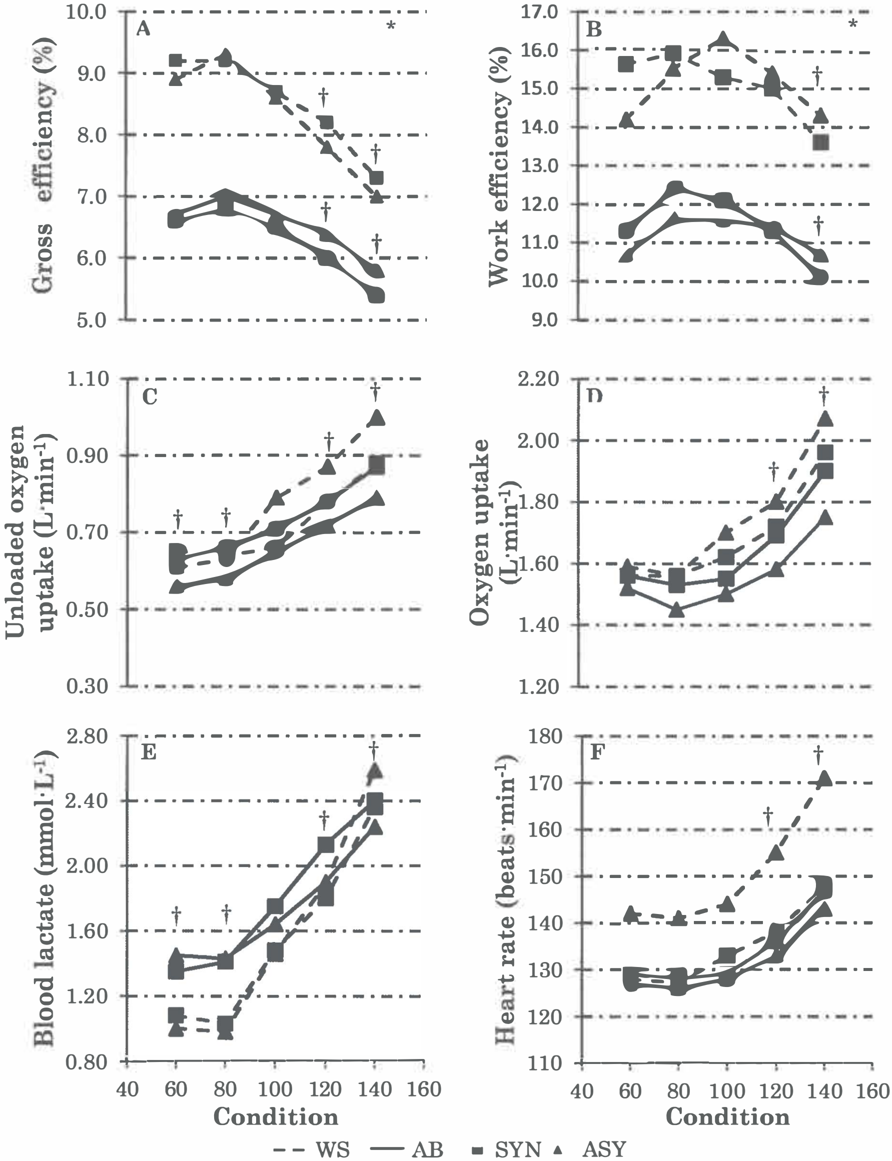


Figure 4.2: (A) Mean values for gross efficiency (GE, %), (B) work efficiency (WE, %), (C) unloaded oxygen uptake and (D) oxygen uptake (L·min^{-1}), blood lactate ($[La]_b$, mmol·L^{-1}), and (F) heart rate (HR, beats·min^{-1}) for wheelchair sportsmen (WS) and able-bodied (AB) individuals during synchronous (SYN) and asynchronous (ASY) propulsion across range of arm frequencies. Asterisk (*) indicates significant difference between WS and AB; dagger (†) indicates significant difference from 100% FCF. There was no significant difference between SYN and ASY.

Impact of wheelchair propulsion experience

As previously described, the patterns of results were similar for both the AB and WS groups. The most notable finding was the significantly greater efficiency recorded for the WS group under all conditions (p = 0.001). Wheelchair experience did not result in any differences in the patterns of response to changes in propulsion mode or arm frequency as previously described. The greater efficiency of the experienced wheelchair users at the same relative work load must have resulted from improved coordination, especially in the push phase, and possibly a more effective transfer of force between the hand and the wheel, as there were no differences in the energy cost of unloaded propulsion.

Discussion

The data on ME and other physiological measures show a combination of different phenomena: (*i*) the significant impact of arm frequency above FCF and non-significance below FCF; (*ii*) the absence of significant difference between propulsion modes for both groups; (*iii*) the significant impact of wheelchair propulsion experience on ME; (*iv*) the RPE displayed similar trends to the physiological variables, whereas RPE-P produced the highest perceived exertion scores. Discussion of these phenomena follows.

Importantly, the reporting of both physiological and RPE indices seeks to help understand the role of internal and external work production during hand-rim propulsion. As well as the clarification of relationships with arm frequency, propulsion mode, and efficiency, it could offer insight to the underlying reasons for significant differences in efficiency resulting from wheelchair experience and arm frequency.

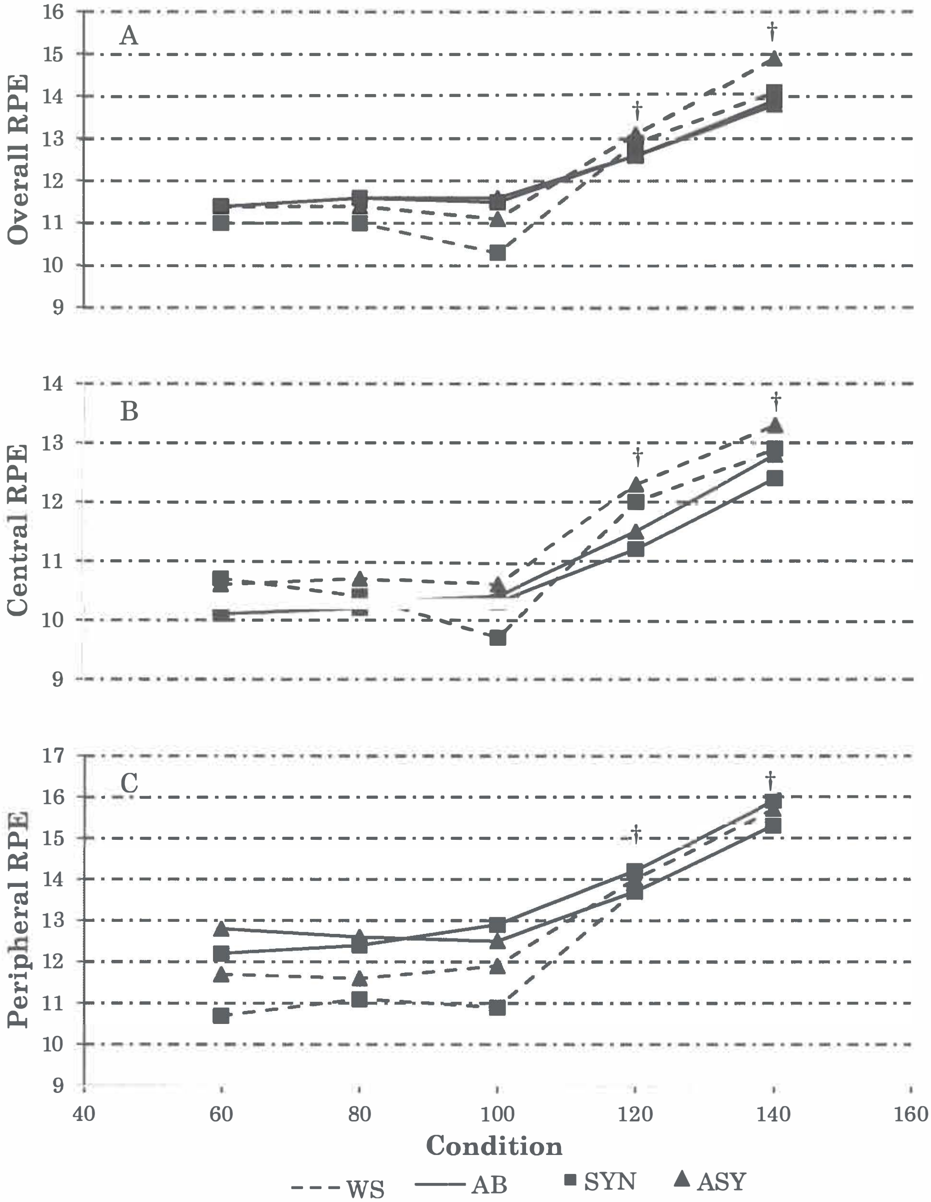


Figure 4.3: Mean rating of perceived exertion (RPE) scores for differentiated RPE measures ((A) overall, (B) central, (C) peripheral) for wheelchair sportsmen (WS) and able-bodied (AB) individuals during synchronous (SYN) and asynchronous (ASY) propulsion across the range of arm frequencies. Dagger (†) indicates significant difference from 100% freely chosen frequency. There was no significant difference between WS and AB or between SYN and ASY.

Impact of arm frequency

The present data make it clear that both arm frequency and propulsion mode had similar effects for both groups on the GE and WE indices, as well as on the other physiological measures **(Figure 4.2)**. The efficiency indices both have their own explanatory role for the effects of arm frequency. Statistical analysis provided evidence that the largest contributing and significant factor to changes in ME and other physiological measures is the arm frequency at which wheelchair propulsion is performed. The results highlighted that the ME of hand-rim propulsion is affected at extreme movement frequencies independently of wheelchair propulsion experience or propulsion mode. The free self-selection (FCF) of arm frequency by both groups did not result in an expected minimization of oxygen cost and optimization of ME at 100% FCF (60% of $\dot{V}O_{2\ peak}$). The non-significant difference in FCF **(Table 4.3)** for the 2 groups implies that this self-selection is not reliant on experience and constant involvement in hand-rim propulsion. It is important to note that the WS were from sporting backgrounds that lend themselves towards fast, quick pushes during intermittent bursts of wheelchair movement [31].

The significant changes in efficiency above 100% FCF and non-significant changes below 100% FCF result from the paced arm frequencies affecting the timing, kinematics, dynamics, and external work per cycle produced. Consequently, these will impact on the internal work or energy required for propulsion. The cyclical timing changes will result in differing magnitudes of accelerations or decelerations of the arm and trunk segments along with the different ranges in segment excursion, thus resulting in different muscle lengths and tensions. Therefore, different arm frequencies, affect the force-velocity and length-tension relationships of the contracting muscles. However, this would not contribute to external power output, which is fixed, but to a change in the internal work of the muscles, hence the overall metabolic cost and ME [30]. Increased arm frequency (>100% FCF) is perhaps thus attributed to increased energy expenditure, elicited from increased internal work. This is a result of increases in the loaded energy cost, because the unloaded energy cost proportion remained more-or-less constant (% of total energy cost) across the range of arm frequencies. In turn this would help explain the significantly higher WE values calculated for both AB and WS. Work efficiency shows the same effect for arm frequency, even when the correction for increased energy cost of $\dot{V}O_{2\,unload}$ is accounted for, thus highlighting that the loaded arm frequency condition brings in other factors that further increase internal work.

There was an absence of significant differences at the lower range of arm frequencies (60% FCF to 100% FCF) and this arises despite the relatively linear change $\dot{V}O_{2\,unload}$ with increasing arm frequency **(Figure 4.2)**. This could imply the existence of counteracting phenomena between the loaded and unloaded conditions, whereby lower arm frequencies benefit from factors that reduce the total amount of internal work during loaded exercise conditions. The lower arm frequencies will essentially lead to lower segment and hand velocities over the larger part of the trajectory. This could allow a more secure, effective coupling and the need for a less controlled transfer of muscle forces through the sequence of contractions, as well as reduced (stabilizing) co-contractions.

It was observed that RPE-P responses were consistently and significantly higher at all arm frequencies than RPE-C and RPE-O scores. This would seem to suggest that local muscular factors (peripheral) in hand-rim propulsion arm work are more important than central cues of exertion when using RPE-O as an indicator of perceived effort, especially at the higher arm frequencies. On the other hand, the non-significant changes in differentiated RPE across arm frequencies in the 60%–100% FCF range, suggests that arm frequency selection in this range will result in acceptable levels of perceived exertion, i.e., shifting the arm frequency anywhere up to 60% of FCF will change RPE by no more than 1 point on the Borg scale.

Table 4.3: Mean values and standard deviation for arm frequencies in wheelchair sportsmen (WS) and able-bodied (AB) individuals during both synchronous (SYN) and asynchronous (ASY) propulsion

	Arm Frequency (total no. of left + right arm movements)			
	AB		WS	
%FCF	Mean	±SD	Mean	±SD
SYN				
60	77	21	83	23
80	101	29	110	31
100	125	36	137	38
120	152	43	167	46
140	177	50	191	51
ASY				
60	70	18	74	12
80	93	23	99	15
100	115	29	122	19
120	140	35	148	23
140	161	39	172	27

Note: There was a non-significant difference between propulsion mode and group ($p > 0.05$).

Impact of propulsion mode

It was interesting to ascertain that propulsion mode produced no significant differences for efficiency between SYN and ASY movement patterns in either of the participant groups. This would suggest that despite wheelchair propulsion experience and constant employment of SYN propulsion mode, the common elements required for hand-rim propulsion are the same for both propulsion modes despite the differences between the 2 modes of propulsion and the specific training status of the WS in SYN propulsion. By suggesting common elements, it is focussing on the similarities such as coupling of the hand-rim, force application, and transfer amongst other movement and technique characteristics that are implicit to both propulsion modes regardless of the experience and arm frequency variables.

Impact of wheelchair propulsion experience

In light of the conditions in the present study, inexperienced, AB individuals and WS employed a wide range of arm frequencies and levels of PO with the GE values across conditions averaging 5.4%–7.0% and 7.0%–9.3%, respectively. These values are in line with previous studies examining efficiency at similar PO levels and in different participant groups [11, 14, 26]. However, the index of WE [13, 14, 16] and the changes in ME [4] during hand-rim propulsion are scarce throughout the literature. Despite differences in hand-rim propulsion experience, similar relationships between arm frequency, mode and physiological parameters were seen. Although there appeared to be a non-significant preference for the SYN mode in the WS and the ASY mode in the AB participants, the implication is that propulsion mode is clearly not as important as the arm frequency when addressing ME, metabolic cost or RPE. As hypothesized, the WS were significantly more efficient. The $\dot{V}O_{2\ unload}$ as expected produced no significant group differences by arm frequency selection. Therefore, the 'passive' internal workload remains somewhat similar in both groups. Although the $\dot{V}O_2$ values reported were similar, the task complexity for WS was increased as a result of the significantly higher velocity and PO to which 60% of $\dot{V}O_{2\ peak}$ corresponded. The explanation for large differences in efficiency between WS and AB is not clearly understood, but this would implicate that there is an overall reduction in the amount of active internal work in the WS that occurs in comparison with AB individuals. The difference in hand-rim propulsion experience could therefore be the result of this improved efficiency, the result of increased skill levels and better training status of the muscles involved in the propulsion process. The more refined movement pattern [22] and suggested better force application pattern seen in WS [21, 32] would reduce energy expenditure at the same exercise intensity. Consequently, changes to force–velocity and force–length characteristics of the muscles will occur. Indeed, it has been shown that hand-rim propulsion practice can improve ME and some technique variables [4] along with changes observed in segmental movement pattern, muscle activity, and co-contraction [5]. Beyond that, motor control improves as an outcome of learning, leading to lower metabolic costs [23]. It is important to note the difference in wheelchair set up of the WS individual wheelchairs **(Table 4.1)**. The interaction of the musculoskeletal system with the form and geometry of the propulsion mechanism and seat configuration has been shown to influence the energy cost, physical strain GE [28] and therefore should not be overlooked.

Comparing perceived exertion of WS with AB participants produced no significant group by arm frequency interaction. This implies that propulsion experience had no different effect on RPE responses between groups for the differentiated RPE scores, although RPE-P was approaching significance at

($p = 0.061$). The WS and AB clearly felt more strain when operating at high frequencies (>100% FCF) as demonstrated in the RPE scores **(Figure 4.3)**. Supporting this was the significant increase in relative exercise intensity significantly beyond the FCF. Subsequently, to meet the task complexity, there is a greater emphasis placed upon the RPE-P because propulsion velocity and (or) PO remained constant. This supports the findings of Ekblom and Goldbarg [6] who stated that peripheral factors are dominant in work with smaller muscle groups. In terms of experience, the AB participants displayed similar perceptual responses. This provided further support to the work of Ekblom and Goldbarg [6] who found differences in RPE to be removed at the same relative exercise intensities.

Methodological considerations

Other important discussion points are, firstly, the use of a standardized chair configuration. Although this may limit the comparisons between AB and WS, it was more valid for the WS to use their own sports chairs and to opt for a standard chair in the AB group, thus eliminating any effects of different chair designs or setups on the physiological measurements. Secondly, one should consider the stationary position of the wheelchair on an ergometer consisting of a single roller with a fixed chain. This was an important feature of the study, allowing for the effects of push strategy to be investigated without the additional effects of coasting direction (of the wheelchair) and external work requirements. More importantly, the PO in both modes remained equal during propulsion. Thirdly, and finally, it is important to note that the AB participants were younger than the WS group and, although described as WS, they did in fact display a limited range of impairments. These limit the generalizability of the results. However, future studies may consider exploring the effects of disability on push strategy (arm frequency and propulsion mode).

Conclusions

Physiological trends did not change as a result of propulsion experience (WS; or AB), despite the arm frequency and propulsion mode manipulations; however, WS are significantly more efficient than AB individuals regardless of arm frequency, propulsion mode, or the higher absolute speed and (or) PO. Reasons for these differences remain unclear and require further investigation. Despite the higher task complexity for WS, it appears possible that the effect of continuous practice (training, sport, and daily activities) leads to the development of more optimal coordination, hence improved propulsion technique, improved ME, and reduced relative metabolic cost. The refined movement patterns (increased skill) reduced oxygen cost, resulting in improved ME at much more complex task requirements.

A curvilinear association of ME with arm frequency was observed and a shift in active internal appeared responsible. Mechanical efficiency and $\dot{V}O_2$ were not optimized at FCF, in contrast to previous research, despite statistically non-significant differences in the lower arm frequencies (60% FCF to 100% FCF). Not exceeding the FCF in either group or propulsion mode is beneficial in terms of reduced metabolic cost and improved efficiency. Propulsion mode (SYN or ASY) produces no negative metabolic effects in either group under the current test conditions.

The psychophysiological cost adheres to the trends of absolute metabolic cost and not ME, although a plateau in the perceived exertion responses was observed between 60% FCF and 100% FCF arm frequencies and rose significantly beyond the 100% FCF condition. Changes in RPE were as a result of arm frequency manipulation and not experience or propulsion mode. Differentiated RPE can be employed to support physiological findings in hand-rim propulsion for both WS and AB individuals; however, no differences between perceived ratings for groups were evident when exercise intensity was maintained. This study also demonstrates the dominant sensation by which individuals perceive and rate exercise conditions.

Acknowledgements

The authors would like to acknowledge RGK Wheelchair manufacturers for the loan of the Quattro basketball wheelchair. They would also like to thank the wheelchair basketball and tennis participants of Great Britain for their commitment to the investigation.

References

1 Borg, G. 1970. Perceived exertion as an indicator of somatic stress. Scand. J. Rehabil. Med. **2**: 92-98. PMID: 5523831.

2 Dallmeijer, A.J., Van der Woude, L.H., Ottjes, L., and De Waardt, E. 2004*a*. A physiological comparison of synchronous and asynchronous hand cycling. Int. J. Sports Med. **25**: 622–626. doi: 10.1055/s-2004-817879. PMID: 15532007.

3 Dallmeijer, A.J., Zentgraaff, I.D., Zijp, N.I., and Van der Woude, L.H.V. 2004*b*. Sub-maximal physical strain and peak performance in handcycling versus hand-rim wheelchair propulsion. Spinal Cord, **42**: 91–98. doi: 10.1038/sj.sc.3101566. PMID: 14765141.

4 de Groot, S., Veeger, D.H.E.V., Hollander, A.P., and Van der Woude, L.H.V. 2002. Wheelchair propulsion technique and mechanical efficiency after 3 weeks of practice. Med. Sci. Sports Exerc. **34**: 756–766. doi: 10.1097/00005768-200205000-00005. PMID: 11984291.

5 de Groot, S., Veeger, D.H.E.V., Hollander, A.P., and Van der Woude, L.H.V. 2003. Short- term adaptations in co-ordination during the initial phase of learning manual wheelchair propulsion. J. Electromyogr. Kinesiol. **13**: 217–228. doi: 10.1016/S1050-6411(03)00018-X. PMID: 12706602.

6 Ekblom, B., and Goldbarg, A.N. 1971. The influence of physical training and other factors on the subjective rating of perceived exertion. Acta Physiol. Scand. **83**: 399–406. PMID: 5134177.

7 Fabre, N., Perrey, S., Arbez, L., Ruiz, J., Tordi, N., and Rouillon, J.D. 2006. Degree of coordination between breathing and rhythmic arm movements during hand rim wheelchair propulsion. Int. J. Sports Med. **27**: 67–74. doi: 10.1055/s-2005-837486. PMID: 16388445.

8 Gayle, G.W., Pohlman, R.L., and Glaser, R.M. 1990. Cardiorespiratory and perceptual responses to arm crank and wheelchair exercise using various hand-rims in male paraplegics. Res. Q. Exerc. Sport, **61**: 224–232. PMID: 2097677.

9 Glaser, R.M., Sawka, M.N., Young, R.E., and Suryaprasad, A.G. 1980. Applied physiology for wheelchair design. J. Physiol. **48**: 41–44.

10 Goosey-Tolfrey, V.L., and Kirk, J.H. 2003. Effect of push frequency and strategy variations on economy and perceived exertion during wheelchair propulsion. Eur. J. Appl. Physiol. **90**: 154–158. doi: 10.1007/s00421-003-0875-6. PMID: 14504947.

11 Goosey-Tolfrey, V.L., Campbell, I.G., and Fowler, N.E. 2000. Effect of push frequency on the economy of wheelchair racers. Med. Sci. Sports Exerc. **32**: 174–181. doi: 10.1097/00005768-200001000-00026. PMID: 10647546.

12 Hassmén, P. 1990. Perceptual and physiological responses to cycling and running in groups of trained and untrained subjects. Eur. J. Appl. Physiol. **60**: 445–451. doi: 10.1007/ BF00705035.

13 Hintzy, F., and Tordi, N. 2004. Mechanical efficiency during hand-rim wheelchair propulsion: effects of base-line subtraction and power output. Clin. Biomech. (Bristol, Avon), **19**: 343–349. doi: 10.1016/j.clinbiomech.2004.01.001. PMID: 15109753.

14 Hintzy, F., Tordi, N., and Perrey, S. 2002. Muscular efficiency during arm cranking and wheelchair exercise: a comparison. Int. J. Sports Med. **23**: 408–414. doi: 10.1055/s-2002-33734. PMID: 12215959.

15 Hopman, M.T.E., Teeffelen, W.M., Van Brouwer, J., Houtman, S., and Binkhorst, R.A. 1995. Physiological responses to asynchronous and synchronous arm-cranking exercise. Eur. J. Appl. Physiol. **72**: 111–114. doi: 10.1007/BF00964124.

16 Lenton, J.P., Fowler, N., Van der Woude, L., and Goosey-Tolfrey, V.L. 2007. Efficiency of wheelchair propulsion and effects of strategy. Int. J. Sports Med. **28**: 1–6. doi: 10.1055/s-2006-924028. PMID: 17133288.

17 Mossberg, K., Willman, C., Topor, M.A., Crook, H., and Patak, S. 1999. Comparison of asynchronous versus synchronous arm crank ergometry. Spinal Cord, **37**: 569–574. doi: 10.1038/sj.sc.3100875. PMID: 10455533.
18 Pandolf, K.B. 1982. Differentiated ratings of perceived exertion during physical exercise. Med. Sci. Sports Exerc. **14**: 397–405. PMID: 7154896.

19 Peronnet, F., and Massicotte, D. 1991. Table of non-protein respiratory quotient: an update. Can. J. Sport Sci. **16**: 23–29. PMID: 1645211.

20 Redfield, R., and Hull, M.L. 1986. On the relation between joint moments and pedalling rates at a constant power in bicycling. J. Biomech. **19**: 317–329. doi: 10.1016/0021-9290(86)90008-4. PMID: 3711132.

21 Robertson, R.N., Boninger, M.L., Cooper, R.A., and Shimada, S.D. 1996. Pushrim forces and joint kinetics during wheelchair propulsion. Arch. Phys. Med. Rehabil. **77**: 856–864. doi: 10.1016/S0003-9993(96)90270-1. PMID: 8822674.

22 Sanderson, D.J., and Sommer, H.J. 1985. Kinematic features of wheelchair propulsion. J. Biomech. **18**(6): 423-429.

23 Sparrow, W.A., and Newell, K.M. 1998. Metabolic energy expenditure and the regulation of movement economy. Psychon. Bull. Rev. **5**: 173–196.

24 Theisen, D., Francaux, M., Fayt, A., and Sturbois, X. 1996. A new procedure to determine external power output during hand-rim wheelchair propulsion on a roller ergometer: a reliability study. Int. J. Sports Med. **17**: 564–571. doi: 10.1055/s-2007-972896. PMID: 8973976.

25 Van der Woude, L.H.V., de Groot, G., Hollander, A.P., Van Ingen Schenau, R.H., and Rozendal, R.H. 1986. Wheelchair ergonomics and physiological testing of prototypes. Ergonomics, **29**: 1561–1573. doi: 10.1080/00140138608967269. PMID: 3102225.

26 Van der Woude, L.H.V., Veeger, H.E.J., Rozendal, R.H., and Sargeant, A.J. 1989. Optimum cycle frequencies in hand-rim wheelchair propulsion. Wheelchair propulsion technique. Eur. J. Appl. Physiol. Occup. Physiol. **58**: 625–632. doi: 10.1007/BF00418509. PMID: 2731532.

27 Van der Woude, L.H.V., Bosmans, I., Bervoets, B., and Veeger, H.E.J. 2000. Handcycling: different modes and gear ratios. J. Med. Eng. Technol. **24**: 242–249. doi: 10.1080/030919000300037168. PMID: 11315650.

28 Van der Woude, L.H.V., Veeger, H.E.J., Dallmeijer, A.J., Janssen, T.W.J., and Rozendal, R.H. 2001. Biomechanics and physiology in active manual wheelchair propulsion. Med. Eng. Phys. **23**: 713–733. doi: 10.1016/S1350-4533(01)00083-2. PMID: 11801413.

29 Van der Woude, L.H.V., Formanoy, M., and de Groot, S. 2003. Hand rim configuration: effects on physical strain and technique in unimpaired subjects? Med. Eng. Phys. **25**: 765–774. doi: 10.1016/S1350-4533(03)00102-4. PMID: 14519349.

30 Vanlandewijck, Y.C., Spaepen, A.J., and Lysens, R.J. 1994. Wheelchair propulsion efficiency: movement pattern adaptations to speed changes. Med. Sci. Sports Exerc. **26**: 1373–1381. PMID: 7837958.

31 Vanlandewijck, Y.C., Theisen, D., and Daly, D. 2001. Wheelchair propulsion biomechanics: implications for wheelchair sports. Sports Med. **31**: 339–367. doi: 10.2165/00007256-200131050-00005. PMID: 11347685.

32 Veeger, H.E.J., Van der Woude, L.H.V., and Rozendal, R.H. 1992. Effect of hand-rim velocity on mechanical efficiency in wheelchair propulsion. Med. Sci. Sports Exerc. **24**: 100–107. PMID: 1548983.

Chapter 5

Effects of 4 weeks asynchronous hand-rim wheelchair practice on mechanical efficiency and timing

John P. Lenton[1,3]
Lucas HV. Van der Woude[2]
Neil E. Fowler[3]
Victoria L. Goosey-Tolfrey[1,3]

Disability and Rehabilitation (2010); 32(26): 2155-2164

[1]Peter Harrison Centre for Disability Sport, School of Sport, Exercise & Health Sciences, Loughborough University, UK.

[2]Center for Human Movement Sciences, University Medical Center Groningen, University of Groningen, the Netherlands.

[3]Exercise & Sport Science, the Manchester Metropolitan University, UK.

Abstract

To investigate the consequence on gross mechanical efficiency (GE), arm frequency and sub-maximal performance, of paced and unpaced practice during asynchronous hand-rim wheelchair propulsion. Twenty five able-bodied participants performed five, 4-minute exercise bouts at 1.7 $m \cdot s^{-1}$, at the freely chosen frequency (FCF) and 4 paced arm frequencies of 60, 80, 120, and 140% FCF. GE, arm frequency and measures of sub-maximal performance were determined. Participants were assigned to an unpaced (FCF, N = 9), paced (80% FCF, N = 8) or control (CON, N = 8) no practice group. The FCF and 80%FCF groups received 4-weeks (unpaced and paced respectively) propulsion practice (3 sessions $\cdot wk^{-1}$, 4 · 4min/trials; 33-35W) at 1.7 $m \cdot s^{-1}$ on a wheelchair ergometer. Following practice, the pre-testing protocol was repeated. Mean GE showed a relative increase in both experimental groups (21% & 17%; FCF and 80% FCF respectively; P = 0.001) compared to no change in CON (-1.5%). The FCF arm frequency decreased in both experimental groups (P = 0.001), with larger changes evident following FCF practice. Four weeks of unpaced or paced practice had a beneficial effect on GE. This improvement seems to be associated with a reduction in arm frequency.

Introduction

The learning and training of manual hand-rim wheelchair propulsion is deemed an essential part of the rehabilitation process for people who become wheelchair-dependent, such as those with a spinal cord injury [1, 2, 3, 4]. That said, the skills required for hand-rim propulsion are more than often learned during rehabilitation as a completely novel task. In light of this, there have been important advances in the study of this learning process/practice period by the Dutch group over the last decade [3, 5, 6, 7, 8, 9, 10].

It is clearly evident that 2yrs and upwards of wheelchair sports experience significantly improves the efficiency of hand-rim propulsion [11]. On the other hand, familiarisation of manual hand-rim propulsion over a practice period of just 3-weeks consisting of only nine trials, has resulted in gross efficiency improvements of 0.33 % and 0.66 % at 0.15 and 0.25 $W{\cdot}kg^{-1}$ respectively (mean power output of 11.6 vs. 19.3 W) [5]. Moreover, the suggestion by de Groot and colleagues [12], that the pumping stroke pattern is an energetically more efficient stroke pattern when compared to other stroke techniques in a very early learning phase, demonstrated strong evidence that technical practice may improve efficiency. Consequently, this work has led to studies examining the adaptations of wheelchair propulsion at set time intervals during the rehabilitation period [13], and the changes in physical capacity after the rehabilitation period [14]. It has been suggested that the improvements in gross efficiency are the result of the changes in the temporal parameters of the propulsion technique [12]. We know from previous work that temporal parameters are paramount, and that operating at the freely chosen frequency (FCF) provides for the greatest gross efficiency [15, 16]. More recently, however, when the combined influence of arm frequency and propulsion mode (asynchronous and synchronous) was studied it was suggested that operating at 60-80% of the FCF is less physiologically demanding [17]. Such findings suggest that there may be a physiological advantage in practicing with a lower push frequency and are also supportive to the notion that this may reduce the likelihood of overuse injuries during wheelchair propulsion [18]. Thus, the adaptations of wheelchair propulsion to slow paced frequency practice versus unpaced practice may be more favourable in terms of mechanical efficiency.

In terms of propulsion strategy, early work suggested that asynchronous propulsion and high drive ratio resulted in less wasted movements [19]. Nevertheless, the work of Lenton and colleagues [20] have challenged these findings, and under their experimental conditions found the synchronous mode offered greater efficiency during wheelchair propulsion at equal arm frequencies. However, further work has demonstrated in able-bodied, inexperienced individuals that there is no significant difference in the efficiency during synchronous and asynchronous propulsion [17]. Since, theories relating to the learning process of the more conventional style of manual wheelchair propulsion are emerging; it is of interest to determine whether gross efficiency could be refined through an asynchronous practice strategy. It is important to note, that the term push rate/push frequency during asynchronous propulsion has often been used inter-changeably with the term arm movement [20]. However, to clarify, from here on push rate/push frequency will be described as the total number of arm movements and the term arm frequency used, this is consequently the addition of the left and right side to account for the alternate arm pushing style of the asynchronous strategy.

There are several studies that have focused on the learning process of manual wheelchair propulsion [6, 11, 16, 21, 22, 23, 24]. Of these studies, it has been suggested that visual feedback can help participants to achieve a more effective hand-rim wheelchair force production [6] and help to regulate the pace of trials (e.g., to slow a participant's arm frequency) which under certain conditions have been found to improve gross efficiency [11, 17]. We wish to extend this work by: 1) verifying the effects of hand rim wheelchair learning in a unpaced vs. paced frequency condition and 2) to examine whether a different mode (asynchronous) propulsion will follow a similar and consistent pattern of adaptation as is seen in synchronous propulsion.

Therefore, the purpose of this study was to investigate the consequence of unpaced and paced practice during asynchronous hand-rim wheelchair propulsion training on gross mechanical efficiency (GE), timing and sub-maximal performance. Based on previous work [11, 17] it was hypothesised that practice at 80% of FCF (paced) will achieve larger improvements in mechanical efficiency in relation to an equivalent period of unpaced practice or no practice.

Method

Participants

Twenty five healthy, male, able-bodied participants (22 ± 4 years; body mass 81.4 ± 10.8kg) volunteered and gave written informed consent prior to participation for this study. Approval for the study procedures was obtained from the University Research Ethics Committee. Prerequisite for participation was no prior experience in wheelchair propulsion or training in upper body sports activities. For this reason, the risk of any previously acquired preference of arm movement frequency or strategy was minimal. Body mass was recorded to the nearest 0.1 kg using a seated balance scale (Seca 710, Hamburg, Germany).

Wheelchair ergometer

All participants were tested in the same hand-rim basketball wheelchair (Quattro, RGK, Burntwood, Staffordshire, England) using the wheelchair ergometer interfaced with a computer (Compaq Armada 1520, Series 2920A). A 15° cambered chair was fitted with 0.66 m diameter wheels and 0.61 m hand-rims, with a total mass of 12.9 kg. Rear wheel tyre pressure was standardised to 758 kPa (7.58 bar). No individual adjustments relative to anthropometric measures of the participants were made to the wheelchair. The wheelchair ergometer consisted of a single roller (length, 1.14 m; circumference, 0.48 m) and a flywheel sensor connected to the roller. A laptop computer calculated and displayed the wheelchair velocity. Each participant performed a deceleration test and power output (PO) was calculated using the principles described by Theisen et al. [25]. For further details of this procedure please refer to Lenton et al. [20].

Testing protocol

All participants performed a sub-maximal wheelchair exercise test on the roller ergometer (pre-test) at the beginning of the four week practice period. This pre-test involved participants performing a discontinuous sub-maximal test consisting of five different arm frequencies (freely chosen (FCF) and 60, 80, 120 and 140% of FCF) at a speed of 1.7 $m \cdot s^{-1}$. Trunk movements were not restricted. The experimental design was similar to that previously reported by

Lenton et al. [11, 17]. An audio-visual metronome was used to pace the arm frequency.

Participants completed a 5-minute warm-up prior to the test starting at a self-selected arm frequency and propulsion velocity which was guided such that the participant's HR did not exceed 130 beats $\cdot$min^{-1}. Following an 8 minute rest period, a 1 minute 'habituation period' began to allow the participant to become accustomed to the arm frequency followed by a 4 minute test period. The FCF was determined during the first 4 minute exercise trial and arm frequency (defined as the total number of left and right arm movements) was recorded each minute and then averaged. Subsequent exercise bouts were performed at paced arm frequencies derived from this first measure. An 8 minute recovery period separated each test condition. This rest period was deemed sufficient to allow participant's HR to return to or close to their baseline HR. The order of the four arm frequency trials was counter-balanced to ensure that possible effects of fatigue and/or learning were mitigated.

Participants were pair matched according to their FCF and GE, then divided into two experimental practice groups (FCF, unpaced, n = 9; 80% FCF, paced, n = 8) and a control group consisting of no practice (CON, n = 8). Both experimental groups practiced at 1.7 m$\cdot$s^{-1} (average; 33-35 W) on the roller ergometer. The FCF group performed trials at an unpaced / unregulated frequency whereas the 80% FCF group had their arm frequency regulated to 80% of the pre-test FCF through use of an audio-visual metronome. Group characteristics are listed in **Table 5.1**. The experimental groups under-took a 4 week practice period comprising three visits per week, totalling 12 practice trials. Each practice trial consisted of four 4 minute practice blocks on the wheelchair ergometer. Arm frequency was monitored throughout each session. One week post-practice participants repeated the same protocol as in the pre-test to form the post-test data, whereby FCF was re-tested.

Physiological measures

Throughout the pre- and post-test measurement sessions, 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 concentration of oxygen and carbon dioxide in the expired air samples was 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 ($\dot{V}O_2$), carbon dioxide output ($\dot{V}CO_2$), expired minute ventilation, and respiratory exchange ratio (RER) were determined. A capillary blood sample was collected from the earlobe immediately following each condition. Blood lactate concentration ([La]b) was determined using an automatic analyser (YSI 1500 Sport, Yellow Springs, Ohio). The YSI analyser was calibrated with a lactate standard of 5mmol$\cdot L^{-1}$ prior to testing.

Participants received detailed instructions about the use of the 15 point Borg scale [26], with examples given of how they might score differentiated ratings of perceived exertion (RPE). At the end of the final minute of each exercise trial, the RPE scale was presented to the participant who was then asked to state the number reflecting their perceived exertion for (i) a "central" rating (RPE-C; sensation of cardiorespiratory stress) and (ii) a "peripheral" rating (RPE-P; sensation of strain from working muscles - arms).

The Gross mechanical efficiency was calculated as the ratio of the external work to energy expended for one minute of exercise. The work accomplished was determined by calculating the external work during hand-rim wheelchair propulsion on the wheelchair ergometer, for all arm frequencies. The energy expenditure was obtained from the product of $\dot{V}O_2$ and the oxygen energetic equivalent by using the associated measurements of RER and standard conversion tables [27]. Gross efficiency of propulsion was determined according to the ratio: GE = (External Work Accomplished / Total Energy Expended) $\cdot$ 100 (%).

Data analysis

The Statistical package for Social Sciences (SPSS, version 12.0; Chicago, IL, USA) was used for all the statistical analyses. Means and standard deviations were computed for all variables. Pre-practice group comparisons with ANOVA were applied to all data. A 2 x 3 (time by group) mixed measures ANOVA, with time as the within factor, was applied to all physiological data. An ANOVA for repeated measures with weeks (1 to 4) and practice trials (1 to 12) as main factor and group (80% FCF and FCF) as the between factor was applied to detect differences in arm frequency during practice. Significance for all tests was assumed at $p \leq 0.05$. A Bonferroni post hoc test was applied to further analyse significant main effects.

Results

Participants and FCF pre-practice

All participants completed all of the trials. Mean age was significantly lower for the FCF (P=0.003) and 80% FCF (P=0.001) practice groups in comparison to the control group, however, body mass did not differ significantly between the groups **(Table 5.1)**. More importantly, no significant differences were found in pre-test levels of FCF, gross efficiency and power output between the experimental and control groups **(Table 5.1)**.

Practice period (unpaced and paced)

The mean arm frequency during each practice trial for both experimental groups is plotted in **Figure 5.1**. This shows a progressive and significant decrease in arm frequency for the unpaced FCF group over the 12 practice sessions (93 ± 26 vs. 67 ± 31 arm movements·min^{-1}; main effects P=0.001). For the paced group the audio paced 80% FCF was held at a constant average of 101 ± 17 arm movements·min^{-1} throughout this 4-week practice period.

Table 5.1: Mean and (SD) of the group characteristics and pre-test levels of FCF, gross efficiency and power output

	Participant Group			
	FCF (n=9)	80% FCF (n=8)	CON (n=8)	P value
Age (yrs)	20 (2)†	20 (1)†	26 (5)	0.333
Body Mass (kg)	80.8 (12.0)	82.5 (13.3)	81.0 (7.5)	0.794
Freely Chosen Frequency (arm movements·min^{-1})	115 (29)	126 (20)	106 (21)	0.409
Gross Efficiency (%)	6.3 (1.1)	6.5 (1.0)	6.6 (0.5)	0.724
Power Output (W)	33.1 (3.3)	34.5 (3.2)	35.3 (1.7)	0.417

FCF = Freely Chosen Frequency Practice Group; 80% FCF = 80% FCF Practice Group; CON = Control Group ANOVA results (P value) between groups. † Significant difference between FCF, 80% FCF group and CON group (P < 0.05)

FCF post-practice

Following the practice period, under the conditions of FCF arm frequency showed a significant reduction for both experimental groups (115 ± 29 to 69 ± 24 and 126 ± 20 to 98 ± 16 arm movements·min^{-1} for FCF and 80% FCF respectively; P = 0.001) in comparison to the CON group. Subsequently, a positive shift in GE was evident under both conditions as a consequence of practice (6.3 ± 1.1% to 7.6 ± 0.8% and 6.5 ± 1.0% to 7.6 ± 0.8% for FCF and 80%FCF respectively; P = 0.001). No significant changes in these parameters were noted for the control group (6.6 ± 0.5% to 6.5 ± 0.3%) **(Figure 5.2)**. The relative increase in GE in the practice groups was 21% (FCF) and 17% (80% FCF). Notably, the FCF group reduced their arm frequency by 40% throughout the practice period, while the experimental participants who were being paced at 80% FCF, reduced their arm frequency by 22% such that the post-training FCF closely matched that used during the training period. Importantly there were no significant changes in the power output from pre- to post-tests and the insignificance remained across the three groups. Work per cycle was significantly increased from pre to post-tests in the FCF condition for both practice groups (17.0 ± 3.9 J to 21.1 ± 4.6 J (P = 0.003) and 19.6 ± 10.2 J to 33.7 ± 14.4 J (P = 0.002) for 80% FCF and FCF respectively.

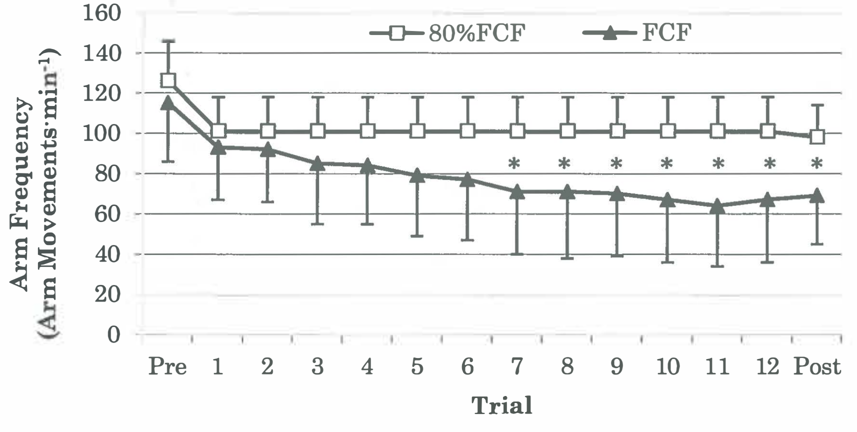


Figure 5.1: Arm frequency over time (12 practice trials) for both experimental groups (80% FCF and FCF). * Significant difference between 80% FCF group and FCF group (P < 0.05). † Significant difference between previous practice week in FCF group (P < 0.05).

Physiological changes

Heart rate, sub-maximal $\dot{V}O_2$, blood lactate concentration and RPE-P decreased significantly (P=0.001) following practice in the post-test **(Table 5.2)**. The sub-maximal $\dot{V}O_2$ significantly decreased in both experimental groups showing a relative decrease of 14-15%. On the other hand the CON group remained almost constant for physiological variables, with the exception of blood lactate concentration whereby a significant increase (P=0.001) was observed from pre- to post-test **(Table 5.2)**.

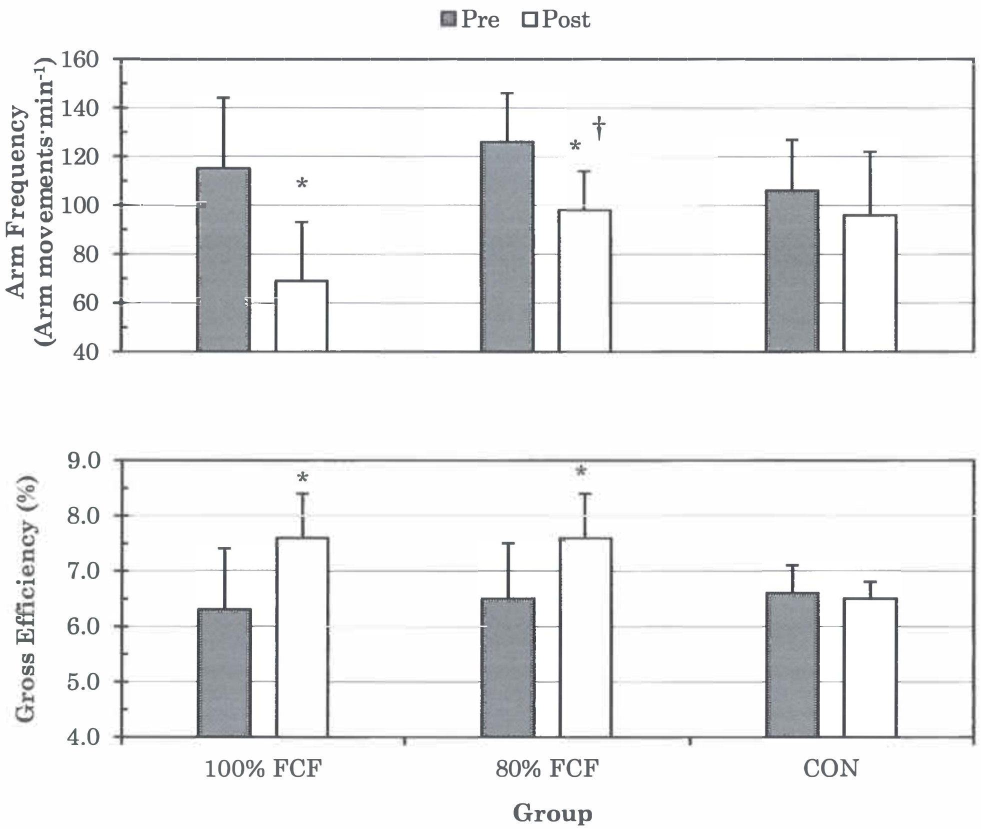


Figure 5.2: Gross efficiency and arm frequency results pre and post-practice period of the FCF condition for the three groups (mean and SD). * Significant difference between pre and post-tests (P < 0.01). † Significant difference between practice groups post practice (P < 0.01).

Table 5.2: Physiological adaptations (mean ± (SD)) at FCF pre and post-practice for oxygen uptake ($\dot{V}O_2$), heart rate (HR) blood lactate concentration ($[La]_b$) and ratings of perceived exertion (RPE) for the 3 experimental groups.

	FCF		80% FCF		CON	
	Pre	**Post**	**Pre**	**Post**	**Pre**	**Post**
$\dot{V}O_2$ (L·min^{-1})	1.49 (0.19)	1.27 (0.12)*†	1.48 (0.16)	1.27 (0.14)*†	1.42 (0.06)	1.43 (0.04)
HR (beats·min^{-1})	136 (15)†	112 (10)*	132 (25)	108 (18)*	112 (15)	110 (12)
$[La]_b$ (mmol·L^{-1})	2.07 (0.75)	1.65 (0.70)*	2.30 (0.93)	1.89 (0.61)*	1.80 (0.58)	2.22 (0.62)*
RPE Local	12.0 (2.1)	10.0 (1.8)*†	11.6 (2.1)	10.4 (1.8)†	11.4 (1.8)	12.1 (0.8)
RPE Central	9.6 (1.5)	8.9 (1.6)	9.6 (2.4)	8.5 (1.8)*	10.3 (1.3)	10.3 (1.6)
Power Output (W)	33.1 (3.3)	33.4 (2.4)	34.5 (3.2)	33.5 (2.5)	35.3 (1.7)	34.8 (1.2)
Work per cycle (J)	1.49 (0.19)	1.27 (0.12)*	1.48 (0.16)	1.27 (0.14)	1.42 (0.06)	1.43 (0.04)

FCF =Freely Chosen Frequency Practice Group; 80% FCF = 80% FCF Practice Group; CON = Control Group
* Significant difference between pre and post-tests.
† Significant difference between FCF or 80% FCF and CON group.

Gross efficiency and arm frequency across the frequency spectrum

Figure 5.3 illustrates the arm frequency and GE across the full range of frequencies (60 to 140% of FCF) which were determined pre- and post- the practice period. The significant arm frequency reductions of 22% and 40% (P=0.001) from pre- to post-practice was not seen in the control group whereby their arm frequency was reduced between pre- and post-practice by 9%, this was non-significant (P=0.276). For both the 80% FCF and FCF groups, there appeared to be improvements in GE at all selected frequencies yet with a greater divergence at the higher frequencies (120 and 140 % FCF).

Interestingly, following paced practice at 80% FCF, which was on average 101 ± 17 arm movements $\cdot min^{-1}$, this then became the self-selected post-practice 100% FCF (98 ± 16 arm movements $\cdot min^{-1}$). This pre-practice 80% FCF condition has found to have the highest GE value (6.9 ± 0.9%), yet despite this leftward shift in arm frequency **(see Figure 5.3 point a)**, 80% FCF remained the condition that was found to have the highest GE (7.6 ± 0.7%; 10% improvement) for this paced practice group. **Figure 5.3** indicates no change in the efficiency for the CON group following practice.

Discussion

The purpose of the study was to investigate the consequence of paced and unpaced asynchronous hand-rim wheelchair propulsion practice on GE, timing and sub-maximal performance. Whilst previous research has demonstrated that 3-weeks synchronous propulsion practice (9 practice trials, 2 · 4-min/trial) is sufficient to increase GE [5], it had not been confirmed whether paced vs. unpaced asynchronous practice would yield similar results. In summary, we were fortunate that the experimental design resulted in the 80% FCF condition to be the closest to the optimal cadence in terms of GE, supportive to previous work [11, 17]. That said, the group that practiced at this frequency (paced group) did not gain any notable advantage in terms of GE following the 4-week practice period when compared to the unpaced group (both 7.6% efficiency). This was despite a significant difference in arm frequency between the two practice groups and this lower frequency of the FCF group may well be of an advantage in regards to overuse injuries. Lower arm frequencies have long been suggested by clinical biomechanists to be beneficial for the health of the musculoskeletal system [28], by reducing the high mechanical loads on the upper extremity. The lower arm frequencies would allow an increased time at which to impart a force onto the hand-rim with an increased push angle. Consequently there are lower segment and hand velocities which could allow for more secure and effective coupling to the hand-rim helping to reduce the required energy cost of the task. For rehabilitation instructing individuals to adopt the lower arm frequencies could therefore, be important to not only improve efficiency but also reduce overuse injury, which appear to be associated with higher frequencies and increased segmental velocities. However, this significant improvement in GE compared to the CON group (P=0.007), for both experimental groups supported the idea that the learning process of 4-weeks is sufficient to elicit changes in wheelchair propulsive performance, independent of the unpaced/paced strategy. Since the unpaced group reduced their frequency following practice to 69 ± 29 arm movements·min^{-1}, whilst the paced group to only 98 ± 16 arm movements·min^{-1}, it would be of interest to extend this practice duration as a two-phase manipulation where unpaced practice followed the paced practice to explore if any further efficiency gains could be made. Nevertheless, the results confirmed that even without feedback (unpaced trial) metabolic energy expenditure is significantly reduced following practice.

Based on the work of Lenton et al [11, 17] it was hypothesized that practice at 80% of FCF (paced) would achieve a larger improvement in GE in relation to the same practice period of unpaced practice or no practice. This hypothesis was not confirmed by the results of the present study since no difference was found between the practice groups with the post GE values. This study did however, accept the second working hypothesis and found that the adaptations during asynchronous wheelchair propulsion did follow a similar and consistent pattern of adaptation as is seen in synchronous propulsion [5, 6].

FCF pre-practice

In comparison with most recent literature on asynchronous wheelchair propulsion [11], the arm frequency selected by participants in this study, which ranged from 106 – 126 arm movements·min^{-1} was found to be similar at the current testing conditions ($v = 1.7 m \cdot s^{-1}$). Moreover, in line with the cycling literature (for an overview, see Vercruyssen et al. [29]), but with a focus on manual wheelchair propulsion, the present study indicated that regardless of group, there was a tendency for arm frequency selection (FCF) to be higher than the most efficient one, which tended to be when the arms were operating slower (80% FCF). This is a finding that is becoming more familiar in the wheelchair propulsion literature, where the earlier concept that the FCF is the optimal [15, 16], has since been challenged during both synchronous and asynchronous wheelchair propulsion by Lenton and colleagues, [11, 17]. These latter studies have suggested that lower arm frequencies are more efficient than higher ones, although it is accepted that these findings were at differing propulsion conditions in terms of velocity and external power output. That said, following this initial selection of FCF, the purpose of this study was to subsequently explore the effects of lower paced practice versus FCF practice.

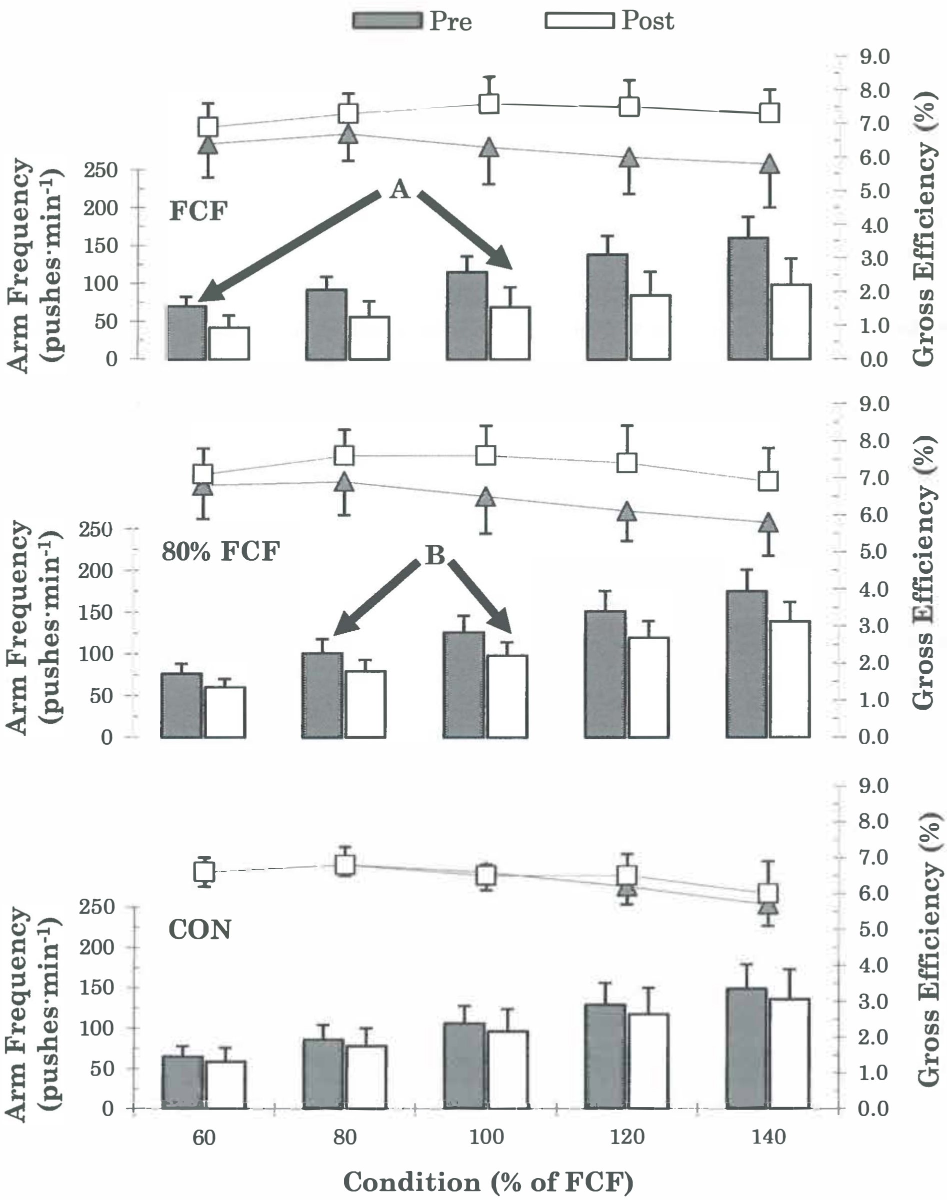


Figure 5.3: Arm frequency (bar chart) and GE (line graph) of 60 to 140% FCF frequencies pre and post the practice. FCF = freely chosen frequency practice group; 80% FCF = 80% of FCF practice group; CON = Control group. A indicates that 60% FCF pre-test arm frequency equalled the post-test FCF after practicing at FCF. B indicates that 80% FCF pre-test arm frequency equalled the post-test FCF after practice at 80%FCF.

Practice (unpaced and paced)

Of great interest is the fact that the two experimental groups gained similar improvements in GE despite considerable differences in paced/unpaced practice and subsequent differences in FCF (up to 29 arm movements·min^{-1}). This improvement equated to GE increases of on average 1.1-1.3%, which may appear to be only a small change, but from a clinical perspective would result in the reduction of physical strain during daily activity tasks. However, this GE improvement is greater when compared to a 3 week learning study, in which a maximum increase of 0.6% resulted from low-intensity wheelchair propulsion practice (three times a week, two 4-min exercise blocks of 0.15 W·kg^{-1} and 0.25 W·kg^{-1}, respectively) [5]. More recently de Groot et al. [10] showed increases of 1.3 - 1.9% following 7 weeks (three times a week, 70min) of low intensity wheelchair training (30% of Heart Rate Reserve) at an average power output of 20W throughout the training. The pre- and post- tests involved two exercise blocks were which were on average 13 and 26 W. The power output of the present study remained constant throughout practice at ~34 W and thus was higher than in the former two studies. Despite differences in power output and duration of practice between these studies, it would appear that this study supports the notion that in order to change the efficiency of propulsion, the duration of the practice/training seems important, i.e. more practice/training leads to more improvement in gross efficiency [10, 11].

There is certainly evidence of a habitual learning effect which is likely to have a neural / co-ordination effect [30] – evidenced by the fact that post training both groups had adapted to a FCF which reflected that used in the practice period. Since both groups had similar GE post practice it is likely that the FCF at this stage was indicative of their habituated preference rather than a physiologic reason. Supportive to previous work, it would appear that skill learning of wheelchair propulsion involves the search for a ‘body scheme’ that requires minimal energy expenditure [31]. This study was limited to timing parameters that is discussed in more detail in the next section, however, with the possible coupling features of breathing and movement [32]; we speculate that the metabolic cost is not the only factor that is involved in this choice.

FCF post-practice and other physiological parameters

Timing is a leading parameter in cyclic motor learning and our findings relating to the reduction of arm frequency confirms not only previous work on manual wheelchair propulsion [5, 6, 10], but the suggestion that the learning of repetitive gross-motor tasks might be characterized by a 'longer-slow' control mode, i.e., a decreased arm frequency because of the larger stroke angle/longer push time [33]. The key timing parameter of arm frequency changed significantly over a relatively short period of time and the timing associated with this change appear to be related to the improved GE. The mean power output did not change with practice, yet there were notable reductions in arm frequency after practice, which resulted in an increase in work per cycle **(Table 5.2)**. This notion would appear to be supported by de Groot and colleagues who reported an increase in work per cycle following 3 weeks of low intensity practice [5] and within only 12 minutes of short term propulsion practice [7], attributed to the reduction in arm frequency. On the other hand, contrary to this aforementioned work [10] found that during a 7 week low intensity training no significant changes were observed in peak torque or peak power output during propulsion despite significant changes in arm frequency. However, it is suggested that this could well be the result of the large standard deviation found in the experimental group. If indeed the work per cycle is increased with reduced arm frequency then this could point to a possible explanation for greater reductions in RPE-P over RPE-C which is an area that warrants further attention. The fact that the blood lactate concentration was significantly reduced following practice is supportive to previous work which found that decreased lactate production is related to a decreased cadence [16, 34, 35]. That said, we have no explanation as to why the CON group were found to have increased blood lactate concentration during their post-test following no practice. As expected, practice had favourable effects on oxygen cost and heart rate.

Gross efficiency and arm frequency across the frequency spectrum

Despite, Groot et al., [12] stating that novice subjects seem to find the efficiency optimum at the start of practice there was a tendency to suggest that the 80% FCF was more favourable in terms of GE, which supported the work of Lenton et al.[11, 17]. Nevertheless, following both practice conditions, participants appeared to work considerably more efficiently at the higher arm frequencies (120 and 140% FCF; **Figure 5.3**). Interestingly, when participants practiced at a 20% slower frequency (80% FCF) the GE optimum reset following the practice period by shifting to the right. Consequently the practiced arm frequency became the FCF in the post-test and this remained the most efficient condition. On the other hand, following FCF practice the participants conformed to de Groot and co-workers [5] assumption that they found the efficiency optimum and the FCF (post-practice) was more favourable when compared to the other frequency conditions. This was not the case during the pre-test before practice and without the controlled practice arm frequency, the arm frequency decreased by 40% at FCF post-test. This decrease showed that after practice the pre-test 60% FCF condition was now the participants FCF in the post-test.

Finally, it has been suggested that GE increases significantly across the time course of unpaced practice [5], this combined with the reduction in FCF during practice as noted under the unpaced practice generates a question of great interest. This being, whether participants (a) became more economical because they reduced the arm frequency; or (b) if they were able to drop the frequency because they were more economical.

Limitations and implications

Since very little is known regarding the effect of wheelchair propulsion practice the present study employed able-bodied, inexperienced participants in one standardised chair configuration condition, eliminating the effects of chair designs/setups on physiological measurements. Importantly they reflect as closely as possible novice wheelchair users in the early stages of rehabilitation. Their use is prevalent in the literature, and is essential to gain theoretical concepts of the learning process of manual wheelchair propulsion in the first instance. Whilst it is acknowledged this will have an influence on the absolute efficiency of propulsion [11], we reiterate that, the purpose of the study was to evaluate the impact of propulsion practice and thus it was important to eliminate any bias caused by habitual use. Our data clearly demonstrate the power that habituation has on the critical variables in terms of GE improvements and reductions HR and local RPE. This is important as currently the only longitudinal data on mechanical efficiency during initial rehabilitation in persons with spinal cord injury is de Groot et al. [36].

The chosen propulsion velocity was selected from previous research to ensure that participants were working sub-maximally throughout the exercise trials and practice conditions [11, 17, 20]. However, we are unable to confirm whether the improvement in GE was independent of physiological condition since an aerobic capacity test was not performed pre- and post- the practice period. It is likely that the participants' fitness could have improved slightly, yet we hoped to have kept this to the minimum with the exercise intensity corresponding to around 57% ± 7% $\dot{V}O_2$ peak [11, 17] and exercise duration kept to only 16 minutes (4 · 4min blocks) of propulsion during each practice session.

Of practical relevance is the feedback mechanism of pacing via the use of audio cues and its application to assist recently spinal cord injured individuals in a rehabilitation centre towards learning the complex task of wheelchair propulsion. Furthermore, music at different tempos may assist this process by encouraging the individual to meet the requirements for the exercise duration and intensity whilst maintaining a suitable cadence for optimum GE [37].

Conclusion

Under the current experimental conditions, 4-weeks of asynchronous hand-rim wheelchair propulsion practice had a beneficial effect on GE, timing and sub-maximal performance in novices. The GE profile showed a shift towards the most efficient frequency being that most closely matching the frequency adopted in training and in all cases this being lower in the post-test than the initial FCF. Improvements in efficiency were clearly associated with a reduction in arm frequency. This effect was demonstrated most clearly by the comparison between the final FCF which for the paced group became the same as their paced practice frequency whilst for the unpaced group this fell to the lower level achieved in the final weeks of practice. Further detailed analysis of the kinematics and muscle activation of this unconventional propulsion strategy would help to further understand the mechanisms involved with the efficiency of wheelchair propulsion and adaptations as a consequence of practice.

Acknowledgements

The authors would like to acknowledge RGK Wheelchair manufacturers for the loan of the Quattro basketball wheelchair. They would also like to thank all the participants for their time and commitment to the testing.

References

1 Jacobs PL, Nash MS. Exercise recommendations for individuals with spinal cord injury. Sports Med 2004; 34(11): 727-751.

2 Kilkens OJ, Dallmeijer AJ, Nene AV, Post MW, van der Woude LHV. The longitudinal relation between physical capacity and wheelchair skill performance during inpatient rehabilitation of people with spinal cord injury. Arch Phsy Med Rehabil 2005; 86(8): 1575-1581.

3 de Groot S. Course of gross mechanical efficiency in handrim wheelchair propulsion during rehabilitation of people with spinal cord injury: a prospective cohort study. Arch Phys Med Rehabil 2005; 86(7): 1452-1460.

4 van der Woude LHV, de Groot S, Janssen TWJ. Manual wheelchairs: Research and innovation in rehabilitation, sports, daily life and health. Med Eng Phys 2006; 28: 905-915.

5 de Groot S, Veeger DHEV, Hollander AP, van der Woude LHV. Wheelchair propulsion technique and mechanical efficiency after 3 wk of practice. Med Sci Sports and Exerc 2002; 34(5): 756-766.

6 de Groot S, Veeger DHEV, Hollander AP, van der Woude LHV. Consequence of feedback based learning of an effective hand rim wheelchair propulsion force production on mechanical efficiency. Clin Biomech 2002; 17(3); 219-226.

7 de Groot S, Veeger DHEV, Hollander AP, van der Woude LHV. Adaptations in physiology and propulsion technique during the initial phase of learning manual wheelchair propulsion. Am J Phys Med Rehab 2003; 82(7): 504-510.

8 de Groot S, Veeger DHEV, Hollander AP, van der Woude LHV. Short term adaptations in co-ordination during the initial phase of learning manual wheelchair propulsion. J Electromyogr Kinesiol 2003; 13(3): 217-228.

9 de Groot S, Veeger DHEV, Hollander AP, van der Woude LHV. Influence of task complexity on mechanical efficiency and propulsion technique during learning of hand rim wheelchair propulsion. Med Eng Phys 2005; 27(1): 41-49.

10 de Groot S, de Bruin M, Noomen SP, van der Woude LHV. Mechanical efficiency and propulsion technique after 7 weeks of low-intensity wheelchair training. Clin Biomech 2008; 23: 434-441.

11 Lenton JP, Fowler NE, van der Woude LHV, Goosey-Tolfrey VL. Wheelchair propulsion: Effects of experience and push strategy on efficiency and perceived exertion. Appl Physiol Nutr Metab 2008; 33: 870-879.

12 de Groot S, Veeger DHEV, Hollander AP, van der Woude LHV. Effect of wheelchair stroke pattern on mechanical efficiency. Am J Phys Med Rehab 2004; 83(3): 640-649.

13 Dallmeijer AJ. Hand-rim wheelchair propulsion capacity during rehabilitation of persons with spinal cord injury. J Rehabil Res Dev 2005; 42(3 suppl 1): 65-73.

14 Haisma JA, Bussmann JB, Stam HJ, Sluis TA, Bergen MP, Dallmeijer AJ, de Groot S, van der Woude LHV. Changes in physical capacity during and after inpatient rehabilitation in subjects with a spinal cord injury. Arch Phys Med Rehabil 2006; 87(6): 741-748.

15 van der Woude LHV, Veeger HEJ, Rozendal RH, Sargeant AJ. Optimum cycle frequencies in hand-rim wheelchair propulsion. Wheelchair propulsion technique. Eur J Appl Physiol Occup Physiol 1989; 58: 625-632.

16 Goosey VL, Campbell IG, Fowler NE. Effect of push frequency on the economy of wheelchair racers. Med Sci Sports Exerc 2000; 32(1): 174-181.

17 Lenton JP, van der Woude LHV, Fowler NE, Goosey-Tolfrey VL. Effects of arm frequency during synchronous and asynchronous wheelchair propulsion on efficiency. Int J Sports Med 2009; 30: 233-239.

18 Boninger ML, Koontz AM, Sisto SA, Dyson-Hydson TA, Chang M, Price R, Cooper RA. Pushrim biomechanics and injury prevention in spinal cord injury: recommendations based on CULP-SCI investigations. J Rehabil Res Dev 2005; 42(3 suppl 1): 9-19.

19 Glaser RM, Sawka MN, Young RE, Suryaprasad AG. Applied physiology for wheelchair design. J Physiol 1980; 48: 41-44.

20 Lenton JP, Fowler NE, van der Woude LHV, Goosey-Tolfrey VL. Efficiency of wheelchair propulsion and effects of strategy. Int J Sports Med 2008; 29: 384-389.

21 Veeger HE, van der Woude LHV, Rozendal RH. A computerized wheelchair ergometer: Results of a comparison study. Scan J Rehabil Med 1992; 24(1): 17-23.

22 Kotajarvi BR, Basford JR, An K, Morrow DA, Kaufman KR. The effect of visual biofeedback on the propulsion effectiveness of experienced wheelchair users. Arch Phys Med Rehabil 2006; 87: 510-515.

23 Cooper RA. SmartWheel: From concept to clinical practice. Prosthet Orthot Int 2009; 33(3): 198-209.

24 Cowan RE, Boninger ML, Sawatzky BJ, Mazoyer BD, Cooper RA. Preliminary outcomes of the SmartWheel users' group database: A proposed framework for clinicians to objectively evaluate manual wheelchair propulsion. Arch Phys Med Rehabil 2008; 89: 260-268.

25 Theisen D, Francaux M, Fayt A, Sturbois X. A new procedure to determine external power output during hand-rim propulsion on a roller ergometer: A reliability study. Int J Sports Med 1996; 17: 564-571.

26 Borg G. Perceived exertion as an indicator of somatic stress. Scan J Rehab Med 1970; 2(2): 92-98.

27 Perronet F, Massicote D. Table of non-protein respiratory quotient: an update. Can J Sport Sci 1991; 16: 23-29.

28 Boninger ML, Baldwin M, Cooper RA, Koontz A, Chan L. Manual wheelchair pushrim biomechanics and axle position. Arch Phys Med Rehabil 2000; 81(5); 608-613.

29 Vercruyssen F, Hausswirth C, Smith D, Brisswalter J. Effect of exercise duration on optimal pedalling rate choice in triathletes. Can J Appl Physiol 2001; 26(1): 44-54.

30 Sparrow WA, Irizarry-Lopez VM. Mechanical efficiency and metabolic cost as measures of learning a novel gross motor task. J Mot Behav 1987; 19(2): 240-264.

31 Almåsbakk B, Whiting HTA, Helgerud, J. The efficient learner. Biol Cybern 2001; 84: 75-83.

32 Amazeen PG, Amazeen EL, Beek PJ. Coupling of breathing and movement during manual wheelchair propulsion. J Exper Psychol. Hum Percept Perform 2001; 27(5): 1243-1259.

33 Sparrow WA, Newell KM. Metabolic energy expenditure and the regulation of movement economy. Psychonomic Bulletin & Review 1998; 5(2): 173-196.

34 Cox MH, Miles DS, Verde TJ, Nessenthaler G. Influence of pedal frequency on the lactate threshold of elite cyclists. Med. Sci. Sports Exerc 1994; 26:S67.

35 Goosey-Tolfrey VL, Kirk JH. Effect of push frequency and strategy variations on economy and perceived exertion during wheelchair propulsion. Eur J Appl Physiol 2002; 90: 154-158.

36 de Groot S, Dallmeijer AJ, van Asbeck FWA, Post MWN, Bussmann JBJ, van der Woude LHV. Mechanical efficiency and wheelchair performance during and after spinal cord injury rehabilitation. Int J Sports Med 2007; 28: 880-886.

37 Waterhouse J, Hudson P, Edwards B. Effects of music tempo upon sub-maximal cycling performance. Scand J Med Sci Sports 2010; 20(4): 662 – 669.

Chapter 6

Hand-rim forces and gross mechanical efficiency at various frequencies of wheelchair propulsion

John P. Lenton[1,3]
Lucas HV. van der Woude[2]
Neil E. Fowler[3]
Graham Nicholson[4]
Keith Tolfrey[1]
Victoria L. Goosey-Tolfrey[1,3]

International Journal of Sports Medicine 2012 (in press)

[1]Peter Harrison Centre for Disability Sport, School of Sport, Exercise & Health Sciences, Loughborough University, UK.

[2]Center for Human Movement Sciences, University Medical Center Groningen, University of Groningen, the Netherlands.

[3]Department of Exercise & Sport Science, the Manchester Metropolitan University, UK.

[4]ASPIRE Centre for Disability Sciences, Institute of Orthopaedics and Musculoskeletal Science, University College London, UK.

Abstract

To determine the effects of push frequency changes on force application, fraction of effective force (FEF) and gross efficiency (GE) during hand-rim propulsion. 8 male able-bodied participants performed five 4-min sub-maximal exercise bouts at 1.8 $m \cdot s^{-1}$; the freely chosen frequency (FCF), followed by 4 counter-balanced trials at 60, 80, 120 and 140 % FCF. Kinetic data was obtained using a SMART Wheel, measuring forces and moments. The GE was determined as the ratio of external work done and the total energy expended. Increased push frequency led to reductions in peak resultant force ($P < 0.05$), ranging from 167 to 117 N and peak tangential force ($P < 0.05$), ranging from 117 to 77 N. However, FEF only demonstrated a significant difference between 60 % and 140 % FCF (69 ± 9 % and 63 ± 7, respectively; $P < 0.05$). Work per cycle decreased significantly ($P < 0.05$) and rate of force development increased significantly ($P < 0.05$) with increased push frequency. GE values were significantly lower at 60 %, 120 % and 140 % FCF than 80 % and 100 % FCF ($P< 0.05$). No meaningful associations were present between FEF and GE. Under the current testing conditions, changes in push frequency are accompanied with changes in the absolute force values, albeit without changes in either the gross pattern/trend of force application or FEF. Changes in GE are not explained by different levels of force effectiveness.

Introduction

A large majority of individuals with spinal cord injuries or lower limb disabilities are dependent upon the use of a manual wheelchair for both daily living and sporting activities. However, the gross efficiency (GE), this being the ratio of the external work done and the total energy expended, of hand-rim propulsion remains somewhat low. Reported GE values range anywhere from 2 to 11% for studies involving able-bodied individuals as well as inexperienced and experienced wheelchair users [13, 17, 30, 34]. In contrast, other forms of upper body locomotion, such as arm cranking [19] and hand-cycling [31] report much greater GE with values commonly ranging from 14 to 19%. The underlying reasons for this remain a topic of interest for research in both rehabilitation and sports environments.

Previous literature has reported GE to be highly influenced by propulsion conditions, such as hand-rim velocity and rolling resistance [30, 34, 37], wheelchair configuration including propulsion mechanism [35], seat height [33], wheel camber [20], wheel size [21] and differences in motor skills or expertise [10, 11, 17]. Propulsion technique in particular has been shown to be influenced by the push strategy employed; propulsion mode and/or push frequency [8, 17, 18, 38]. These latter studies have found lower arm frequencies to be associated with increased GE yet not always optimised at an individual's self-selected push frequency.

It has been suggested by clinical biomechanists that lower push frequencies are more beneficial than higher frequencies for the health of the musculoskeletal system [3]. The rationale behind this is that lower push frequencies allow for increased push time and a longer push stroke, reducing the number of pushes required per unit of time. Consequently the number of coupling and uncoupling actions of the hand to the hand-rim (as well as the idle recovery phases) is lower as will be the overall segmental (thus muscle) accelerations. There is debate in the literature whether larger forces and moments increase the probability of the risk of injury in wheelchair users [4, 22, 28]. Despite this it would be reasonable to suggest that although the magnitude of force required at lower push frequencies is greater, the rate of rise of these forces may be reduced as a result of the increase in push time. It has been reported that the rate of force development in wheelchair propulsion is related to the risk of injury [5]. Hence it appears to be beneficial for wheelchair users to: (a) reduce peak hand-rim forces and or push frequency; as well as (b) reduce the rate of rise of force during the push phase of the propulsion cycle to reduce the loading on the joints of the upper body (shoulder, elbow and wrist) involved during propulsion.

When considering the force exerted on the hand-rim it is best described in terms of the radial, axial and tangential components of the resultant (total) force. The radial and axial components create friction between the hand and the hand-rim simultaneously to ensure a tangential force component is applied to the hand-rim [29]. In guided movements, the forces that are applied by the hands do not directly influence the trajectory of the hands. The ratio of the tangential force and the resultant force at the hand-rim gives an indication to what is known in the literature as fraction of effective force (FEF) [30]. The theory of improved FEF from more tangentially directed forces has, however, been disputed [2, 9, 33]. Efficiency is reduced slightly as a consequence of a learned higher FEF [9]. The concept of FEF and its possible relationship with push frequency and efficiency remains interesting. When mean external work remains constant and push frequency is manipulated then reciprocal changes in the resultant and tangential forces would be anticipated. However, increased push frequencies, above the self-selected frequency, could lead to misdirected tangential forces to a larger extent hence we would report lower FEF at greater frequencies. It is unclear how the ratio of the tangential and resultant forces is affected by push frequency manipulation and whether or not there is an association with push frequency and/or GE.

To our knowledge there is very little literature that has investigated the hand-rim forces during wheelchair hand-rim propulsion under varying conditions of push frequency. Gaining an insight into this type of information should assist our understanding of the relationship of efficiency with push frequency and, extend what is already known in the area. Therefore, the purpose of this study was twofold; 1) describe the force application profiles of hand-rim propulsion at a range of push frequencies, 2) describe the relationship between force application and GE. We hypothesise that: 1) an increased push frequency reduces absolute force application parameters and FEF; 2) the rate of rise of force increases reciprocally with push frequency and 3) GE decreases with push frequencies that exceed the freely chosen frequency (FCF).

Material and Methods

Eight able-bodied male participants (22 ± 4 years) volunteered for this study and gave written informed consent prior to participation following a detailed explanation of all testing procedures. Body mass was recorded to the nearest 0.1 kg using a seated balance scale (Seca 710, Hamburg, Germany) and seated height in the wheelchair was measured to the nearest 0.01m using a portable height stadiometer. Participant physical characteristics are given in **Table 6.1**. 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 [12]. Participants had prior experimental experience in wheelchair exercise, but were not specifically trained in upper body sports activities or hand-rim wheelchair propulsion.

Table 6.1: Participant physical characteristics

Participant	Age (years)	Height (m)	Seated Height (m)	Body Mass (Kg)	Mean Power Output (W)	Total Resistance (N)
1	20	1.74	1.38	83.8	46.7	26.7
2	20	1.87	1.42	105.1	63.6	35.3
3	19	1.77	1.40	77.8	55.4	31.2
4	24	1.79	1.40	80.9	50.2	27.4
5	31	1.89	1.44	90.9	59.4	33.4
6	19	1.71	1.39	63.3	44.7	24.9
7	21	1.86	1.40	90.8	55.6	30.5
8	22	1.81	1.41	91.5	50.8	28.1
Mean	22	1.81	1.41	85.5	53.3	29.7
SD	4	0.06	0.02	12.3	6.4	3.5

Instrumentation

For the wheelchair trials, all participants were tested in the same 15° cambered hand-rim basketball wheelchair (Quattro, RGK, Burntwood, Staffordshire, England) which was a typical characteristic sports wheelchair used during the early stages of skill acquisition. The wheelchair was configured with a force sensing SMART^{Wheel} (Three Rivers Holdings, Mesa, AZ) to collect kinetic data. Wheels were fitted with the standard solid tyres provided by the SMART^{Wheel} manufacturer (wheel diameter of 0.592-m and hand-rim diameter of 0.534-m). The characteristics and properties of the SMART^{Wheel} are described elsewhere [6, 26]. The SMART^{Wheel} 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 SMART^{Wheel}, 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 SMART^{Wheel} and calculated from the torque applied to the wheel axis (Mz) and their angular velocity (ω) [23].

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

As the SMART^{Wheel} 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 ≤1 Nm) and the angular velocity of the wheel, time averaged from the onset of the first push to the completion of the final push (the end of the recovery phase).

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

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

Since the wheelchair propulsion was performed at a constant speed the propulsive work done and total resistance must be equal to the resistive work done therefore; it can be assumed that the mean total resistance must be equal to the mean propulsive force which can be calculated.

Testing procedure

The testing followed the same procedure as previously reported experiments [8, 17, 18, 38]. 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 $m \cdot s^{-1}$. The propulsion velocity employed was selected to ensure sub-maximal exercise for the able-bodied participants based on previous research work [17]. An audio-visual metronome was used to pace the push frequency requirements.

Participants completed a 5-minute warm-up prior to performing the sub-maximal push frequency conditions at a self-selected push frequency and propulsion velocity, which was guided with HR not exceeding 130 $beats \cdot min^{-1}$. Following an 8-minute rest period, a 1-minute 'habituation period' was performed to allow the participant to become accustomed with the push frequency to be employed during the following 4-minute test period. The FCF condition was the initial 4-minute exercise bout and the push frequency was counted and recorded each minute, then the mean frequency was calculated. Subsequent exercise bouts were performed at 60, 80, 120 and 140% of the FCF [17, 18]. An 8-minute recovery period separated each test condition to allow for HR to return close to their baseline and permit lactate diffusion. The order of the four manipulated exercise bouts was counter-balanced to ensure that each participant performed the conditions in a distinctly different order, thus possible effects of fatigue and/or learning were mitigated.

Kinetic measures

The forces and moments applied to the hand-rim were recorded for 30 seconds during the final minute of each exercise bout. These kinetic data were obtained via an infrared wireless transmitter at 240 Hz using the SMART^{Wheel} in the research mode setting. All kinetic data were filtered using the SMART^{Wheel} manufacturer's 32-tap finite impulse response (FIR) low pass digital filter with a cut-off frequency of 20Hz. This process allowed for filtered forces and moments applied for each push frequency to be determined.

For each push phase of the propulsion cycle, the SMART^{Wheel} provided the unilateral forces (F) and moments (M) in the three wheel-based reference planes, *Fx* – horizontally forward; *Fy* – vertically downward; *Fz* – horizontally inwards; and *Mz* - referred to the moment produced around the hub in the plane of the wheel [1, 6]. The beginning and end of the pushes were derived from the *Mz* and was identified from the absolute value of 1Nm. The push starts when *Mz* was >1 Nm and the end of the push was ≤1 Nm. The criteria for the push identification was written into a custom excel spread sheet used for processing and analysis of all Smart^{Wheel} data.

The resultant force (F_{RES}), which is the total force applied to the hand-rim, was calculated by vector addition of F_x, F_y and F_z:

$$F_{RES} = \sqrt{\left(F_x^{\ 2} + F_y^{\ 2} + F_z^{\ 2}\right)} \ \text{(N)} \qquad [6]$$

The tangential force (F_{TAN}) which is the force directed tangential to the hand-rim, was calculated from torque (M_z) and the hand-rim radius (R_r) and is defined as the ratio between the two values, according to:

$$F_{TAN} = M_z / R_r \ \text{(N)} \qquad [26]$$

The FEF on the hand-rims, by definition the ratio between the magnitude of the resultant force applied and the tangential component, was calculated for each instant in the measurement period and expressed as a percentage. This method was selected in preference to utilising the ratio between the peak F_{TAN} and Peak F_{RES} as these do not necessarily occur at the same instant.

$$FEF\ (\%) = (F_{TAN} / F_{RES}) \cdot 100\ (\%) \qquad [6]$$

The FEF was expressed as the time average FEF over the measurement period. The instantaneous FEFs for each measurement point were time averaged for all complete pushes of the 30 second data collection period.

In addition the rate of force development was calculated as the ratio between the changes in F_{RES} from the initial contact to the Peak F_{RES} and the changes in time between these two events [4]. All forces and moments were expressed as peak and mean values per push which were then averaged over the total number of pushes produced in the 30 second collection period.

Timing

The temporal parameters associated with propulsion were calculated from the kinetic data. Push times (PT) were defined as the amount of time that the hand exerted a positive torque around the wheel axis. Recovery times (RT) were defined as the period of time between the end of a push and the start of the next push. Consequently the cycle time (CT) is the summation of PT and RT. The push angles (PA) were also derived and defined as the relative angle over which the push occurs on the hand-rim.

Physiological measures

Throughout the test, 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 ($\dot{V}O_2$) and respiratory exchange ratio (RER) were calculated.

Efficiency

Gross mechanical efficiency was calculated as the ratio of the external work to energy expended during exercise. External work done (W) was determined from the power output (Po) values derived from the SMART^{Wheel} during the hand-rim wheelchair propulsion for all push frequencies. The metabolic energy expenditure (E) was obtained from the product of $\dot{V}O_2$) and the oxygen energetic equivalent derived from the RER and standard conversion tables [24]. The following equation was used to calculate GE in accordance with previous literature [32]:

$$GE = \frac{W}{E} \cdot 100 \ (\%)$$

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

Statistical analysis

The data were stored and 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 physiological and kinetic variables. Separate one-way within measures ANOVA were used to examine the effect of the freely chosen push frequency manipulation on kinematic and physiological variables. Bonferroni comparisons were used to identify significant pairwise differences. Relationships between force/timing variables and efficiency/push frequency were examined by Pearson's product moment correlations. A probability threshold of $P \leq 0.05$ was considered to be statistically significant.

Results

The eight able-bodied males physical characteristics are displayed in **Table 6.1**, with age 22 ± 4 years, height 1.81 ± 0.06 m, seated height 1.41 ± 0.02 m and body mass 85.5 ± 12.3 kg. The participants performed the five, 4 min exercise bouts with a mean total resistance of 29.7 ± 3.5 N (range 24.9 to 35.3 N; **Table 6.1**). The resistance of the wheelchair/roller ergometer system is greater than that of previous literature whereby rolling resistance is generally reported [16, 17, 18, 35]. Mean power output was 53.3 ± 6.4 W (range 46.7 to 63.6 W; **Table 6.1**) due to individual differences in rolling resistance of participants, however, across conditions (60 to 140% FCF) there was no significant difference in power output (52.6 to 54.1 W; **Table 6.2**). The mean FCF was 59 ± 8 pushes$\cdot$min^{-1} **(Table 6.2)**. The calculation of the metabolic energy expenditure (used in the calculation of GE) required RER to be ≤ 1.00. However, the maximum energy equivalent of 5.189 kcal (21.7kJ) was used when the RER for two of the participants 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 analysis revealed that removal of these data did not alter the statistical outcome.

The push frequency manipulation had a significant effect on the force application variables **(Table 6.2)**. Peak F_{RES} and peak F_{TAN} declined across the five push frequencies; Bonferroni adjusted pairwise comparisons between the push frequencies revealed that the values at 60% FCF were invariably higher than at all of the other frequencies with a more gradual decline from 80% to 140% FCF **(Table 6.2)**. The rate of decline was greatest between the lowest push frequencies of 60 to 80% FCF and 80 to 100% FCF (10.7% and 13.5%) in comparison to the higher push frequencies of 100 to 120% FCF and 120 to 140% FCF (4.8% and 7.1%). Mean FEF was only significantly different between the two extreme push frequencies of 60% and 140% FCF. Mean FEF was not related meaningfully to GE or push frequency **(Figure 6.1)**. As expected, work per cycle was affected by push frequency ($P < 0.05$) and decreased with higher push frequency ($r = -0.79$). Changes in push frequency altered the rate of force development ($P < 0.05$); rates at 120% and 140% FCF were significantly higher than at 60% and 100% **(Table 6.2)**.

As anticipated, push time, recovery time and the push angle all decreased with increasing push frequency ($P < 0.05$). Push frequency had a significant effect on GE whereby 60%, 120% and 140% FCF were all lower than the FCF (100%; **Figure 6.2**). As the small difference in GE of 0.1% between 80% and 100% FCF was not significant ($P = 1.00$), it is not possible to conclude that FCF was the most favourable push frequency in our study. The relationship between push frequency and GE appears to be curvilinear with a plateau in GE over the 80% and 100% FCF conditions **(Figure 6.2)**.

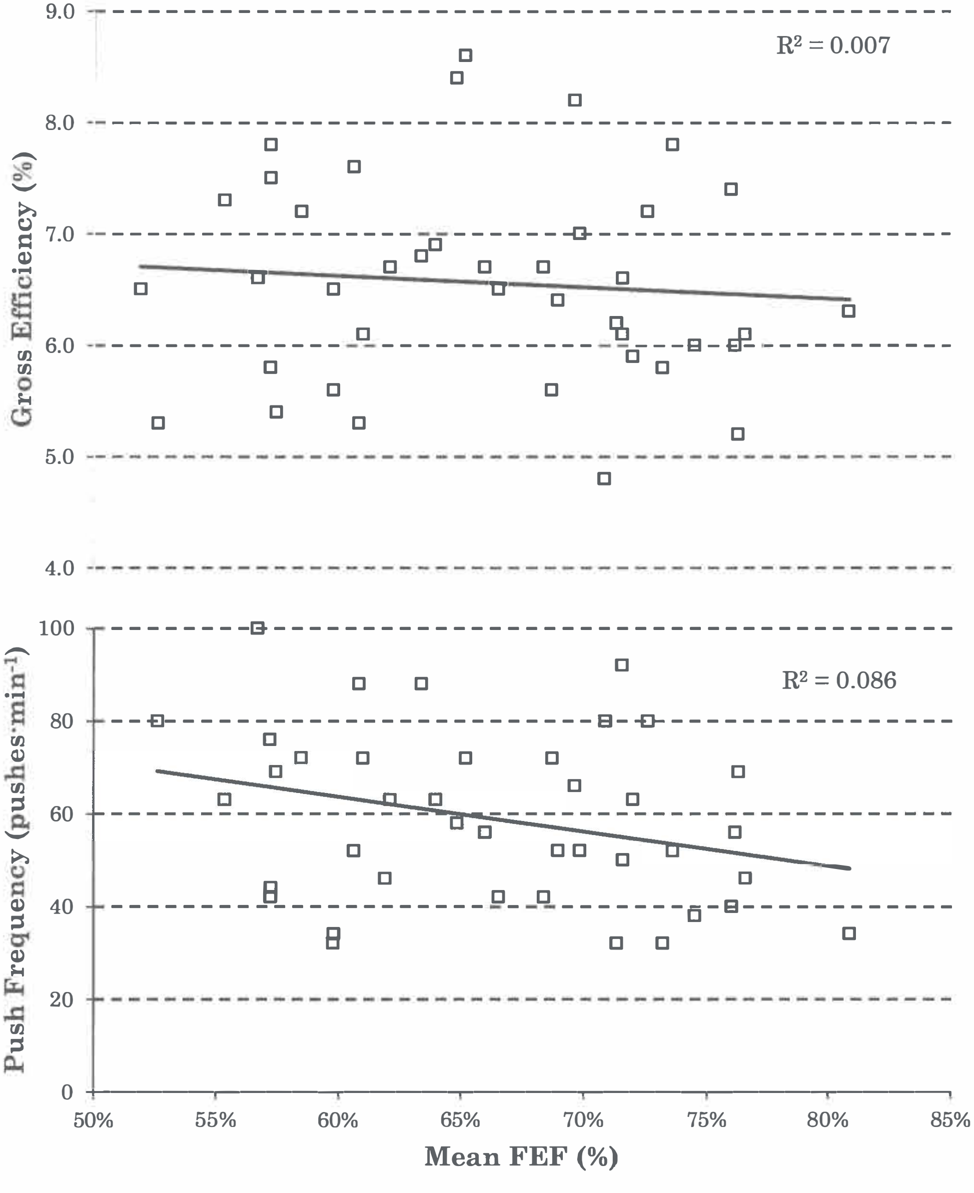


Figure 6.1: Relationship between Mean FEF and both gross efficiency and push frequency. R^2 derived from Pearson Product Moment Correlation.

Table 6.2: Effect of freely chosen push frequency manipulation on kinetic variables

Kinetic Variables	% Freely Chosen Frequency (FCF)				
	60% (a)	80% (b)	100% (c)	120% (d)	140% (e)
Power Output (W)	52.6 (5.9)	52.9 (6.6)	54.1 (5.8)	53.7 (7.6)	53.3 (6.7)
Push Frequency (pushes·min^{-1}) *	36 (4)^{b,c,d,e}	48 (6)^{a,c,d,e}	59 (8)^{a,b,d,e}	71 (9)^{a,b,c,e}	83 (11)^{a,b,c,d}
Work per cycle (J) *	83.6 (14.3)^{b,c,d,e}	65.5 (10.9)^{a,c,d,e}	55.1 (8.9)^{a,b,d,e}	45.0 (9.1)^{a,b,c}	39.8 (8.0)^{a,b,c}
Peak F_{RES} (N) *	168 (31)^{b,c,d,e}	150 (33)^{a,d,e}	133 (21)^{a}	124 (25)^{a,b}	118 (23)^{a,b}
Mean F_{RES} (N) *	100 (22)^{b,c,d,e}	91 (23)^{a}	80 (12)^{a}	79 (15)^{a}	75 (15)^{a}
Peak F_{TAN} (N) *	117 (20)^{b,c,d,e}	104 (21)^{a,d,e}	90 (12)^{a}	84 (16)^{a,b}	78 (15)^{a,b}
Mean F_{TAN} (N) *	70 (16)^{b,c,d,e}	61 (14)^{a}	55 (8)^{a}	52 (10)^{a}	48 (8)^{a}
Mean FEF (%)*	69 (9)^{e}	66 (8)	68 (5)	65 (8)	63 (7)^{a}
Rate Force Development (N·s^{-1}) *	602 (207)^{d,e}	684 (278)	669 (181)^{d,e}	841 (223)^{a,c}	928 (249)^{a,c}
Push time (s) *	0.38 (0.04)^{b,c,d,e}	0.34 (0.05)^{a,d,e}	0.31 (0.03)^{a,d,e}	0.27 (0.03)^{a,b,c}	0.27 (0.03)^{a,b,c}
Recovery time (s) *	1.21 (0.19)^{b,c,d,e}	0.90 (0.15)^{a,c,d,e}	0.70 (0.12)^{a,b,d,e}	0.56 (0.10)^{a,b,c,e}	0.48 (0.09)^{a,b,c,d}
Push Angle (°) *	134.7 (11.5)^{b,c,d,e}	120.3 (13.2)^{a,d,e}	110.2 (10.6)^{a,d,e}	96.3 (10.3)^{a,b,c}	92.6 (11.7)^{a,b,c}

All values are mean ±SD. * Main Effect of ANOVA. Letters in parentheses after the FCF percentages can be used to identify Bonferroni adjusted pairwise differences in the table. e.g., ^{a} means the value is different from the 60% FCF condition, whereas ^{b} is different from the 80% FCF condition and so on. All differences are $P<0.05$

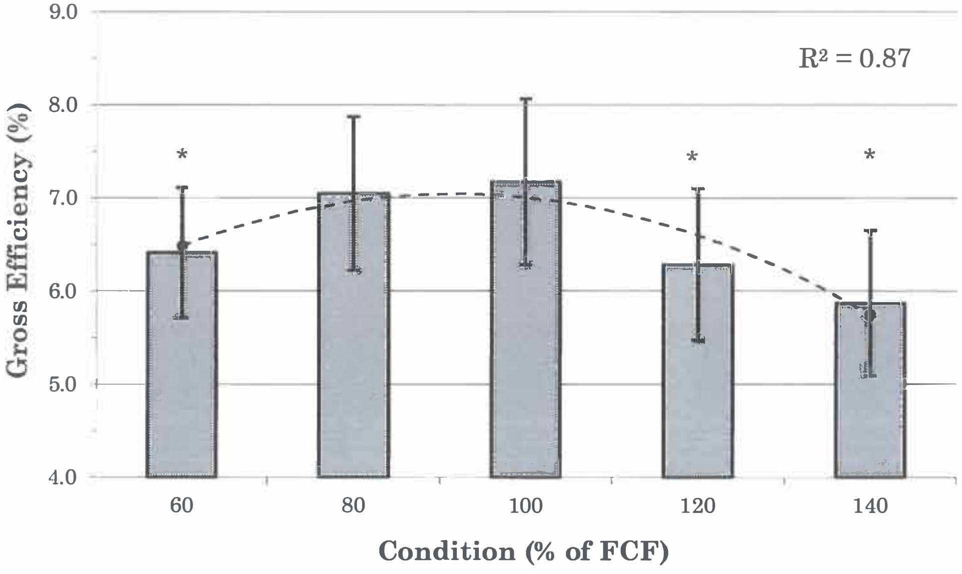


Figure 6.2: Gross efficiency values (mean ± SD) for hand-rim propulsion across range of arm frequencies in the eight able-bodied participants. * Significant difference between 100% FCF ($P \leq 0.05$). R^2 derived from Pearson Product Moment Correlation.

Discussion

With a dearth of literature, this study describes the effects of forces applied to the hand-rim during manual wheelchair propulsion whilst specifically manipulating push frequency. This provides an important insight into the association of force application and push frequency, albeit under the experimental conditions imposed. The findings support the first hypothesis that increased push frequency results in the reduction of absolute force for both F_{RES} and F_{TAN}. However, this was not the case with the FEF. The rate of force development increased significantly with increased push frequency supporting the hypothesis of a reciprocal increase with increasing push frequency. The GE showed a curvilinear trend with increased push frequency and supported the hypothesis whereby GE decreases with push frequencies exceeding FCF. There was no association of GE or push frequency with FEF or any of the force parameters. For this reason the effectiveness of force application does not relate to the GE changes observed with changes in push frequency.

Force application

The suggestion that an ineffective force production (low FEF), could in part be responsible for lower GE of propulsion [8, 34] is not supported in this study. Our findings support more recent work that FEF does not correlate to the GE [2, 9, 10, 15]. As de Groot and colleagues [9] have demonstrated, efficiency was lower with a forcefully induced higher FEF compared to a lower FEF. The use of FEF as an indicator of efficient propulsion cannot be supported with the current findings whereby push frequency was manipulated. It is clear that the most effective propulsion technique from a kinetic / dynamic viewpoint (FEF) is not necessarily the most efficient one. Bregman et al. [2] observed that the force direction during propulsion is a compromise between efficiency and the constraints imposed by the wheelchair-user system. They implied that training should not be aimed at the optimisation of the propulsion force because this may be less efficient and more straining for the musculoskeletal system. Similarly in a recent study on seat height [33] it was reported that simply improving mechanical efficiency through seat height changes does not necessarily optimise the force application characteristics and FEF.

Fraction of effective force across the push frequencies was not reflective of the efficiency. The extreme ends of the push frequency scale (60% & 140% FCF) produced a significant difference in FEF without significant changes in GE. The values of Mean FEF ranged from 63 ± 7% at 140% FCF to 69 ± 9% at 60% FCF. These values of FEF are comparable with those found in the literature for hand-rim propulsion in both able-bodied and spinal cord injured participants [2, 7, 33], but slightly lower than the values found by Kotajarvi et al. [15] albeit under different testing conditions. This relatively small and insignificant change in FEF across push frequency may be the direct result of the fact that hand-rim propulsion is a guided movement. Increasing push frequency resulted in lower resultant forces being applied to the hand-rim during propulsion. Interestingly the reductions in peak resultant force were only significant when comparing the 100%, 120% and 140% FCF conditions to the 60% and 80% FCF conditions. This finding was despite the significant changes in push angle and push time throughout the frequency conditions, therefore investigating the rate of force development would appear to be important to help explain the relationship of force with push frequency. As push frequency is manipulated, participants can be seen to adopt a consistent and stable model to satisfy the movement requirements under the given task boundaries of each condition [27]. In each of the different push frequency conditions, the general geometric orientation and co-ordination of the overall upper body remains constant and the arms adapt to the altered frequency by regulating the force magnitude but not its overall effectiveness, i.e. ratio of component forces. The present study indicates that the rate of force development is significantly increased at the higher frequencies. Boninger and colleagues [3, 4] associated increases in cadence, force magnitude and rate of force development with an increased risk of injury. In the context of push frequency it is important to know how this rate of force development is affected and its associated risks. Reduction in push frequency results in a decreased rate of force development although the consequence of that are increased peak forces during each push. On the other hand, higher push frequencies demonstrate smaller peak forces but subsequently higher rates of force development more frequently. Therefore, the question remains as to which is better for hand-rim wheelchair propulsion, as results show that the physiological efficiency is not linked to the effectiveness of force application.

Push frequency manipulation results in changes to the cyclical timing and the push angles, indicating a reduced push angle with higher push frequencies. Both of these variables are assumed to be responsible for the changes seen in the resultant force applied because of the requirement to maintain the same external workload and thus the production of more or less work per push with a lower or higher push frequency **(Table 6.2)**. Hence, at lower arm frequencies there are higher resultant forces and as push frequency increases the resultant force decreases, however, this resultant force is not significantly reduced statistically within the arm frequency range of 100% to 140% FCF, although there is a trend for this to continue to decrease and could be clinically significant. The results for peak resultant force and push angle appear to be supported by similar findings in a population of wheelchair users, albeit using a different methodological approach [25]. Richter and colleagues report a self-selected mean cadence of 52 pushes$\cdot$min^{-1} along with a decreased cadence (-10%) which are comparable to the push frequencies of the current FCF and 80% FCF conditions. Importantly they revealed the associated changes in peak resultant force and push angle were of a similar magnitude, although the absolute peak resultant force was much lower [25]. Interestingly this study reports the same relationship and changes in the tangential force; as a result FEF is not affected significantly. Bregman et al. [2] suggested that propulsion technique is mainly determined by the geometrical boundaries of the musculoskeletal system. In that context FEF is suggested to be an invariant characteristic of the biological system, that only changes with extreme geometric changes (i.e. seat height) or with continued learning and training where detailed fine tuning is critical and will lead to (ultra) small long term shifts in FEF. Results of previous studies indeed provide evidence for these notions [2, 9, 10, 15]. Our data support the notion that adaptation to frequency involves a regulation of the force magnitude and movement velocity but does not involve a fundamental shift in co-ordination strategy in this cyclic movement.

Gross efficiency

The present study supports the findings of previous research into the effects of push frequency on GE [8, 17, 18, 38], whereby it has been shown that higher push frequencies (>100% FCF) reduce the GE of propulsion significantly. Unlike previous findings by Lenton et al. [17, 18] the 60% FCF conditions GE was significantly lower, however, it was not possible to identify any significant difference between the 80% and 100% FCF conditions. It is apparent that changes in GE with changes in push frequency are not a direct result of an altered FEF. It seems to be that they must be associated with the different magnitude and frequency of de- / accelerations of the arm segments and trunk, as well as the different ranges in segment excursion and thus muscle contraction velocities, ranges and tension. Different push frequencies result in changes in push angle, thus in the range of motion of the muscles, changes in the force-length/velocity and length tension of the contracting muscles, thus influencing the energy required for the contraction and production of work done against the hand-rim. The increased number of recovery phases, couplings and un-couplings (and the associated small negative braking force increases) increases energy expenditure, elicited from the increased work to move the arms. The role that movement of the trunk and head segment plays during propulsion could offer additional explanation as differences caused by push frequency manipulations may well affect energy cost of the movements. Results of the current study suggest that in the current experimental set-up, push frequencies in untrained subjects at or below FCF are close to optimal energy cost.

Experimental considerations

Able-bodied participants, with limited wheelchair experience, provided a relatively homogenous participant group, not highly trained in any of the push frequencies. Importantly they would be able to perform the exercise conditions sub-maximally, despite the larger power output requirements as a result of the SMART^{Wheel} use (smaller wheel and increased rolling resistance with solid tyres). Able-bodied participants were used to negate the influence of disability and the probable effects of limited arm or trunk function along with possible effects of habituation and training at given arm frequencies. Use of a standardised basketball wheelchair configuration eliminated any effects of different chair designs/setups, however, it is accepted that this would have an effect on the relative geometry of the chair/user interface for individuals, influencing the physiological demands, force production and propulsion mechanics to that in a conventional daily wheelchair. Nevertheless it is felt that the trends and relationships of the data would not alter significantly. Another consideration was the use of a stationary wheelchair ergometer consisting of a single roller and fixed chain. This was an important feature of the study allowing for the effects of force application in relation to arm frequency manipulation to be investigated without the additional effects of coasting direction (of the wheelchair), and thus the external work requirements. Importantly, the power output across the arm frequencies is equal within each participant. The resistance of the wheelchair/roller ergometer system is greater than previous published literature. The increased resistance could be attributed to a number of factors: Firstly the camber of 15^{o} is significantly greater in the standardised basketball wheelchair than in propulsion studies using everyday wheelchairs. Secondly there is the use of the standard solid tyres provided by the SMART^{Wheel} manufacturer, which have a considerable higher rolling resistance than pneumatic tyres [14, 16]. The third factor is the difference in roller ergometers whereby this study used a single roller ergometer with a much smaller roller circumference than that of the split roller ergometer with significantly greater roller circumference, hence greater resistance. 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, for example; reduced rolling resistance and in different populations of wheelchair users.

Conclusions

In conclusion, increased push frequency generally resulted in a reduction in the absolute values of the force parameters measured and consequently reduced push angle and decreased work/cycle. The exception to this was the rate of force development which increased and FEF remained somewhat unchanged. The FEF and force parameters studied did not reflect the trend in GE of propulsion at different push frequencies, thus supporting current views on FEF suggesting that FEF is invariant under the current testing conditions. Push frequency merely affects the force components in such a way that the ratio of the tangential force to the resultant force remains somewhat proportional to one another despite changes in push angle and push time. Despite the GE of propulsion not being able to be linked directly with FEF it is important to acknowledge the important relationship of force application with push frequency. Results of the current study support previous findings that push frequencies in untrained participants at or below FCF are close to optimal energy cost and efficiency. The practical implications of these results are very important for wheelchair users, coaches or rehabilitation practitioners because it demonstrates the effects that changes in push frequency have on the push forces. Understanding the force changes that occur with changing frequency can support wheelchair users in their choice of push frequency to adopt during daily activities and or sports. Coaches and rehabilitation practitioners may well pay particular attention to the magnitude of the forces and rate of force development for prescription purposes when working with a wheelchair user with respect to the physical capacity of an individual.

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

1 Asato KT, Cooper RA, Robertson RN, Ster, JF. SMART^{Wheel}: development and testing of a system for measuring manual wheelchair propulsion dynamics. IEEE Trans Biomed Eng 1993; 40: 1320-1324.

2 Bregman DJJ, van Drongelen S, Veeger HEJ. Is effective force application in handrim wheelchair propulsion also efficient? Clin Biomech 2009; 24: 13-19.

3 Boninger ML, Baldwin M, Cooper RA, Koontz A, Chan L. Manual wheelchair pushrim biomechanics and axle position. Arch Phys Med Rehab 2000; 81: 608-613.

4 Boninger ML, Cooper RA, Baldwin MA, Shimada SD, Koontz A. Wheelchair pushrim kinetics: body weight and median nerve function. Arch Phys Med Rehab 1999; 80: 910-915.

5 Boninger ML, Souza AL, Cooper RA, Fitzgerald SG, Koontz AM, Fay BT. Propulsion patterns and pushrim biomechanics in manual wheelchair propulsion. Am J Phys Med Rehab 2002; 76: 420-426.

6 Cooper RA, Robertson RN, van Sickle DP, Boninger ML. Methods for determining three-dimensional wheelchair pushrim forces and moments: a technical note. J Rehab Res Dev 1997; 34: 162-170.

7 Dallmeijer AJ, van der Woude LHV, Veeger HEJ, Hollander AP. Effectiveness of force application in manual wheelchair propulsion in persons with spinal cord injuries. Am J Phys Med Rehab 1998; 77: 213-221.

8 Goosey VL, Campbell IG, Fowler NE. Effect of push frequency on the economy of wheelchair racers. Med Sci Sports Exerc 2000; 32: 174-181.

9 de Groot S, Veeger HEJ, Hollander AP, van der Woude LHV. Consequence of feedback-based learning of an effective hand rim wheelchair force production on mechanical efficiency. Clin Biomech 2002a; 17: 219-226.

10 de Groot S, Veeger HEJ, Hollander AP, van der Woude LHV. Wheelchair propulsion technique and mechanical efficiency after 3 wk of practice. Med Sci Sports Exerc 2002b; 34: 756-766.

11 de Groot S, Veeger HEJ, Hollander AP, van der Woude LHV. Effect of wheelchair stroke pattern on mechanical efficiency. Am J Phys Med Rehab 2004; 83: 640-649.

12 Harriss DJ, Atkinson G. International Journal of Sports Medicine – Ethical Standards in Sport and Exercise Science Research. Int J Sports Med 2009; 30: 701 – 702.

13 Hintzy F, Tordi N. Mechanical efficiency during hand-rim wheelchair propulsion: effects of base-line subtraction and power output. Clin Biomech 2004; 19: 343–349.

14 Kauzlarich JJ, van der Woude LHV, Hopman MTE, van Kemenade CH (eds). Biomedical aspects of manual wheelchair propulsion: The state of the Art II, IOS Press, Amsterdam: Washington DC, 1999: 158-170.

15 Kotajarvi, BR, Basford JR, An KN, Morrow DA, Kaufman KR. The effect of visual biofeedback on the propulsion effectiveness of experienced wheelchair users. Arch Phys Med Rehab 2006; 87: 510-515.

16 Kwarciak AM, Yarossi M, Ramanujan A, Dyson-Hidson TA, Sisto SA. Evaluation of wheelchair tire rolling resistance using dynamometer-based coast down tests. J Rehab Res Dev 2009; 46(7): 931-938.

17 Lenton JP, Fowler NE, van der Woude LHV, Goosey-Tolfrey VL. Wheelchair propulsion: effects of experience and push strategy on efficiency and perceived exertion. Appl Physiol Nutr Metab 2008; 33: 870-879.

18 Lenton JP, van der Woude LHV, Fowler NE, Goosey-Tolfrey VL. Effects of arm frequency during synchronous and asynchronous wheelchair propulsion on efficiency. Int J Sports Med 2009; 30: 233-239.

19 Marais G, Dupont L, Maillet M, Weisslans T, Vanvelcenaher J, Pelayo P. Cardiorespiratory and efficiency responses during arm and leg exercises with spontaneously chosen crank and pedal rates. Ergonomics 2002; 45: 631-639.

20 Mason B, van der Woude LHV, de Groot S, Goosey-Tolfrey VL. The effects of camber on the ergonomics of propulsion in wheelchair athletes. Med Sci Sports Exerc 2011; 43: 319-26.

21 Mason B, van der Woude LHV, Lenton JP, Goosey-Tolfrey VL. Effects of wheel and hand-rim diameter on sub-maximal wheeling performance in elite wheelchair athletes. Med Sci Sports Exerc 2011; Jun 22: [Epub ahead of print]. PMID: 21701409.

22 Mercer JL, Boninger M, Koontz A, Ren D, Dyson-Hudson T, Cooper R. Shoulder joint kinetics and pathology in manual wheelchair users. Clin Biomech 2006; 21: 781-789.

23 Niesing R, Eijskoot F, Kranse R, den Ouden AH, Storm J, Veeger HJ, van der Woude LHV, Snijders CJ. Computer-controlled wheelchair ergometer. Med Biol Eng Comput 1990; 28: 23-29.

24 Peronnet F, Massicotte D. Table of non-protein respiratory quotient: an update. Can J Sport Sci 1991; 16: 23-29.

25 Richter WM, Kwarciak AM, Guo L, Turner JT. Effects of single-variable biofeedback on wheelchair handrim biomechanics. Arch Phys Med Rehabil 2011; 92: 572-577.

26 Robertson RN, Boninger ML, Cooper RA, Shimada SD. Pushrim forces and joint kinetics during wheelchair propulsion. Arch Phys Med Rehab 1996; 77: 856-864.

27 Rozendaal LA, Veeger HEJ, van der Woude LHV. The push force pattern in manual wheelchair propulsion as a balance between cost and effect. J Biomech 2000; 36: 239-247.

28 Subbarao JV, Klopfstein J, Turpin R. Prevalence and impact of wrist and shoulder pain in patients with spinal cord injury. J Spinal Cord Med 1995; 18: 9-13.

29 Vanlandewijck Y, Theisen D, Daly D. Wheelchair propulsion biomechanics: implications for wheelchair sports. Sports Med 2001; 31: 339-367.

30 Veeger HEJ, van der Woude LHV, Rozendal RH. Effect of hand-rim velocity on mechanical efficiency in wheelchair propulsion. Med Sci Sports Exerc 1992; 24: 100-107.

31 Verellen J, Theisen D, Vanlandewijck Y. Influence of crank rate in hand cycling. Med Sci Sports Exerc 2004; 36: 1826-1831.

32 Whipp BJ, Wasserman K. Efficiency of muscular work. J Appl Physiol 1969; 26: 644-648.

33 van der Woude LH, Bouw A, van Wegen J, van As H, Veeger D, de Groot S. Seat height: effects on submaximal hand rim wheelchair performance during spinal cord injury rehabilitation. J Rehab Med 2009; 41: 143-149.

34 van der Woude LHV, van der Hendrich KMM, Veeger HEJ, van Ingen Schenau GJ, Rozendal RH, de Groot G, Hollander AP. Manual wheelchair propulsion: effects of power output on physiology and technique. Med Sci Sports Exerc 1988a; 20: 70-78.

35 van der Woude LH, van Kranen E, Ariëns G, Rozendal RH, Veeger HE. Physical strain and mechanical efficiency in hubcrank and handrim wheelchair propulsion. J Med Eng Tech 1995; 19: 123-131.

36 van der Woude LHV, Veeger HEJ, Dallmeijer AJ, Janssen TWJ, Rozendal LA. Biomechanics and physiology in active manual wheelchair propulsion. Med Eng Phys 2001; 23: 713-733

37 van der Woude LH, Veeger HE, Rozendal RH, van Ingen Schenau GJ, Rooth F, van Nierop P. Wheelchair racing: effects of rim diameter and speed on physiology and technique. Med Sci Sports Exerc 1988b; 20: 492-500.

38 van der Woude LHV, Veeger HEJ, Rozendal RH, Sargeant AJ. Optimum cycle frequencies in hand-rim wheelchair propulsion. Wheelchair propulsion technique. Eur J Appl Physiol Occup Physiol 1989; 58: 625-632.

Chapter 7

Hand-rim forces and gross mechanical efficiency in asynchronous and synchronous wheelchair propulsion: a comparison

John P. Lenton[1,3]
Lucas HV. Van der Woude[2]
Neil E. Fowler[3]
Graham Nicholson[4]
Keith Tolfrey[1]
Victoria L. Goosey-Tolfrey[1,3]

Submitted

[1]Peter Harrison Centre for Disability Sport, School of Sport, Exercise & Health Sciences, Loughborough University, UK.

[2]Center for Human Movement Sciences, University Medical Center Groningen, University of Groningen, the Netherlands.

[3]Department of Exercise & Sport Science, the Manchester Metropolitan University, UK.

[4]ASPIRE Centre for Disability Sciences, Institute of Orthopaedics and Musculoskeletal Science, University College London, UK.

Abstract

To describe and compare the force application characteristics of asynchronous (ASY) hand-rim propulsion under different frequency conditions to that of synchronous (SYN) hand-rim propulsion in able-bodied participants. Eight able-bodied participants performed two-sub-maximal exercise tests using both propulsion modes on a wheelchair roller ergometer. Each test consisted of a series of five, 4-minute exercise blocks at 1.8 $m \cdot s^{-1}$; 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 significantly higher force measures ($P \leq 0.05$) and FEF ($P = 0.016$) compared to SYN push frequencies, although no significant effect on GE. This trend continues with pair-matched push frequencies (ASY_{80}:SYN_{60}, ASY_{100}:SYN_{80}, ASY_{120}:SYN_{100} and ASY_{140}:SYN_{120}) as ASY propulsion resulted in significantly higher F_{RES} and F_{TAN} values, as well as higher rates of force development ($P \leq 0.05$), whilst no significant differences in GE values. The ASY propulsion mode followed the same trend with respect to push frequency as the SYN mode, with changes in push frequency accompanied by changes in absolute force values. Changes in absolute force were achieved without alteration in either the gross pattern of force application or FEF or GE for both ASY and SYN propulsion. Matched push frequencies demonstrated significant differences in force parameters and non-significant differences in GE, highlighting the effect of propulsion mode. ASY propulsion offers no kinetic or physiological advantage during hand-rim wheelchair propulsion 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]. Whilst 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, bicycling, and rowing) and may take advantage of inherent neural pathways for the reciprocal stimulation of the contra-lateral 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 requires 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 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 [9].

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 movement pattern [1, 8, 31], whereas in arm-cranking it is the ASY movement pattern [12, 22). 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 two 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), the ratio between the magnitude of the tangentially directed force and the total force applied to the handrim [29]. The hypothesis that increasing FEF would improve efficiency has however, been disputed [6, 13, 32]. Previous research comparing propulsion modes has predominantly focussed on manipulating the freely chosen frequency when investigating push frequency [11, 19-21, 34]. With the exception of one research study by Lenton and colleagues [18] there has never been any emphasis placed upon matching the push frequencies (total number of left and right arm movements) in ASY and SYN propulsion. 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 the relationship between force application and GE for ASY and 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 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 modes.

Material and Methods

Eight able-bodied male participants (22 ± 4 years) volunteered for this study and gave written informed consent prior to participation following a detailed explanation of all testing procedures. Body mass was recorded to the nearest 0.1 kg using a seated balance scale (Seca 710, Hamburg, Germany) and seated height in the wheelchair was measured to the nearest 0.01m using a portable height stadiometer. Participant physical characteristics are given in **Table 7.1**. Approval for the study procedures was obtained from the University Research Ethics Committee. Participants had prior experimental experience in wheelchair exercise, but were not specifically trained in upper body sports activities or hand-rim wheelchair propulsion.

Table 7.1: Participant physical characteristics

Participant	Age (years)	Height (m)	Seated Height (m)	Body Mass (Kg)	Mean Power Output (W)	Total Resistance (N)
Mean	22	1.81	1.41	85.5	53.3	29.7
SD	4	0.06	0.02	12.3	6.4	3.5

Instrumentation

For the wheelchair trials, all participants were tested in the same 15° cambered hand-rim basketball wheelchair (Quattro, RGK, Burntwood, Staffordshire, England) which was a typical characteristic of a sports wheelchair used during the early stages of skill acquisition. The wheelchair was configured with a force sensing SMART^{Wheel} (Three Rivers Holdings, Mesa, AZ) to collect kinetic data. Wheels were fitted with the standard solid tyres provided by the SMART^{Wheel} manufacturer (wheel diameter of 0.592-m and hand-rim diameter of 0.534-m). The characteristics and properties of the SMART^{Wheel} are described elsewhere [7, 26]. The SMART^{Wheel} 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 SMART^{Wheel}, 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 SMART^{Wheel} and calculated from the torque applied to the wheel axis (Mz) and their angular velocity (ω) [23].

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

As the SMART^{Wheel} 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 (the end of the recovery phase).

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

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

Since the wheelchair propulsion was performed at a constant speed the propulsive work done and total resistance must be equal to the resistive work done therefore; it can be assumed that the mean total resistance must be equal to the mean propulsive force which can be calculated.

Testing procedure

The testing followed the same procedure as previously reported experiments [11, 19, 20, 34]. 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% & 140% of FCF) at 1.8 $m \cdot s^{-1}$. The propulsion velocity employed was selected to ensure sub-maximal exercise for the able-bodied participants based on previous research work [19-21]. An audio-visual metronome was used to pace the push frequency requirements.

Participants completed a 5-minute warm-up prior to performing the sub-maximal push frequency conditions at a self-selected push frequency and propulsion velocity, which was guided with HR not exceeding 130 $beats \cdot min^{-1}$. Following an 8-minute rest period, a 1-minute 'habituation period' was performed to allow the participant to become accustomed with the push frequency to be employed during the following 4-minute test period. The FCF condition was the initial 4-minute exercise bout and the push frequency was counted and recorded each minute, then the mean frequency was calculated. Subsequent exercise bouts were performed at 60, 80, 120 and 140% of the FCF [19-21]. An 8-minute recovery period separated each test condition to allow for

HR to return close to their baseline and permit lactate diffusion. The order of the four manipulated exercise bouts was counter-balanced to ensure that each participant performed the conditions in a distinctly different order, thus possible effects of fatigue and/or learning were mitigated.

Kinetic measures

The forces and moments applied to the hand-rim were recorded for 30 seconds during the final minute of each exercise bout. These kinetic data were obtained via an infrared wireless transmitter at 240 Hz using the SMART^{Wheel} in the research mode setting. All kinetic data were filtered using the SMART^{Wheel} manufacturer's 32-tap finite impulse response (FIR) low pass digital filter with a cut-off frequency of 20Hz. This process allowed for filtered forces and moments applied for each push frequency to be determined.

For each push phase of the propulsion cycle, the SMART^{Wheel} provided the unilateral forces (F) and moments (M) in the three wheel-based reference planes, *Fx* – horizontally forward; *Fy* – vertically downward; *Fz* – horizontally inwards; and *Mz* - referred to the moment produced around the hub in the plane of the wheel [2, 7]. The beginning and end of the pushes were derived from the *Mz* and was identified from the absolute value of 1Nm. The push starts when *Mz* was >1 Nm and the end of the push was ≤1 Nm. The criteria for the push identification was written into a custom excel spread sheet used for processing and analysis of all Smart^{Wheel} data.

The resultant force (F_{RES}), which is the total force applied to the hand-rim, was calculated by vector addition of F_x, F_y and F_z:

$$F_{RES} = \sqrt{\left(F_x{}^2 + F_y{}^2 + F_z{}^2\right)} \text{ (N)} \qquad [7]$$

The tangential force (F_{TAN}) which is the force directed tangential to the hand-rim, was calculated from torque (M_z) and the hand-rim radius (R_r) and is defined as the ratio between the two values, according to:

$$F_{TAN} = M_z / R_r \text{ (N)} \qquad [26]$$

The FEF on the hand-rims, by definition the ratio between the magnitude of the resultant force applied and the tangential component, was calculated for each instant in the measurement period and expressed as a percentage. This method was selected in preference to utilising the ratio between the peak F_{TAN} and Peak F_{RES} as these do not necessarily occur at the same instant.

$$FEF\ (\%) = (F_{TAN} / F_{RES}) \cdot 100\ (\%) \qquad [7]$$

The FEF was expressed as the time average FEF over the measurement period. The instantaneous FEFs for each measurement point were time averaged for all complete pushes of the 30 second data collection period.

In addition the rate of force development was calculated as the ratio between the changes in F_{RES} from the initial contact to the Peak F_{RES} and the changes in time between these two events [4]. All forces and moments were expressed as peak and mean values per push which were then averaged over the total number of pushes produced in the 30 second collection period.

Timing

The temporal parameters associated with propulsion were calculated from the kinetic data. Push times (PT) were defined as the amount of time that the hand exerted a positive torque around the wheel axis. Recovery times (RT) were defined as the period of time between the end of a push and the start of the next push. Consequently the cycle time (CT) is the summation of PT and RT. The push angles (PA) were also derived and defined as the relative angle over which the push occurs on the hand-rim.

Physiological measures

Throughout the test, 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 ($\dot{V}O_2$) and respiratory exchange ratio (RER) were calculated.

Efficiency

Gross mechanical efficiency was calculated as the ratio of the external work to energy expended during exercise. External work done (W) was determined from the power output (Po) values derived from the SMART^{Wheel} during the hand-rim wheelchair propulsion for all push frequencies. The metabolic energy expenditure (E) was obtained from the product of $\dot{V}O_2$ and the oxygen energetic equivalent derived from the RER and standard conversion tables [24]. The following equation was used to calculate GE in accordance with previous literature [30]:

$$GE = \frac{W}{E} \cdot 100 \ (\%)$$

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

Statistical analysis

The data were stored and 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 physiological and kinetic variables. For analysis unmatched push frequencies are ASY_{60}:SYN_{60}, ASY_{80}:SYN_{80}, ASY_{100}:SYN_{100}, ASY_{120}:SYN_{120}, ASY_{140}:SYN_{140} and matched push frequencies obtained from matching the absolute push frequencies in the propulsion modes are ASY_{80}:SYN_{60}, ASY_{100}:SYN_{80}, ASY_{120}:SYN_{100}, ASY_{140}:SYN_{120}.

Separate one-way within measures ANOVA were used to examine the effect of the freely chosen push frequency manipulation on kinematic and physiological variables for both ASY and SYN propulsion. Subsequently separate one-way within 2-factor repeated measures ANOVA was used to compare the unmatched and matched push frequency conditions of ASY and

SYN propulsion modes. Bonferroni comparisons were used to identify significant pairwise differences. A probability threshold of $P \leq 0.05$ was considered to be statistically significant.

Results

At the propulsion velocity of 1.8m$\cdot$s^{-1}, the mean power output during ASY propulsion was 53.9 ± 5.9. W (range 43.5 to 61.6 W) and rolling resistance on average was 30.2 ± 3.4 N. Similarly, the SYN propulsion power output was 53.3 ± 6.4 W (range 44.7 to 63.6 W) and rolling resistance was 29.7 ± 3.5 N, were slightly lower but not significantly different. Participants performed all exercise bouts sub-maximally (RER below 1.00), with the exception of two participants during the SYN 140% FCF exercise condition producing an RER of 1.01 and 1.02 respectively. In this instance, the effect on the GE calculations was deemed to be negligible and separate analysis revealed that removal of these data did not alter the 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 **Figure 7.1 (A-F)**, GE, work per cycle, push frequency and kinematic parameters are shown in **Figure 7.2 (A-F)**. Propulsion modes demonstrate the same trends with respect to push frequency for F_{RES}, F_{TAN} (both peak and mean values), FEF and rate of force development, whereas there is no significant interaction of push frequency and propulsion mode. There is a significant effect for propulsion mode whereby all the measured force variables were significantly higher in ASY than SYN propulsion. The trend in FEF for both ASY and SYN propulsion was for it to decrease with increasing push frequency (74.2 – 71.1%, 69.1 – 62.6%; respectively) with the ASY propulsion FEF consistently higher **(Figure 7.1E)**. The mean FEF for ASY propulsion (72.9 ± 5.2%) was significantly higher than in the SYN mode (66.3 ± 7.2%), $P = 0.016$. The work per cycle was significantly affected by push frequency ($P=0.001$), demonstrating a linear relationship in both propulsion modes. However, ASY values were significantly greater than SYN values ($P = 0.044$) resulting in increased work done per propulsion cycle throughout the push frequency manipulations. As expected, PT, RT and PA all decreased significantly with increasing push frequency ($P = 0.001$) for both propulsion modes. Pairwise comparisons demonstrated significantly lower ($P = 0.001$) GE for push frequency conditions below the FCF in ASY propulsion and the highest push frequency of 140% FCF, whereas it was above the FCF in SYN propulsion and the lower extreme push frequency of 60% FCF ($P < 0.05$).

Matched push frequency

The experimental protocol allowed for the comparison of propulsion modes whereby the unilateral push frequency was more or less equal, see **Figure 7.2E**. Analysis of the matched push frequencies resulted in non-significant differences in push frequency; ASY_{80}:SYN_{60} ($P = 0.317$), ASY_{100}:SYN_{80} ($P = 0.935$), ASY_{120}:SYN_{100} ($P = 0.746$) and ASY_{140}:SYN_{120} ($P = 0.315$). Significantly greater force parameters of Peak F_{RES}, Mean F_{RES}, Peak F_{TAN}, Mean F_{TAN}, FEF and Rate of force development ($P < 0.05$) were found for the ASY propulsion mode. However, no significant differences were seen in GE, work per cycle or recovery time **(Figure 7.3)** between the propulsion mode combinations. Optimal efficiency was found in the range of SYN80:ASY100 and SYN100:ASY120 **(Figure 7.3A)**. Both these SYN:ASY combinations have an average push frequency of between 48 and 59 pushes $\cdot min^{-1}$ at the propulsion velocity of $1.8 m \cdot s^{-1}$.

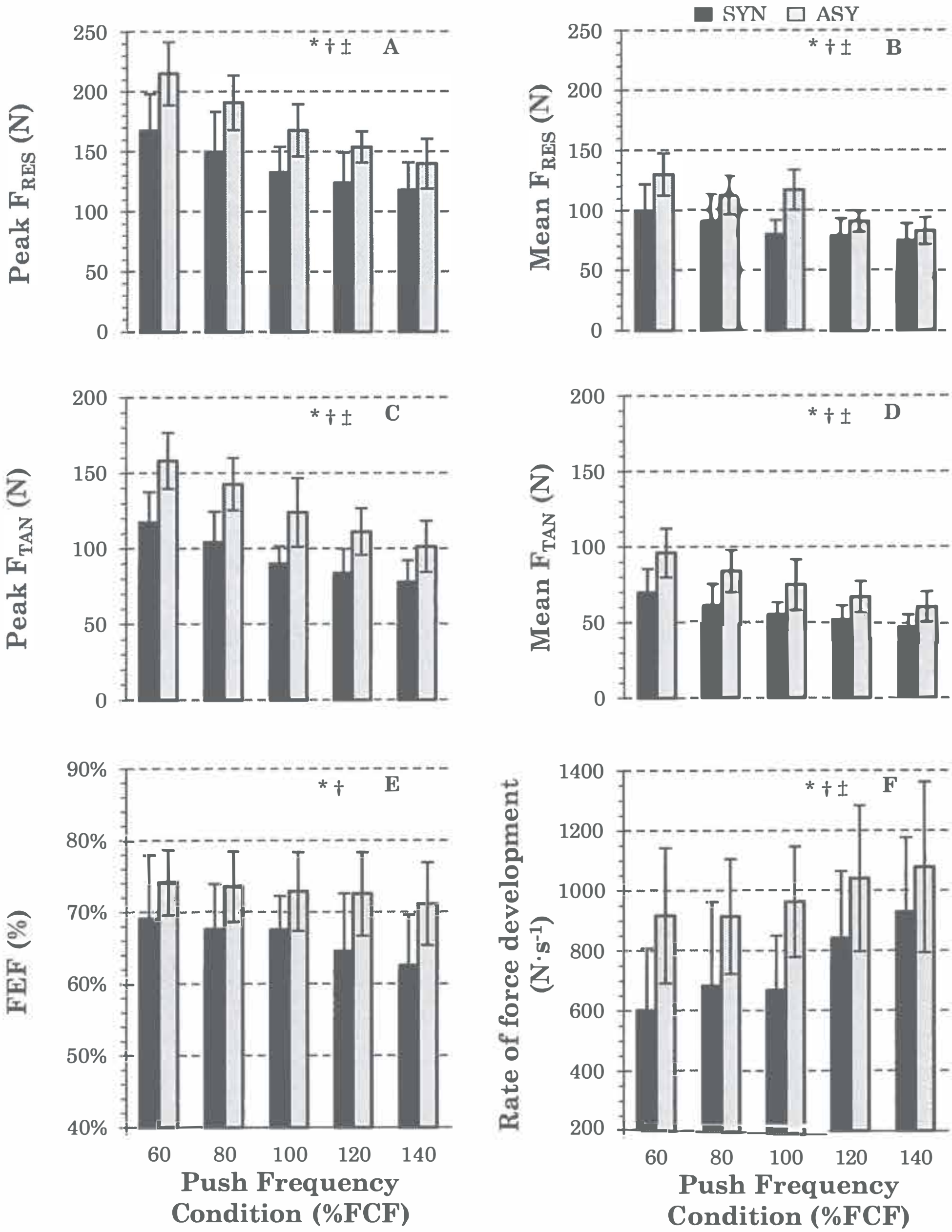


Fig 7.1: Unmatched push frequencies: Mean values ± SD for force parameters in synchronous (SYN) and asynchronous (ASY) hand-rim propulsion across range of push frequencies. (A) peak resultant force, (B) mean resultant force, (C) peak tangential force, (D) mean tangential force, (E) mean FEF and (F) rate of force development * Significant main effect mode (ASY vs. SYN). † Significant main effect frequency. ‡ Significant main effect mode*frequency ($P \leq 0.05$).

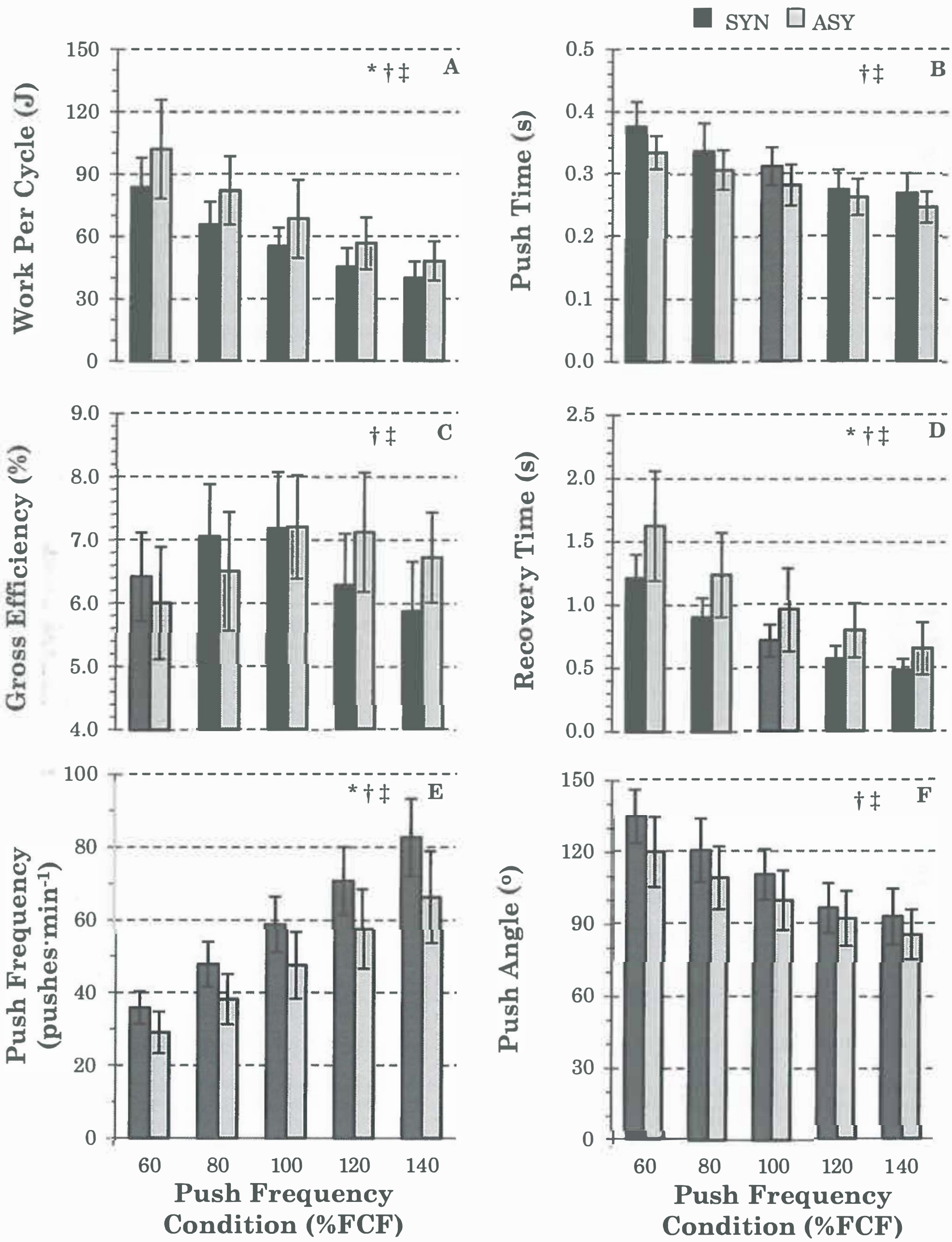


Fig 7.2: Unmatched push frequencies: Mean values ± SD for efficiency and timing parameters in synchronous (SYN) and asynchronous (ASY) hand-rim propulsion across range of push frequencies. (A) work per cycle, (B) push time, (C) gross efficiency, (D) recovery time, (E) push frequency and (F) push angle * Significant main effect mode (ASY vs. SYN). † Significant main effect frequency. ‡ Significant main effect mode*frequency ($P \leq 0.05$).

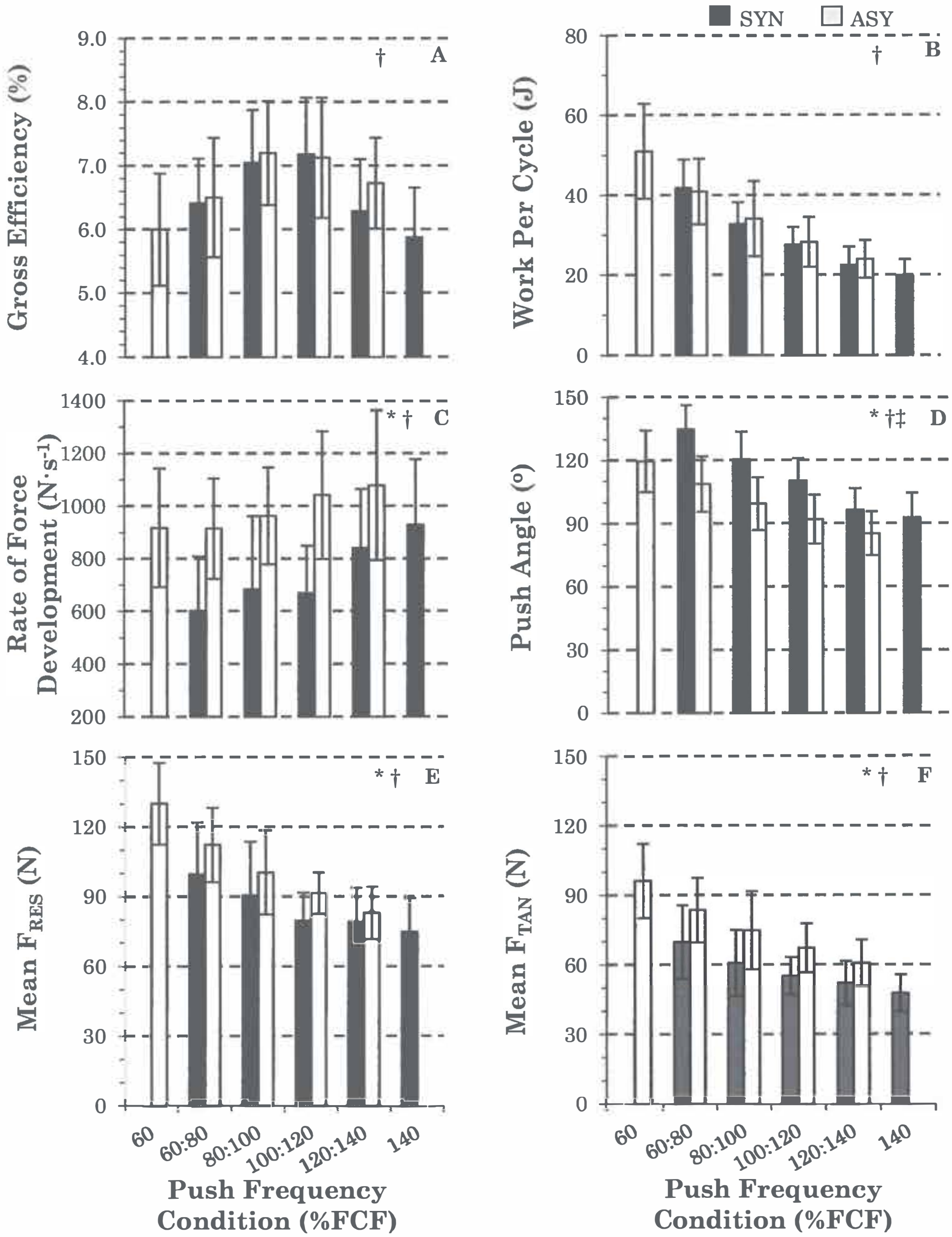


Fig 7.3: Matched Push Frequencies: Mean values ± SD for selected force parameters, timing and efficiency in synchronous (SYN) and asynchronous (ASY) hand-rim propulsion across matched push frequencies. (A) gross efficiency, (B) work per cycle, (C) rate of force development, (D) push angle, (E) mean resultant force and (F) mean tangential force. * Significant main effect mode (ASY vs. SYN). † Significant main effect frequency. ‡ Significant main effect mode*frequency ($P \leq 0.05$).

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 in both ASY and SYN propulsion modes; 2) significantly greater forces in the ASY propulsion mode; 3) no significant interaction (propulsion mode*push frequency) for force parameters when absolute push frequency is pair matched in ASY and SYN propulsion modes. In light of these findings we were able to accept 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 modes.

ASY vs. SYN propulsion mode

The Peak/Mean F_{RES} and F_{TAN} displayed identical trends with respect to push frequency for both modes of propulsion. As push frequency increased (60% to 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% to 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 were only observed at the extreme push frequencies (60% and 140% FCF). On the other hand the ASY propulsion mode showed a significantly superior F_{TAN} to F_{RES} ratio, although despite the difference in FEF between modes, the FEF had no significant association with trends in GE. 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, 13, 16, 28]. The relatively stable nature of FEF may be the result of the push phase being a guided movement and no geometric changes to the wheelchair/user interface, the magnitude of the resultant and tangential forces simply altered without the ratio of the two changing. The magnitude of the required force is being controlled by the push frequency, and the work required per stroke under the condition of a constant power output.

Matched push frequencies

When the absolute push frequencies were matched there was a significantly greater rate of force development in the ASY propulsion. This may be the consequence of the significant difference in PA and the PT. 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 [27]. Increased push frequency causes the rate of force development to increase as does the use of ASY propulsion since both changes reduce the period over which active work can be done on the handrim. Despite this study not investigating risk of injury Boninger and colleagues [3, 4, 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 adopt the SYN style of propulsion and at lower frequencies if we consider reducing the magnitude of forces and the rate of the force development to be desirable. However, GE suggests a different decision would be made should we be looking to optimise the efficiency of propulsion because there is no direct link between the efficiency values and kinetic force data.

Force changes are apparently controlled by the task geometry and movement frequency. The findings suggest that SYN propulsion is a better option to 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 Dieen and colleagues [9] for better performance in unilateral movement as a result of the inherent neural pathways for the reciprocal stimulation of the contra-lateral muscle groups does not appear to apply to hand-rim wheelchair propulsion under the current test conditions.

Bregman et al. [6] suggest that propulsion technique is mainly determined by the geometrical boundaries of the musculoskeletal system. 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. Results from other studies indeed provide evidence for these notions [6, 13, 14, 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 co-ordination strategy in this cyclic movement.

Gross efficiency

The significant difference in GE in the present study is similar to that of previous research [19-21], whereby it has been shown that higher push frequencies (>100% FCF) reduce the efficiency of propulsion. However, in the ASY propulsion it was the lower push frequencies that resulted in significant changes to the GE **(Figure 7.2C)**. This finding is likely to be as a result of the significantly lower FCF of the ASY mode (48 pushes$\cdot$min^{-1}) in comparison to the SYN mode (59 pushes$\cdot$min^{-1}). To test this theory the push frequency conditions were pair matched for the two modes of propulsion and this produced no significant difference in the GE for ASY vs. SYN propulsion **(Figure 7.3A)**.

As the changes in the force application in this study 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) enable 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$\cdot$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 are reduced which coincides with an increased rate of force development.

Experimental considerations

Able-bodied participants, with limited wheelchair experience, provided a relatively homogenous participant group, not highly trained in any of the push strategies. Importantly they would be able to perform the exercise conditions sub-maximally, despite the larger power output requirements as a result of the SMARTWheel use (smaller wheel and increased rolling resistance with solid tyres). Able-bodied participants were used to negate the influence of disability and the probable effects of limited arm or trunk function along with possible effects of habituation and training at given arm frequencies. Use of a standardised basketball wheelchair configuration eliminated any effects of different chair designs/setups, however, it is accepted that this would have an effect on the relative geometry of the chair/user interface for individuals, influencing the physiological demands, force production and propulsion mechanics to that in a conventional daily wheelchair. Nevertheless it is felt that the trends and relationships of the data would not alter significantly. Another consideration was the use of a stationary wheelchair ergometer consisting of a single roller and fixed chain. This was an important feature of the study allowing for the effects of force application in relation to push strategy to be investigated without the additional effects of coasting direction (of the wheelchair), and thus the external work requirements. Importantly, the power output across the push strategies is equal within each participant. The resistance of the wheelchair/roller ergometer system is greater than previous published literature. The increased resistance could be attributed to a number of factors: Firstly 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 tyres provided by the SMARTWheel manufacturer, which have a considerable higher rolling resistance than pneumatic tyres [15, 17]. Thirdly is difference in roller ergometers whereby this study used a single roller ergometer with a much smaller roller circumference than that of the split roller ergometer with significantly greater roller circumference, hence greater resistance. 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, for example; reduced rolling resistance and in different populations of wheelchair users.

Conclusions

In conclusion, the effect of push frequency in SYN and ASY propulsion modes displayed the same relationship with force parameters. Increased push frequency resulted in decreased absolute force and increased rate of force development. The FEF was unrelated to GE, thus supporting the view that FEF is overwhelmingly governed by the user/chair geometry. The ASY propulsion mode consistently required significantly greater absolute forces than the SYN mode. With matched push frequencies (in propulsion modes) the interaction of mode and frequency reported no significant differences, although propulsion mode in isolation continued to demonstrate significantly greater force values in the ASY propulsion. The rate of force development remained significantly higher in ASY propulsion which could be important in relation to the risk of injury. The FEF remained consistently higher in ASY propulsion although without any effect on GE.

Understanding how individuals apply forces to the hand-rim together with the effects of propulsion mode and push frequency is important for determining intervention strategies. Particularly if findings can help contribute to perhaps help reduce the levels of force exerted on the upper extremity joints and limit the risk of injury whilst maintaining optimal levels of efficiency. Future research is needed to investigate the relationship of push strategies under various propulsion velocity and power output conditions aiming to optimise efficiency but minimise the risk of injury.

Acknowledgements

We are grateful to Prof. Martin Ferguson-Pell for the loan of the SMART^{Wheel} (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

1 Abel T, Kroner M, Rojas Vega S, Peters C, Klose C, Platen, P. Energy expenditure in wheelchair racing and handbiking – a basis for prevention of cardiovascular diseases in those with disabilities. Eur J Cardiovasc Prev Rehabil 2003; 10: 371-376.

2 Asato KT, Cooper RA, Robertson RN, Ster, JF. SMART^{Wheel}: development and testing of a system for measuring manual wheelchair propulsion dynamics. IEEE Trans Biomed Eng 1993; 40: 1320-1324.

3 Boninger ML, Baldwin M, Cooper RA, Koontz A, Chan L. Manual wheelchair pushrim biomechanics and axle position. Arch Phys Med Rehab 2000; 81: 608-613.

4 Boninger ML, Cooper RA, Baldwin MA, Shimada SD, Koontz A. Wheelchair pushrim kinetics: body weight and median nerve function. Arch Phys Med Rehab 1999; 80: 910-915.

5 Boninger ML, Souza AL, Cooper RA, Fitzgerald SG, Koontz AM, Fay BT. Propulsion patterns and pushrim biomechanics in manual wheelchair propulsion. Am J Phys Med Rehab 2002; 76: 420-426.

6 Bregman DJJ, van Drongelen S, Veeger HEJ. Is effective force application in handrim wheelchair propulsion also efficient? Clin Biomech 2009; 24: 13-19.

7 Cooper RA, Robertson RN, van Sickle DP, Boninger ML. Methods for determining three-dimensional wheelchair pushrim forces and moments: a technical note. J Rehab Res Dev 1997; 34: 162-170.

8 Dallmeijer AJ, van der Woude LHV, Veeger HEJ, Hollander AP. Effectiveness of force application in manual wheelchair propulsion in persons with spinal cord injuries. Am J Phys Med Rehab 1998; 77: 213-221.

9 van Dieen JH, Ogita F, de Haan A. Reduced neural drive in bilateral exertions: a performance-limiting factor? Med Sci Sports Exerc 2003; 35(1), 111-118.

10 Glaser RM, Sawka MN, Young RE, Suryaprasad AG. Applied physiology for wheelchair design. J Physiol 1980; 48: 41-44.

11 Goosey VL, Campbell IG, Fowler NE. Effect of push frequency on the economy of wheelchair racers. Med Sci Sports Exerc 2000; 32: 174-181.

12 Goosey-Tolfrey VL, Sindall P. The effects of arm crank strategy on physiological responses and mechanical efficiency during sub-maximal exercise. J Sports Sci 2007; 25(4): 453-460.

13 de Groot S, Veeger HEJ, Hollander AP, van der Woude LHV. Consequence of feedback-based learning of an effective hand rim wheelchair force production on mechanical efficiency. Clin Biomech 2002a; 17: 219-226.

14 de Groot S, Veeger HEJ, Hollander AP, van der Woude LHV. Wheelchair propulsion technique and mechanical efficiency after 3 wk of practice. Med Sci Sports Exerc 2002b; 34: 756-766.

15 Kauzlarich JJ, van der Woude LHV, Hopman MTE, van Kemenade CH (eds). Biomedical aspects of manual wheelchair propulsion: The state of the Art II, IOS Press, Amsterdam: Washington DC, 1999: 158-170.

16 Kotajarvi, BR, Basford JR, An KN, Morrow DA, Kaufman KR. The effect of visual biofeedback on the propulsion effectiveness of experienced wheelchair users. Arch Phys Med Rehab 2006; 87: 510-515.

17 Kwarciak AM, Yarossi M, Ramanujan A, Dyson-Hidson TA, Sisto SA. Evaluation of wheelchair tire rolling resistance using dynamometer-based coast down tests. J Rehab Res Dev 2009; 46(7): 931-938.

18 Lenton JP, Fowler N, Woude L van der, Goosey-Tolfrey VL. Efficiency of wheelchair propulsion and effects of strategy. Int J Sports Med 2007; 28: 1–6.

19 Lenton JP, Fowler NE, van der Woude LHV, Goosey-Tolfrey VL. Wheelchair propulsion: effects of experience and push strategy on efficiency and perceived exertion. Appl Physiol Nutr Metab 2008; 33: 870-879.

20 Lenton JP, van der Woude LHV, Fowler NE, Goosey-Tolfrey VL. Effects of arm frequency during synchronous and asynchronous wheelchair propulsion on efficiency. Int J Sports Med 2009; 30: 233-239.

21 Lenton JP, van der Woude LHV, Fowler NE, Goosey-Tolfrey VL. Effects of 4 weeks asynchronous hand-rim wheelchair practice on mechanical efficiency and timing Disability and Rehabilitation 2010; 32(26): 2155-2164.

22 Mossberg K, Willman C, Topor MA, Crook H, Patak S. Comparison of asynchronous versus synchronous arm crank ergometry. Spinal Cord 1999; 37: 569–574.

23 Niesing R, Eijskoot F, Kranse R, den Ouden AH, Storm J, Veeger HJ, van der Woude LHV, Snijders CJ. Computer-controlled wheelchair ergometer. Med Biol Eng Comput 1990; 28: 23-29.

24 Peronnet F, Massicotte D. Table of non-protein respiratory quotient: an update. Can J Sport Sci 1991; 16: 23-29.

25 Rankin JW, Kwarciak AM, Mark Richter W, Neptune RR. The influence of altering push force effectiveness on upper extremity demand during wheelchair propulsion. J Biomech 2010; 43(14): 2771-2779.

26 Robertson RN, Boninger ML, Cooper RA, Shimada SD. Pushrim forces and joint kinetics during wheelchair propulsion. Arch Phys Med Rehab 1996; 77: 856-864.

27 Rozendaal LA, Veeger HEJ, van der Woude LHV. The push force pattern in manual wheelchair propulsion as a balance between cost and effect. J Biomech 2000; 36: 239-247.

28 Vanlandewijck Y, Theisen D, Daly D. Wheelchair propulsion biomechanics: implications for wheelchair sports. Sports Med 2001; 31: 339-367.

29 Veeger HEJ, van der Woude LHV, Rozendal RH. Effect of hand-rim velocity on mechanical efficiency in wheelchair propulsion. Med Sci Sports Exerc 1992; 24: 100-107.

30 Whipp BJ, Wasserman K. Efficiency of muscular work. J Appl Physiol 1969; 26: 644-648.

31 van der Woude LHV, Bosmans I, Bervoets B, Veeger HEJ. Handcycling: different modes and gear ratio. J Med Eng Tech 2000; 24: 242–249.

32 van der Woude LH, Bouw A, van Wegen J, van As H, Veeger D, de Groot S. Seat height: effects on submaximal hand rim wheelchair performance during spinal cord injury rehabilitation. J Rehab Med 2009; 41: 143-149.

33 van der Woude LHV, Veeger HEJ, Dallmeijer AJ, Janssen TWJ, Rozendal LA. Biomechanics and physiology in active manual wheelchair propulsion. Med Eng Phys 2001; 23: 713-733

34 van der Woude LHV, Veeger HEJ, Rozendal RH, Sargeant AJ. Optimum cycle frequencies in hand-rim wheelchair propulsion. Wheelchair propulsion technique. Eur J Appl Physiol Occup Physiol 1989; 58: 625-632.

Chapter 8

General Discussion

The aim of the present thesis was to further understand the physiological, psycho-physiological and biomechanical differences between different push strategies in hand-rim propulsion. Investigating mechanical efficiency, the associated (psycho-) physiological strain and the underlying (biomechanical) factors of push strategy in novices and trained athletes and the process of implicit learning of hand-rim wheelchair propulsion in novices were deemed to be critical elements in wheeling performance. To help investigate if an asynchronous propulsion mode can be more efficient than the synchronous propulsion mode the early experimental studies **(chapters 2-4)** sought to determine the influence of propulsion mode and or push frequency, identifying the influence of propulsion experience whilst also ascertaining any relationships with ratings of perceived exertion. The later experimental studies **(chapters 5-7)** progressed to determine the effect of wheelchair practice on mechanical efficiency and identify the relationships of force application characteristics.

The current chapter focuses on the combined outcomes of the experimental chapters, integrating the findings in the context of the overall research aim. **Figure 8.1** is modified from the initial conceptual model presented in **chapter 1 (Figure 1.1)**, illustrating the factors that influence wheelchair propulsion performance, in particular highlighting those that have been investigated throughout the experimental chapters.

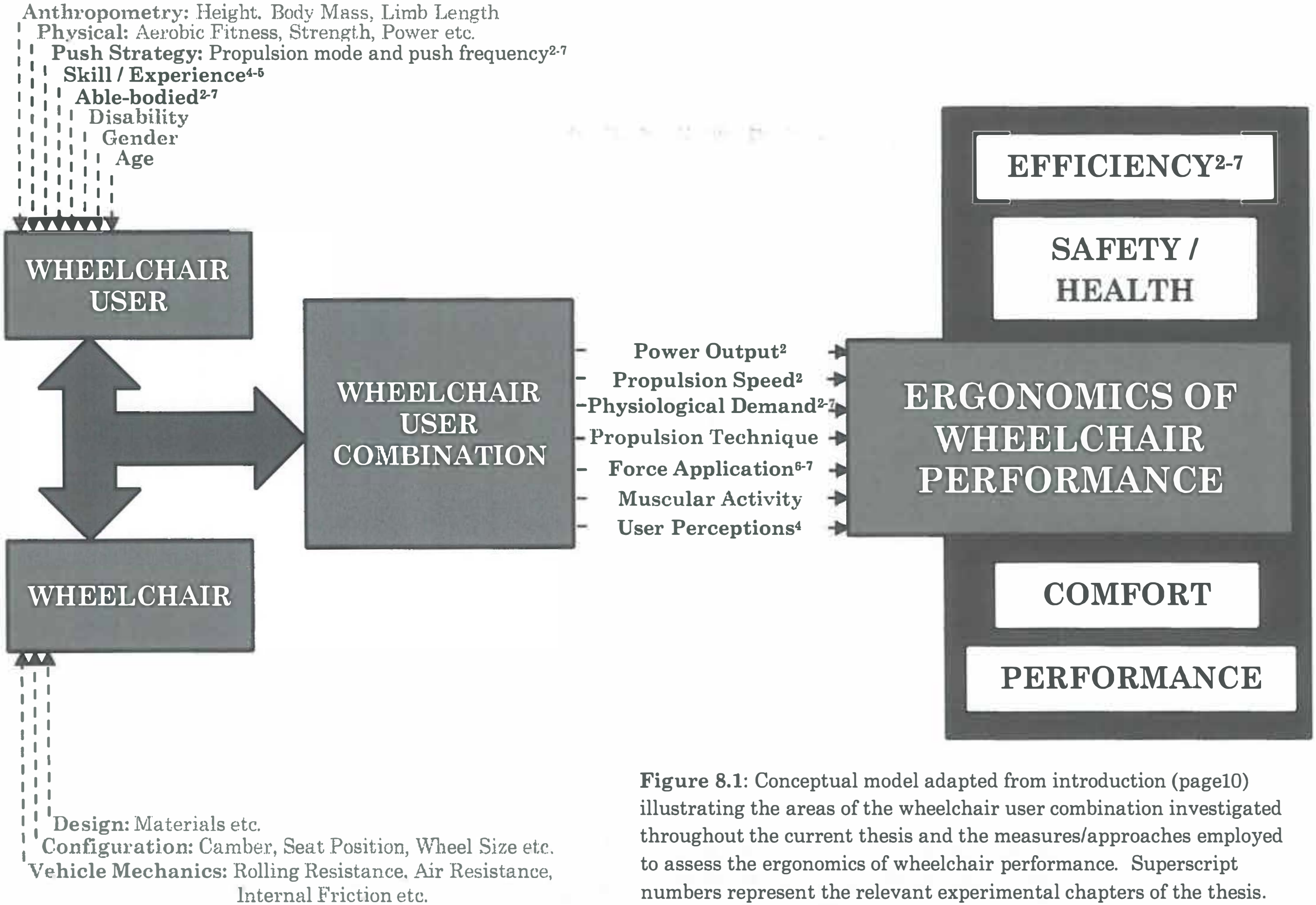


Figure 8.1: Conceptual model adapted from introduction (page10) illustrating the areas of the wheelchair user combination investigated throughout the current thesis and the measures/approaches employed to assess the ergonomics of wheelchair performance. Superscript numbers represent the relevant experimental chapters of the thesis.

The discussion will focus on the subsequent sub-sections:

- Indices of mechanical efficiency
- Synchronous vs. asynchronous propulsion modes
- Push (Arm) frequency
- Hand-rim propulsion practice
- Force Application

Indices of mechanical efficiency

The first three experimental chapters reported gross, net and work efficiency. The rationale for this was that each separate index of efficiency would help understand the efficiency associated with hand-rim propulsion and explain the effects of push strategy. The most frequently cited efficiency index used throughout the literature is gross efficiency, hence provided opportunities for comparisons with previous work. Hintzy & Tordi [32] suggested that both gross and net efficiency better reflected the actual efficiency of hand-rim propulsion whereas work efficiency investigated the efficiency of the muscular contraction during this movement. Reporting gross and work efficiency indices helped to begin to understand the role of the different elements of hand-rim propulsion with different push strategies; since the gross efficiency includes a composite measure of the energy cost (based on metabolic costs) for example of moving the arms, stabilising the body and accelerating the wheel and while work efficiency off-sets the cost of the arm movements and stabilisation associated with unloaded exercise.

Depending upon the base-line used, each efficiency index provided different values (Gross 4.2 – 9.3%; Net 5.4 – 11.2%; Work 6.2 – 16.3%) throughout the experimental chapters. In light of the conditions in the current thesis the gross efficiency values are in line with previous studies at similar levels of work done (power output) and in different participant groups, **(Chapter 1, Table 1.1)** [18, 32, 33, 56]. Despite the obvious absolute differences in the efficiency indices the trends with push frequency were identical **(Chapter 3 & 4)**.

Mechanical efficiency indices are all dependent upon velocity of propulsion and push (arm) frequency. It is suggested that increased internal work is responsible for this as the proportion of unmeasured work in the total energy expenditure changes significantly and cannot be measured in the unloaded condition. Consequently, the ratio between work done and the energy expended is increased, decreasing efficiency. Physiological responses and mechanical efficiency indices are influenced by a combination of propulsion mode, frequency and velocity, supported by findings in the experimental chapters.

Push Strategy

Propulsion mode

It is evident in chapters three to seven that in terms of mechanical efficiency there is no significant advantage of the traditional synchronous mode over the alternative asynchronous mode, in contrast to the initial assumptions of the thesis, earlier work of Glaser et al [17] and significant advantage of synchronous handcycling [9, 50, 54]. It is important here to acknowledge the findings could be attributed to the eliminated steering component by using a wheelchair roller ergometer for the wheelchair hand-rim propulsion. Whereas the alternative findings in the hand-cycling literature incorporate the steering component in the task requirement which could influence metabolic costs associated to the asynchronous mode. Despite the lack of statistical significance the asynchronous propulsion mode generally displayed lower physiological responses and increased efficiency throughout the experimental chapters, excluding in the experienced wheelchair sportsmen. Interestingly when adopting either propulsion mode the self-selected frequency is almost identical in relation to the total number of left and right arm movements employed to fulfil the task requirements. Despite the lack of significant differences some suggestions are offered to the explanation and understanding of the findings includes; 1) differences in muscle activity, however, this remains an unknown requiring further research. 2) asynchronous propulsion allows greater continuity of the hand-rim force application, reducing fluctuations in the velocity profile and therefore, the inertial forces overcome with each stroke are reduced. 3) asynchronous limb movement patterns are employed in other more efficient modes of locomotion (e.g. walking, bicycling, rowing) and may take advantage of inherent neural pathways for the reciprocal stimulation of the contra-lateral muscle groups [13]. In addition Glaser et al. [17] indicated through subjective evaluation that the asynchronous mode provides greater stability as a consequence of the trunk rotation over the forward and back motion of the synchronous mode. This suggests that maybe decreased muscle activity is required for stability and therefore, a reduced $\dot{V}O_2$ response and improved efficiency under the current testing conditions on the roller ergometer. This hypothesis warrants further evaluation and prolonged exposure to the asynchronous mode to further investigate any optimisation and benefits to that of synchronous propulsion.

Alternatively the lack of significant differences between synchronous and asynchronous movement patterns in either of the participant groups suggests that despite wheelchair propulsion experience and constant employment of synchronous propulsion mode, the common elements required for hand-rim propulsion are the same for both propulsion modes despite the differences between the two modes of propulsion and the specific training status of the experienced wheelchair sportsmen in synchronous propulsion. By suggesting common elements, it is focussing on the similarities such as coupling of the hand-rim, force application, and transfer amongst other movement and technique characteristics that are implicit to both propulsion modes regardless of the experience and push (arm) frequency variables.

Push (arm) frequency

In accordance with existing literature [15, 18, 56] there is a curvilinear association of efficiency with arm frequency (synchronous and asynchronous). The previous research demonstrated that the most optimal gross efficiency is achieved when operating at the self-selected frequency [18, 56]. However, the current thesis challenges these findings as it was not possible to ascertain an optimal frequency condition in either propulsion mode albeit under the testing conditions on a roller ergometer. Push (arm) frequency demonstrates significant effects on mechanical efficiency values when performing at sub-maximal propulsion speeds that correspond to approximately 60% $\dot{V}O_2$ peak. Mechanical efficiency values in both propulsion modes are significantly lowered at higher push frequencies (beyond the self-selected frequency), supporting previous findings. However, unlike the aforementioned research the data was unable to elicit significant differences in mechanical efficiency with reductions in push frequency, up to 60% of the self-selected. This absence of a significant difference occurs in spite of the relatively linear change in the absolute $\dot{V}O_2$ with increasing push frequency and the different movement patterns of synchronous and asynchronous modes. However, $\dot{V}O_2$ unload (internal work) demonstrated somewhat similar proportions of the absolute $\dot{V}O_2$ (43% +/- 3%) across push frequency hence the task requirements of the loaded condition would appear to be responsible for any differences in efficiency and can be reflected in the similar trends of gross and work efficiency. This may possibly imply the existence of counteracting phenomena between the loaded and unloaded conditions, whereby lower arm frequencies benefit from factors that reduce the total amount of work associated with moving the arms at loaded exercise conditions. Through a combination of changes that may occur (i.e. improved technique at lower arm frequency, amount of work per push, acceleration / deceleration changes, muscle activity etc.), the energy costs balance one another to avoid significant changes in efficiency within the specified range for the same external workload.

Suggestions for the significant and non-significant differences focus around muscle mechanics and the force-velocity relationship of the various muscles involved in the task of propulsion i.e. muscle fibre composition and recruitment patterns [16, 44]. A reduction of linear velocity at the same power output indeed improves the efficiency in hand-rim propulsion [49] as the energy demands are reduced because of the lower hand and segment velocities are apparent over a larger part of the propulsion trajectory. Hence this could allow for more secure, effective coupling and the need for a less controlled transfer of muscle forces through the sequence of contractions. In addition, changes in frequency may affect the suggested coupling between arm motion and breathing pattern [2]. This higher form of co-ordination may possibly be disturbed at the non-preferred higher arm frequencies and be closer to the metabolic optimal at the lower range of arm frequencies. At the higher frequencies there is a shift in the 'active' internal work required to move the arms and the force application coupled with movement velocity increases the metabolic demand. The increased number of recovery phases, couplings and un-couplings (and the associated small negative braking force increases) will contribute to the increased energy expenditure.

Propulsion experience and motor learning

Chapter 4 findings demonstrated how propulsion experience significantly improves the efficiency of hand-rim propulsion, supporting all previous research whereby experienced wheelchair users are significantly more efficient than able-bodied or novice wheelchair users. The impact of propulsion experience clearly demonstrates that significantly greater mechanical efficiency is associated with experienced users **(chapter 4)** as was shown in previous research [18, 32, 56]. The values reported for gross efficiency (AB ~7.0%; WS ~9.0%) are in line with previous literature and despite this significant difference there are similar relationships with push (arm) frequency, propulsion mode and other physiological parameters.

The 'passive' internal workload remains somewhat similar as expressed in the $\dot{V}O_{2\ unload}$ results throughout push (arm) frequency conditions. Importantly it should be noted that the task complexity in experienced users was increased as a result of the significantly higher velocity and power output to which 60% of $\dot{V}O_{2\ peak}$ corresponded in the experimental conditions. However, the explanation for large differences in efficiency is not clearly understood, but implications are that with experience comes practice and refinement of propulsion technique (increased skill and co-ordination levels) and physiological adaptation whereby perhaps the better training status of the muscles employed in propulsion hence there is an overall reduction in the amount of active internal work done. The more refined movement pattern [43] and suggestion of better force application pattern seen in wheelchair users [41, 49] is suggested to reduce energy expenditure. Interestingly self-selection of push frequency is not reliant on experience and constant involvement in hand-rim propulsion. It is important to note that the wheelchair sportsmen were from sporting backgrounds that lend themselves towards fast, quick pushes during intermittent bursts of wheelchair movement [47].

The psychophysiological cost (rating of perceived exertion) adhered to the trends of absolute metabolic cost and not mechanical efficiency regardless of experience with more strain being felt when operating at push (arm) frequencies greater than the self-selected frequency. Greater emphasis is placed upon the peripheral rating of perceived exertion supporting the suggestion that peripheral factors are dominant in work with smaller muscle groups [14]. Our data clearly demonstrate the power that habituation has on the critical variables in terms of mechanical efficiency improvements and reductions in physiological and psychophysiological variables.

Experienced wheelchair users throughout the literature and the wheelchair sportsmen studied in this thesis demonstrate significantly higher efficiency for hand-rim propulsion. As mentioned earlier learning, practice and training are deemed an essential part of the rehabilitation process for people who become wheelchair-dependent in terms of skill and wheelchair capacity [26, 29, 30, 35-37]. Indeed, it has been shown that hand-rim propulsion practice can improve mechanical efficiency and some technique variables [21-24] along with changes observed in segmental movement pattern, muscle activity, and co-

contraction [23, 24]. Beyond that, motor control improves as an outcome of learning, leading to lower metabolic costs [46]. Experimental **chapters 3 and 4** offer an insight into the physiological advantage to be gained from practicing hand-rim propulsion at lower frequencies, supported by the notion that this may reduce the likelihood of overuse injuries during wheelchair propulsion [6]. Thus, the adaptations of wheelchair propulsion to slow paced frequency practice versus unpaced practice may be more favourable. Four weeks of asynchronous hand-rim propulsion practice **(chapter 5)** at either paced or unpaced frequencies led to improvements of between 1.1-1.3% in gross efficiency in novices, which are clearly associated to the reduction in push and or arm frequency. This effect was demonstrated most clearly by the comparison between the final freely chosen frequencies which for the paced group became the same as their paced practice frequency whilst for the unpaced group this fell to the lower level achieved in the final weeks of practice. Further detailed analysis of the kinematics and muscle activation of this unconventional propulsion strategy – also on a longer time scale - would help to further understand the mechanisms involved with the efficiency of wheelchair propulsion and adaptations as a consequence of practice. Having seen only four-weeks of propulsion practice significantly improve efficiency by on average 1.0 - 1.3%, the question remains as to why the rate of change is much slower with the long term effect of practice (propulsion experience on average of 16 years daily wheelchair and 11 years sports wheelchair – **chapter 4**)? This experience equates to a large percentage of practice/wheelchair use yet we only see differences in efficiency on average of approximately 2.5% **(chapter 4)** between novice able-bodied individuals and wheelchair sportsmen. There would appear to be a need for the study of long term practice on mechanical efficiency of hand-rim wheelchair propulsion to help answer this question accurately and perhaps establish a timeline for the optimisation of mechanical efficiency. It would also help contribute to the underlying question surrounding the relatively low mechanical efficiency associated with this upper-body exercise modality.

There is certainly evidence of a habitual learning effect which is likely to have a neural / co-ordination effect [45] – evidenced by the fact that post training both groups had adapted to a freely chosen frequency which reflected that used in the practice period. Since both groups had similar gross efficiency post practice it is likely that the freely chosen frequency at this stage was indicative of their habituated preference rather than a physiologic reason. Supportive to previous work, it would appear that skill learning of wheelchair propulsion involves the search for a 'body scheme' that requires minimal energy expenditure [1]. Timing is a leading parameter in cyclic motor learning and our findings relating to the reduction of arm frequency confirms not only previous work on manual wheelchair propulsion by de Groot and colleagues [21-26], but the suggestion that the learning of repetitive gross-motor tasks might be characterized by a 'longer-slow' control mode, i.e., a decreased arm frequency because of the larger stroke angle/longer push time [46]. However, the question remains in light of the findings from practice as to whether participants become more economical because of the reduction in push (arm) frequency or if they have the ability to reduce the frequency of movement because they are more economical?

Force application

To the authors' knowledge, the force application data presented in the thesis is the first to describe the effects of forces applied to the hand-rim during manual wheelchair propulsion for push strategies, more specifically the relationship with propulsion mode and push frequency. The experimental **chapters 6 and 7** have facilitated findings that demonstrate: 1) the significant effect of push frequency; 2) the significant differences of forces applied in synchronous and asynchronous modes; 3) with matched push frequency the insignificant interaction effect for asynchronous vs. synchronous modes.

The values of mean fraction of effective force ranged from 63 – 74% and were comparable with those found in the literature for hand-rim propulsion in both able-bodied and spinal cord injured participants [7, 10, 51]. Increased push frequency results in the reduction of absolute force for both resultant and tangential force whereas the rate of force development increased significantly with increased push frequency. Identical trends were seen in both propulsion modes although asynchronous propulsion produced significantly higher values throughout conditions. It is suggested that this is the combined effect of the significantly lower self-selected frequency condition, and the unilateral nature of the force application to the hand-rim as opposed to the bilateral nature of the synchronous propulsion mode. With the reciprocal changes in resultant and tangential force across push frequencies the fraction of effective force ratio remained insignificantly different; however, mode comparison indicated a significant increase in the asynchronous propulsion mode, the result of a superior tangential to resultant ratio. Despite this finding the fraction of effective force had no significant association with trends in gross efficiency for either propulsion mode and or push frequency. As the fraction of effective force does not correlate to the mechanical efficiency it is in support of previous research [7, 21, 38, 40]. Therefore, the use of the fraction of effective force as an indicator of efficient propulsion cannot be supported with the current findings. The higher fraction of effective force during asynchronous propulsion strategies and subsequent gross efficiency did not significantly differ to that in synchronous propulsion strategies. The differences in the fraction of effective force of propulsion modes in our data were not in the same magnitude as those in a higher forcefully induced fraction of effective force [21]. However, it would appear to support that the most effective propulsion technique from a mechanical viewpoint (i.e. in terms of the fraction of effective force), is not necessarily the most efficient from the physiological perspective.

The rate of force development is significantly increased at the higher frequencies and in the asynchronous mode. Boninger and colleagues [4, 5] associated increases in cadence, force magnitude and rate of force development with an increased risk of injury. In the context of push strategy it is important to know how this rate of force development is affected and its associated risks. The difference in the rate of force development is significant and very important as findings report effects of propulsion frequency and propulsion mode, and the increased push frequency causes the rate of force development to increase along with the asynchronous mode, hence could contribute to an increased risk of injury. Therefore, the initial findings of our study imply wheelchair users should adopt the synchronous style of propulsion if we consider the magnitude of forces and the rate of the force development. As for push frequency lower frequencies lead to increased peak forces during each push, whereas higher push frequencies produce smaller peak forces but subsequently higher rates of force development more frequently. It remains to be seen as to which is better for hand-rim wheelchair propulsion, as results show that the physiological efficiency is not linked to the trends in effectiveness of force application.

Critical Reflections

The current thesis elucidates methodological considerations important in hand-rim propulsion research to which attention was drawn in the general introduction **(Pages 8-11)**. Previous research has seen a vast array of participant groups, protocols and equipment used for the collection and analysis of data from hand-rim propulsion studies, which precludes direct comparisons being made between research studies [55]. Although the findings of this thesis add to the body of knowledge in hand-rim wheelchair propulsion, limitations are re-addressed with discussion in the subsequent sub-sections.

Able-bodied participants

Studies into hand-rim propulsion will continue to employ both able-bodied (non-wheelchair participants) and wheelchair-dependent individuals but clearly, differences exist which need to be considered when evaluating the findings. The study of wheelchair dependent users introduces unknown effects of disability into the outcome parameters, which may be considerable since it is very difficult to generate a homogeneous population. Wheelchair dependent populations lead to large inter-individual differences due to numerous factors, such as disability, injury specificity, training status and level of physical training on the upper body musculature, and disability, i.e. level and completeness of the lesion of those with a spinal cord lesion, age and familiarity with wheelchair use (experience). The selection of able-bodied individuals addresses these issues by permitting the following:

1. A constant level of expertise and training status of all participants in the different testing conditions, a homogenous participant group with controlled bands of error;
2. An understanding of upper-body arm work in a healthy upper-body as any pathological differences can be excluded;
3. The wheelchair configuration remains constant throughout testing conditions removing the subsequent effect that different chair configurations would bring to the analysis.

The use of able-bodied individuals has primarily been to ensure that any differences in variables measured are not biased by the effect of disability in wheelchair population groups along with the ability. Consequently this appears to allow experimental effects to be attributed to changes or adaptations of the intact human system. However, it is crucial that some level of caution must be used when applying data to general hand-rim propulsion. Previous research adheres to the same philosophy and the use of able-bodied participants [3, 8, 11, 12, 15, 19-25, 32, 33, 39, 52, 53, 56].

Experimental set-up

Different measurement systems have their advantages and disadvantages in terms of validity and reliability, however, the comparability of results and applicability of existing knowledge base remains somewhat limited without the standardisation of measurement equipment (roller ergometers) and methodology. Whilst it is acknowledged that field based testing conditions would have presented the most ecologically valid conditions in which to investigate push strategy it would have been the least standardised in terms of velocity and power output. Standardisation was deemed very important in establishing initial research of push strategy, in particular the control of external work requirements achieved through the use of a standardised wheelchair configuration (limiting known effects of chair design and set-up) and the wheelchair roller ergometer.

Hand-rim propulsion research continues to implement a wide range of propulsion speeds and rolling resistance for the manipulation of external power output. The vast majority are limited to slower propulsion speeds unless studying wheelchair sports athletes **(Chapter 1, Table 1.1)**. This results in highly variable exercise intensities amongst individuals tested, which could be attributed to a number of variables for example; testing conditions (i.e. wheelchair ergometer vs. treadmill) or differing levels of physical capacity. To control and elicit, a specific exercise intensity individuals are required to perform at different propulsion speeds. Researchers continue to change power output through increased resistance; however, in everyday and/or sports activities the floor surface in the majority of tasks does not change for that task, hence increased power output is only attainable through increased propulsion speeds. It is important to realise that a speed based protocol is somewhat more realistic to conditions associated with hand-rim wheelchair propulsion, particularly in sporting environments whereby surfaces and slopes remain constant. It is acknowledged that in daily activities the different surfaces and slopes encountered would also contribute to the resistance of propulsion, hence research would benefit from conducting the manipulation of push strategy throughout a range of propulsion speeds.

Conclusions

Based on the collective studies presented in this thesis it has been possible to determine the mechanical efficiency of push strategies and compare asynchronous propulsion to the more traditional synchronous propulsion mode. Consequently a number of conclusions can be drawn with respect to push strategy.

To begin with, the different indices of mechanical efficiency appear to allow for the suggestion that the low efficiency is related to both internal and external work components of the task. It is clear to see that there is no evidence to suggest a rationale for any physiological advantage of employing the asynchronous propulsion mode as opposed to the synchronous propulsion mode. Whilst manipulating the freely chosen frequency **(chapters 3-7)** neither propulsion mode presented significant advantages over the other in terms of mechanical efficiency under the current testing conditions. The only exception to this was in **chapter 2** whereby the synchronous propulsion offered a significant advantage over the asynchronous mode; however, this is likely to be the combined effect of the increased propulsion speed (power output) and the significant difference in total number of arm movements in the push frequency conditions of SYN(40:40) and ASY(20:20) used to perform the same amount of work.

The push frequency plays a major role on the mechanical efficiency particularly above freely chosen push frequencies whereby efficiency is significantly reduced. On the other hand push frequencies ranging from 60 – 100% of the freely chosen push frequency do not have any negative effect on the mechanical efficiency indicating that the human system is somehow able to find a balance between the cost and effect of arm frequency manipulation.

Experience presented the same trends albeit with significantly greater values of mechanical efficiency. The strong association of the peripheral ratings of perceived exertion with gross efficiency suggests that experienced users have learnt to be more efficient.

The practice of hand-rim propulsion supports this suggestion presenting improved efficiency following practice and the link appears to be with reduced frequencies, suggesting that individuals push frequency is linked to habitual practice and a natural lowering. These lower frequencies require higher forces; however, there is no link between forces or the fraction of effective force and gross efficiency which consequently points to a much more complex relationship than simply the force application. Even though the fraction of effective force does not help understand the relatively low mechanical efficiency of hand-rim propulsion it along with along with the rate of rise of force and changes in total and tangential force does present valuable information for push strategy intervention.

Although physiological data could not offer any significant advantage for the asynchronous propulsion mode, the significantly greater forces and rate of force development differences could be clinically important when used to assist wheelchair users in intervention strategies for the learning and practice of hand-rim propulsion. The manipulation of push strategy is a variable that can be changed more easily in the framework of the wheelchair-user combination (**Figure 8.1** – conceptual model), hence individuals, coaches and rehabilitation practitioners can utilise the knowledge to seek improvements in the efficiency of performance for activities of daily life or sporting situations. Reducing the levels of force exerted on the upper extremity joints and attempts to limit the risk of injury whilst at the same time maintaining optimal levels of efficiency look are important.

Implications

Until further research is conducted the findings in this thesis have the following implications:

- Push (arm) frequency is the predominant component of push strategy selection for individuals in hand-rim wheelchair propulsion and can help reduce the physiological demands. Changes in frequency are easy to manipulate and implement.
- Practice is a key element to improved mechanical efficiency and is particularly advantageous at unpaced (freely chosen frequency) and paced (80% of the freely chosen frequency).
- Psychophysiological measures follow the trends in physiological outcomes and may be used in practice to guide intensity of exercise and effort?
- The feedback mechanism of pacing via the use of audio cues can assist with the practice and learning of the complex task of hand-rim

wheelchair propulsion. This would assist the process by encouraging individuals to meet requirements for a more optimum mechanical efficiency.

- Awareness of the rate of rise in forces applied to the hand-rim as push strategy is manipulated and the potential link with risk of injury should be stimulated.
- Propulsion practice should not be aimed at feedback based optimisation of the propulsion force (i.e. the fraction of effective force) because this may be less efficient and more straining for individuals.

Future Directions

It is apparent that the results of this thesis create a framework for further research to explore different interventions for push strategy and continue to develop the understanding of factors associated with the relatively low efficiency. Explanations for both the relatively low efficiency and large differences between wheelchair sportsmen (experienced wheelchair users) and able-bodied (non-wheelchair users) are paramount if we are to seek improvements in the performance and efficiency of propulsion in manual hand-rim wheelchairs. Manual hand-rim wheelchair propulsion will continue to dominate wheelchair sports and provide the most widespread method of wheeled mobility during daily activity. In the context of general mobility, the hand-rim wheelchair has become a task-specific, functional and versatile device that contributes to performance in activities of daily living and wheelchair sports hence is the mechanism that interacts closely with the human system. The investigation of push strategy is a particularly novel concept throughout the current thesis and it is clearly evident from **Figure 8.1** that there are a number of unknowns for the optimisation of push strategy and efficiency of hand-rim propulsion. Therefore, other key areas of study that future investigations could seek to address and further the knowledge into manual hand-rim wheelchair propulsion are discussed in the sub-sections:

1. Optimal push frequency
2. Force Application
3. Muscle activity
4. Adaptations in physiology and propulsion technique(s)
5. Segmental energy flow

Activities of daily life and wheelchair sports require the user to perform at different propulsion speeds (power outputs) whilst propelling a hand-rim wheelchair. Although the data presented in this thesis demonstrated the most optimal mechanical efficiency was found to be within the range of 60% - 100% of freely chosen push frequency, it is important to extend this to investigate the relationship that exists at a range of propulsion speeds. The extension would provide useful information as to the oxygen costs and mechanical efficiency trends to ensure a better understanding when considering push strategy selection. Extending the research further incorporating a range of propulsion speeds would allow the relationship observed in this thesis between push (arm) frequency and mechanical efficiency to be identified. This extension is logical particularly as in sport the amount of work done is affected predominantly by the speed of propulsion performed whereby rolling resistance is a more or less constant variable.

Force Application

The presented force application data does not correlate with mechanical efficiency and was unable to provide an explanation to the relatively low mechanical efficiency, although it did provide an important perspective of the biomechanics of the task. The trends/relationships demonstrated with push frequency/propulsion mode appear important to push strategy selection in relation to the levels of force exerted on the upper extremity and any clinical significance to wheelchair users, as opposed to the reduced energy costs and optimisation of mechanical efficiency. Experienced wheelchair users are more efficient and investigation into the force profiles with respect to push frequency and or propulsion mode in that population could offer some insight to the significant differences and trends reported. Rozendaal and colleagues [42] provided a simulation study on force direction, which suggested that experienced wheelchair users optimise the force pattern by balancing the mechanical effect as well as musculoskeletal cost. In addition the investigation into the braking torques at the start and end of push phase [48, 49] a variable associated with the term ineffective propulsion technique characteristics could also be valuable.

Muscle activity and adaptations in physiology/propulsion technique(s)

Electromyography analyses could be invaluable particularly the muscular activity and changes that occur when push strategy is manipulated may provide a more detailed assessment and understanding of the efficiency. Subsequent relationships with force application parameters could be considerably important. Clearly the efficiency of propulsion is affected significantly by push frequency and given the number of muscles involved in the upper extremity; movements can be conducted with different sets of active muscles. Examining the premise of co-contraction amongst muscles is essential, as in theory the more efficient arm/push frequency would presumably consist of lower levels of co-activity. Is there an optimisation of muscle synergies? Since muscle activity and kinematics in a laboratory environment could easily be measured, this would be very useful information. Any link between electromyography (muscle activity patterns), force production and mechanical efficiency would provide a valuable insight to help understand and explain the relative inefficiency. The inclusion of asynchronous propulsion alongside synchronous propulsion would be a novel approach and the electromyography data collected would add to the knowledge base that exists in the hand-rim propulsion literature.

Chapter 4 highlighted that wheelchair experience significantly improves the gross efficiency of hand-rim propulsion. Previous research and observations point to experienced individuals differing substantially in their propulsion techniques and these differences are the suggested to be responsible for improved efficiency. It would appear that there is a necessity for research into long term learning studies investigating the changes in movement/timing patterns coupled with muscle activity, which may offer valuable insight to the inefficiency and non-significant difference in efficiency of propulsion mode. The shoulder-arm muscle complex can offer a wide range of movements and may well result in a greater variability in repetitive movements of the upper extremity. Identifying the technical aspects of hand-rim propulsion related to efficiency would be important on a theoretical and practical level for both daily activities and sports utilising hand-rim wheelchairs.

Segmental energy flow

The comparison of synchronous and asynchronous propulsion did not discover any significant differences in what remain relatively low efficiency values, particularly in relation to the efficiency reported in handcycling and arm-cranking literature. The fundamental cause of this remains unclear despite the suggestions in this thesis and other researchers. The energy costs of propulsion have been quantified providing an insight into inefficiency; however, the causes remain undetermined. Hence, the investigation of segmental energy flow and the use of energetic analysis techniques could perhaps be pivotal to a better understanding. Studying how and where the energy is transferred during the movement cycle in the two distinct phases of propulsion (propulsion and recovery) could provide the information required to best answer the question of hand-rim propulsion inefficiency. The study of mechanical energy flow in hand-rim propulsion is very limited. The only studies to-date having investigated this are van der Helm & Veeger [31], by Guo and colleagues [27, 28] with the later study manipulating hand-rim diameter and more recently Huang et al. [34] manipulating camber. However, and crucially, the variable push (arm) frequency had not been taken into consideration. As this has been shown in the current thesis to be a major contributing factor to the relatively low efficiency of a push strategy, investigating segmental energy flow could well help evaluate and further understand changes in oxygen cost and efficiency.

References

1 Almåsbakk B, Whiting HTA, Helgerud, J. The efficient learner. Biol Cybern 2001; 84: 75-83.

2 Amazeen PG, Amazeen EL, Beek PJ. Coupling of breathing and movement during manual wheelchair propulsion. J Exp Psychol Hum Percept Perform 2001; 27: 1243-1259.

3 van den Berg R, de Groot S, Swart KM, van der Woude LH. Physical capacity after 7 weeks of low-intensity wheelchair training. Disabil Rehabil 2010; 32(26): 2244-52.

4 Boninger ML, Baldwin M, Cooper RA, Koontz A, Chan L. Manual wheelchair pushrim biomechanics and axle position. Arch Phys Med Rehab 2000; 81: 608-613.

5 Boninger ML, Cooper RA, Baldwin MA, Shimada SD, Koontz A. Wheelchair pushrim kinetics: body weight and median nerve function. Arch Phys Med Rehab 1999; 80: 910-915.

6 Boninger ML, Koontz AM, Sisto SA, Dyson-Hydson TA, Chang M, Price R, Cooper RA. Pushrim biomechanics and injury prevention in spinal cord injury: recommendations based on CULP-SCI investigations. J Rehabil Res Dev 2005; 42(3 suppl 1): 9-19.

7 Bregman DJJ, van Drongelen S, Veeger HEJ. Is effective force application in handrim wheelchair propulsion also efficient? Clin Biomech 2009; 24: 13-19.

8 Brubaker CE, McClay IS, McLaurin CA. Effect of seat position on wheelchair propulsion efficiency. In Proceedings of 2nd International Conference on Rehabilitation Engineering 1984; 12-14. Ottawa: Canadian Medical and Biological Engineering Society.

9 Dallmeijer AJ, Ottjes L, de Waardt E, van der Woude LHV. A physiological comparison of synchronous and asynchronous hand cycling. Int J Sports Med 2004a; 25: 1–5.

10 Dallmeijer AJ, Woude LHV van der, Veeger HEJ, Hollander AP. Effectiveness of force application in manual wheelchair propulsion in persons with spinal cord injuries. Am J Phys Med Rehab 1998; 77: 213-221.

11 Dallmeijer AJ, Zentgraaff ID, Zijp NI, Woude LHV van der. Sub-maximal physical strain and peak performance in handcycling versus hand-rim wheelchair propulsion. Spinal Cord 2004b; 42: 91–98.

12 Davis GM & Shephard RJ. Strength training for wheelchair users. Br J Sports Med 1990; 24(1): 25-30.

13 Van Dieen JH, Ogita F, de Haan A. Reduced neural drive in bilateral exertions: a performance-limiting factor? Med Sci Sports Exerc 2003; 35(1), 111-118.

14 Ekblom B & Goldbarg AN. The influence of physical training and other factors on the subjective rating of perceived exertion. Acta Physiol Scand 1971; 83: 399–406.

15 Fabre N, Perrey S, Arbez L, Ruiz J, Tordi N, Rouillon JD. Degree of coordination between breathing and rhythmic arm movements during hand rim wheelchair propulsion. Int. J. Sports Med 2006; 27: 67–74.

16 Gaesser GA, Brooks GA. Muscular efficiency during steady-rate exercise: effects of speed and work rate. J Appl Physiol 1975; 38: 1132–1139.

17 Glaser RM, Sawka MN, Young RE, Suryaprasad AG. Applied physiology for wheelchair design. J Physiol 1980; 48: 41–44.

18 Goosey VL, Campbell IG, Fowler NE. Effect of push frequency on the economy of wheelchair racers. Med Sci Sports Exerc 2000; 32: 174–181.

19 Goosey-Tolfrey VL, Kirk JH. Effect of push frequency and strategy variations on economy and perceived exertion during wheelchair propulsion. Eur J Appl Physiol 2003; 90: 153–158.

20 Goosey-Tolfrey VL, West M, Lenton JP, Tolfrey K. Influence of varied tempo music on wheelchair mechanical efficiency following 3-week practice. Int J Sports Med 2011; 32(2): 126-31.

21 de Groot S, Veeger HEJ, Hollander AP, van der Woude LHV. Consequence of feedback-based learning of an effective hand rim wheelchair force production on mechanical efficiency. Clin Biomech 2002a; 17: 219-226.

22 de Groot S, Veeger DHEV, Hollander AP, van der Woude LHV. Wheelchair propulsion technique and mechanical efficiency after 3 wk of practice. Med Sci Sports Exerc 2002b; 34: 756–766.

23 de Groot S, Veeger DHEV, Hollander AP, van der Woude LHV. Adaptations in physiology and propulsion technique during the initial phase of learning manual wheelchair propulsion. Am J Phys Med Rehab 2003a; 82(7): 504-510.

24 de Groot S, Veeger DHEV, Hollander AP, van der Woude LHV. Short- term adaptations in co-ordination during the initial phase of learning manual wheelchair propulsion. J. Electromyogr. Kinesiol 2003b; 13: 217–228.

25 de Groot S, Veeger HEJ, Hollander AP, van der Woude LHV. Effect of wheelchair stroke pattern on mechanical efficiency. Am J Phys Med Rehab 2004; 83: 640-649.

26 de Groot S, Veeger DHEV, Hollander AP, van der Woude LHV. Influence of task complexity on mechanical efficiency and propulsion technique during learning of hand rim wheelchair propulsion. Med Eng Phys 2005; 27(1): 41-49.

27 Guo LY, Su FC, An KN. Effect of handrim diameter on manual wheelchair propulsion: mechanical energy and power flow analysis. Clin Biomech 2006; 21(2): 107-15.

28 Guo LY, Su FC, Wu HW, An KN. Mechanical energy and power flow of the upper extremity in manual wheelchair propulsion. Clin Biomech 2003; 18(2): 106-14.

29 Haisma JA, Bussmann JB, Stam HJ, Sluis TA, Bergen MP, Dallmeijer AJ, de Groot S, van der Woude LHV. Changes in physical capacity during and after inpatient rehabilitation in subjects with a spinal cord injury. Arch Phys Med Rehab 2006; 87(6): 741-748.

30 Haisma JA, van der Woude LH, Stam HJ, Bergen MP, Sluis TA, Bussmann JB. Physical capacity in wheelchair-dependent persons with a spinal cord injury: a critical review of the literature. Spinal Cord 2006; 44(11): 642-52.

31 van der Helm TC, Veeger HEJ. Shoulder modelling in rehabilitation: The power balance during wheelchair propulsion. In: van der Woude LHV, Hopman MTE, van Kememade CH (Eds.), Biomedical Aspects of Manual Wheelchair Propulsion: The State of the Art II. IOS Press, Amsterdam, Netherlands 1999; pp. 96–103.

32 Hintzy F, Tordi N. Mechanical efficiency during hand-rim wheelchair propulsion: effects of base-line subtraction and power output. Clin Biomech 2004; 19: 343–349..

33 Hintzy F, Tordi N, Perrey S. Muscular efficiency during arm cranking and wheelchair exercise: A comparison. Int J Sports Med 2002; 23: 408–414.

34 Huang YC, Guo LY, Tsai CY, Su FC. Mechanical energy and power flow analysis of wheelchair use with different camber settings. Comput Methods Biomech Biomed Engin 2011; [Epub ahead of print] PMID: 22148959

35 Jacobs PL, Nash MS. Exercise recommendations for individuals with spinal cord injury. Sports Med 2004; 34(11): 727-751.

36 Kilkens OJ, Dallmeijer AJ, Nene AV, Post MW, van der Woude LHV. The longitudinal relation between physical capacity and wheelchair skill performance during inpatient rehabilitation of people with spinal cord injury. Arch Phsy Med Rehabil 2005; 86(8): 1575-1581.

37 Kilkens OJ, Post MW, Dallmeijer AJ, van Asbeck FW, van der Woude LH. Relationship between manual wheelchair skill performance and participation of persons with spinal cord injuries 1 year after discharge from inpatient rehabilitation. J Rehabil Res Dev 2005; 42(3 Suppl 1): 65-73.

38 Kotajarvi, BR, Basford JR, An KN, Morrow DA, Kaufman KR. The effect of visual biofeedback on the propulsion effectiveness of experienced wheelchair users. Arch Phys Med Rehab 2006; 87: 510-515.

39 Patterson P, Draper S. Selected comparisons between experienced and non-experienced individuals during manual wheelchair propulsion. Biomed Sci Instrum 1997; 33: 477-481

40 Rankin JW, Kwarciak AM, Mark Richter W, Neptune RR. The influence of altering push force effectiveness on upper extremity demand during wheelchair propulsion. J Biomech 2010; 43(14): 2771-2779.

41 Robertson RN, Boninger ML, Cooper RA, Shimada SD. Pushrim forces and joint kinetics during wheelchair propulsion. Arch Phys Med Rehab 1996; 77: 856-864.

42 Rozendaal LA, Veeger HEJ, van der Woude LHV. The push force pattern in manual wheelchair propulsion as a balance between cost and effect. J Biomech 2000; 36: 239-247.

43 Sanderson, D.J., and Sommer, H.J. 1985. Kinematic features of wheelchair propulsion. J. Biomech. 18(6): 423-429.

44 Seabury JJ, Adams WC, Ramey MR. Influence of pedalling rate and power output on energy expenditure during bicycle ergometry. Ergonomics 1977; 20: 491–498.

45 Sparrow WA, Irizarry-Lopez VM. Mechanical efficiency and metabolic cost as measures of learning a novel gross motor task. J Mot Behav 1987; 19(2): 240-264.

46 Sparrow WA, Newell KM. Metabolic energy expenditure and the regulation of movement economy. Psychonomic Bulletin & Review 1998; 5(2): 173-196.

47 Vanlandewijck Y, Theisen D, Daly D. Wheelchair propulsion biomechanics: implications for wheelchair sports. Sports Med 2001; 31: 339-367.

48 Veeger HEJ, van der Woude LHV, Rozendal RH. Within-cycle characteristics of the wheelchair push in sprinting on a wheelchair ergometer. Med Sci Sports Exerc 1991; 23: 264–271.

49 Veeger HEJ, van der Woude LHV, Rozendal RH. Effect of hand-rim velocity on mechanical efficiency in wheelchair propulsion. Med Sci Sports Exerc 1992; 24: 100-107.

50 van der Woude LHV, Bosmans I, Bervoets B, Veeger HEJ. Handcycling: different modes and gear ratio. J Med Eng Tech 2000; 24: 242–249.

51 van der Woude LH, Bouw A, van Wegen J, van As H, Veeger D, de Groot S. Seat height: effects on submaximal hand rim wheelchair performance during spinal cord injury rehabilitation. J Rehab Med 2009; 41: 143-149.

52 van der Woude LHV, Formanoy M, de Groot S. Hand rim configuration: effects on physical strain and technique in unimpaired subjects? Med Eng Phys 2003; 25: 765–774.

53 van der Woude LHV, de Groot G, Hollander AP, Ingen Schenau GJ van, Rozendal RH. Wheelchair ergonomics and physiological testing of prototypes. Ergonomics 1986; 29: 1561–1573.

54 van der Woude LHV, Horstman A, Faas P, Mechielsen S, Bafghi HA, de Koning JJ. Power output and metabolic cost of synchronous and asynchronous sub-maximal and peak level hand cycling on a motor driven treadmill in able-bodied male subjects. Med Eng Phys 2008; 30(5): 574-580.

55 van der Woude LHV, Veeger HEJ, Dallmeijer AJ, Janssen TWJ, Rozendaal LA. Biomechanics and physiology in active manual wheelchair propulsion. Med Eng Physics 2001; 23: 713–733.

56 van der Woude LHV, Veeger HEJ, Rozendal RH, Sargeant AJ. Optimum cycle frequencies in hand-rim wheelchair propulsion. Wheelchair propulsion technique. Eur J Appl Physiol 1989a; 58: 625–632.

Summary

The present thesis investigates the efficiency of synchronous and asynchronous hand-rim wheelchair propulsion strategies. Numerous factors make up the wheelchair-user combination and are suggested to contribute to wheelchair propulsion performance. Factors that can be easily manipulated by individuals are important starting points into the understanding of hand-rim wheelchair propulsion, in particular the physiological aspects and mechanical efficiency. This provides a platform for the both theoretical as well as practical significance in the context of propulsion. Generating information on optimum conditions for cyclic arm work in rehabilitation and wheelchair sports is important for the wheelchair performance and efficiency.

Chapter 1 presented an outline of hand-rim wheelchair propulsion introducing the area of investigation. The use of the conceptual model highlights numerous factors that can influence the performance/efficiency of wheelchair propulsion and reiterates the requirement for an interdisciplinary approach. The model is based upon the three basic qualities of the wheelchair-user combination that are crucial in determining performance in hand-rim wheelchair use [2, 3]. First, there is the user, who produces the energy and power for propulsion; second, the mechanics and technical status of the wheelchair; finally the interaction of the wheelchair and user which essentially will determine the efficiency of the power transfer from the user to the wheelchair. The chapter concludes with the research aims and thesis outline.

Chapter 2 provided information on mechanical efficiency determining the separate contributions of push (arm) frequency and the synchronous/asynchronous (SYN/ASY) propulsion modes on the internal work during hand-rim propulsion. By studying the different indices of efficiency (i.e. Gross, Net and Work) it was possible to assist in the understanding and recognition of the roles that internal and external work production has in hand-rim wheelchair propulsion push strategies. Results of the study exemplified this with significant changes in mechanical efficiency indices as the result of both push (arm) frequency and propulsion mode. Each of the different indices of efficiency has their own explanatory role for the effects of push strategy and is not necessarily redundant in understanding the efficiency and internal work. Effects of different push strategies are critical to the level of external work (velocity and power output) production. The energy cost of unloaded arm movements decreased with a lower number of arm movements, however, the complex task requirements of active hand-rim propulsion at both 1.2 $m \cdot s^{-1}$ and

1.7 $m \cdot s^{-1}$ was overruled for the benefit of a higher push (arm) frequency. Employing paced frequencies significantly affects metabolic and efficiency parameters; however, the asynchronous propulsion mode produced negative metabolic effects whereas the synchronous propulsion offered improved efficiency. It is important to note that this was only evident with a reduction in the total number of arm movements in the asynchronous mode and increased propulsion speed (power output), when comparing ASY(20:20) and SYN(40:40) and not ASY(40:40) to SYN(40:40). The physiological responses and mechanical efficiency indices in this study make it apparent that they are influenced by a combination of propulsion mode, push (arm) frequency, velocity and power output.

Chapter 3 was designed to focus on and determine the relationship of mechanical efficiency indices and different Push (arm) frequencies during synchronous and asynchronous hand-rim wheelchair propulsion. With limited research on push frequency and the results of **chapter 2** this progression was an important development to begin to further investigate the relationship of mechanical efficiency in both propulsion modes. In accordance to previous literature a curvilinear association of mechanical efficiency and push frequency was observed and the suggestion that a shift in 'active' internal work is responsible. However, in contrast the mechanical efficiency and $\dot{V}O_2$ are not optimised at the freely chosen push frequency (100%) due to the absence of any statistically significant differences in the lower push (arm) frequency range of 60 to 100% of the freely chosen push frequency. No significant difference was observed between propulsion modes under the testing conditions demonstrating the greater importance of push frequency. Push frequencies at or below those self-selected are advantageous in relation to oxygen cost and mechanical efficiency. It could be concluded that the 'active' internal work was similar for both modes under the task constraints of the study despite the different underlying task components.

Chapter 4 was an extension to **chapter 3** whereby the investigation introduced hand-rim wheelchair propulsion experience to the relationship of mechanical efficiency with push frequency and propulsion mode. Psycho-physiological measures were also introduced with the use of differentiated ratings of perceived exertion (Peripheral, Central and Overall). Physiological trends did not change as a result of propulsion experience despite the manipulation of push strategy (propulsion mode and push frequency). However, experience resulted in significantly greater mechanical efficiency across the push frequency conditions (% of freely chosen push frequency), propulsion mode and at higher absolute speed/power output. With the exception of hand-rim wheelchair propulsion experience the underlying mechanisms for the differences remain unclear, although it could well be the result of continued practice through training and daily wheelchair propulsion activity. The experience of hand-rim propulsion has allowed for the development of more optimal coordination, which results in improved propulsion technique, hence efficiency and a reduced relative metabolic cost.

The rating of perceived exertion scores followed the trend of absolute metabolic cost and not the mechanical efficiency. The refined movement patterns reduce the oxygen cost resulting in improved efficiency in comparison to unskilled able-bodied individuals. However, it was clear that the sensations experienced from the resulting manipulation of push (arm) frequency were what influenced the ratings of perceived exertion. Previous experience had no influence because of the non-significant difference between wheelchair sportsmen (experienced users) and able-bodied (novices) perceived exertion. The study also outlined that differentiated ratings of perceived exertion could be employed to support physiological findings in hand-rim propulsion in both participant groups. The differentiated ratings indicated that the peripheral exertion was the dominant sensation by which individuals perceive the exercise conditions in this task.

Chapter 5 developed from the findings in **chapter 3 and 4** and extended the hand-rim propulsion practice work of de Groot and colleagues [1]. Thus the consequence of unpaced and paced practice during asynchronous hand-rim wheelchair propulsion training on the gross efficiency, timing and sub-maximal performance was investigated. The concept of asynchronous propulsion practice was a novel concept and the practice element would support the theories suggesting propulsion experience to be a factor in the efficiency of hand-rim wheelchair propulsion. By including paced and unpaced frequency conditions for practice it was possible to investigate which method was more optimal. Hand-rim propulsion practice improved the mechanical efficiency and the profile demonstrated a shift towards a push (arm) frequency being that most closely to the frequency adopted during practice. Improvements were clearly associated with reductions in arm frequency and the freely chosen push frequency of both paced and unpaced groups following practice became the same as that at which they practiced. Despite the significant differences in push (arm) frequency of the paced and unpaced groups post practice the mechanical efficiency demonstrated no significant differences. Thus as in **chapters 3 and 4** there remains a range of frequencies whereby mechanical efficiency continues to be optimal given the task constraints.

Chapter 6 and 7 investigated force production and the fraction of effective force as a result of changes in push strategy (both propulsion mode and push frequency) to help understand the changes seen in mechanical efficiency. The results aimed to provide important information as to the relationship of force application from both a push strategy and mechanical efficiency perspective. In conclusion, increased push frequency generally resulted in a reduction in the absolute values of the force parameters, with the exception of rate of force development which increased. These findings could be useful in the link with overuse injuries. The fraction of effective force remained somewhat unchanged and along with the force parameters studied did not reflect the trend in gross efficiency. Push frequency merely affects the force components in such a way that the ratio of the tangential force to the resultant force remains somewhat proportional to one another despite changes in push angle and push time. Despite the gross efficiency of propulsion not being able to be linked directly with the fraction of effective force it is important to acknowledge the important relationship of force application with push frequency. Results continued to support previous findings that push frequencies in untrained participants at or below the freely chosen push frequency are close to optimal energy cost and efficiency. At identical push frequencies the asynchronous propulsion mode produced significantly greater forces and rate of force development, which could be of importance in relation to the risk of injury. Force application differences appear to be attributable to the mode of propulsion when push frequencies are matched whereas gross efficiency differences are a combination of both propulsion mode and push frequency under given conditions of power output and speed. Understanding how individuals apply force to the hand-rim in push strategies provides important information for determining interventions to perhaps reduce the levels of force exerted on the upper extremity joints and limiting the risk of injury whilst at the same time maintaining optimal levels of efficiency.

Chapter 8 is the general discussion and concluded that the use of mechanical efficiency indices can help to better explain and understand the roles of internal and external work and importantly any conclusions about mechanical efficiency could well be misinterpreted if the indices definitions are not taken into account. With the comparison of the indices it is possible to produce a more complete description of efficiency and begin to focus on developing further research for the explanation of the relatively low efficiency associated with hand-rim wheelchair propulsion. Under the constraints of the studies presented in the thesis it is apparent that the mode of propulsion does not have as important a role to play in the changes in mechanical efficiency. Push (arm) frequency is a key contributor, whilst demonstrating a need for frequencies to remain at the freely chosen push frequency or lower for any the optimisation of mechanical efficiency. It is acknowledged, however, that further verification of the relationships observed would need to progress at different velocities and levels of power output. Experience of propulsion is also important with practice at paced and unpaced arm frequencies having led to improvements in mechanical efficiency. The patterns of force application across push frequency provide important information for users in terms of absolute forces and importantly the rate of force development which is suggested in the literature to be linked to the risk of injury. This information could help in push strategy selection. The limitations of the thesis are discussed in the critical reflections section under the sub-headings of able-bodied participants, experimental set-up and protocol – speed vs. resistance, as well as outcomes on mechanical efficiency and perceived exertion. Finally conclusions, implications of the research and future directions are outlined.

References

1 de Groot S, Veeger DHEV, Hollander AP, van der Woude LHV. Wheelchair propulsion technique and mechanical efficiency after 3 wk of practice. Med Sci Sports Exerc 2002b; 34: 756–766.

2 van der Woude LHV, de Groot G, Hollander AP, Ingen Schenau GJ van, Rozendal RH. Wheelchair ergonomics and physiological testing of prototypes. Ergonomics 1986; 29: 1561–1573.

3 van der Woude LHV, Veeger HEJ, Dallmeijer AJ, Janssen TWJ, Rozendaal LA. Biomechanics and physiology in active manual wheelchair propulsion. Med Eng Physics 2001; 23: 713–733.

Samenvatting

Samenvatting

In het huidige proefschrift wordt de efficiëntie of het mechanisch rendement van synchroon versus asynchroon hoepelrolstoelrijden bij verschillende bewegingsstrategiën onderzocht. Talrijke factoren bepalen de rolstoel-gebruiker combinatie en worden verondersteld bij te dragen aan de rij-prestatie en het functioneren van de persoon in de rolstoel. Factoren die eenvoudig door de gebruiker kunnen worden beinvloed - in het bijzonder de fysiologische aspecten en het mechanische rendement - zijn belangrijke startpunten voor het leren begrijpen van hoepelrolstoelrijden. Deze kennis is van zowel theoretische als praktische betekenis en geeft richting aan het vaststellen van de optimale voorwaarden voor cyclische rolstoelarmarbeid in de revalidatie en rolstoelsport en is bepalend voor het gemak van het functioneren en het presteren van de rolstoelgebruiker.

Hoofdstuk 1 introduceert het onderzoeksterrein rond hoepelrolstoelvoortbeweging. Aan de hand van een conceptueel model worden diverse factoren besproken die invloed kunnen hebben op de prestaties en efficiëntie van rolstoelaandrijving. Hierin wordt verder het belang van een interdisciplinaire onderzoeksbenadering benadrukt. Het model is gebaseerd op de drie centrale domeinen van de rolstoel-gebruiker combinatie, zoals eerder voorgesteld door Woude et al. [53, 56], die van cruciaal belang zijn voor hoepelrolstoelgebruik. Ten eerste is er de gebruiker, die de krachten en energie voor de voortbeweging produceert; ten tweede is er de mechanica en de technische staat van de rolstoel die het uitwendig vermogen bepalen; tot slot is er de interactie tussen de rolstoel en de gebruiker die bepalend zijn voor de efficiëntie van de vermogensoverdracht van de gebruiker naar de rolstoel. Het hoofdstuk wordt afgesloten met de onderzoeksvragen en -doelstellingen.

Hoofdstuk 2 bestudeert het mechanische rendement en de interne arbeid van hoepelrolstoelrijden in afhankelijkheid van arm- of duwfrequentie enerzijds en synchroon/asynchroon (SYN/ASY) aandrijven anderzijds. Door verschillende maten voor efficiëntie (o.a. bruto, netto delta efficiëntie) te bestuderen was het mogelijk om de rollen voor interne en externe arbeidsleverantie tijdens de verschillende strategiën voor hoepelrolstoelrijden nader te onderscheiden. Zo werden als gevolg van zowel armfrequentie en aandrijfmodus significante veranderingen in de verschillende maten voor mechanisch rendement gevonden. Elk van de verschillende maten voor efficiëntie heeft haar verklarende en onderling aanvullende rol voor de gevonden effecten van de duwstrategie op het energieverbruik. Verschillende duwstrategieën zijn cruciaal voor het leveren van verschillende niveau's van externe arbeid (in termen van snelheid en uitwendig vermogen). Het energieverbruik van onbelaste rolstoelduwbewegingen nam af bij een lagere bewegingsfrequentie, maar de complexe taakeisen van actieve hoepelaandrijving bij 1.2 $m \cdot s^{-1}$ en 1,7 $m \cdot s^{-1}$ kwam gunstiger uit voor condities met een hogere frequentie van de armen. Het opleggen van verschillende bewegingsfrequenties beinvloedt de metabole uitkomst en de efficiëntie parameters; het rijden in de asynchrone modus was meer belastend; de synchrone aandrijving bleek efficiënter. Dit was evenwel alleen het geval voor de vergelijking tussen ASY (20:20) en SYN (40:40) en niet voor ASY(40:40) vs SYN (40:40). De fysiologische uitkomsten en de rendementsmaten in deze studie laten zien dat zij worden beïnvloed door een combinatie van aandrijfmodus, armfrequentie, snelheid en uitwendig vermogen.

Hoofdstuk 3 was gericht op een verdere analyse van de relatie tussen verschillende maten voor mechanisch rendement en verschillende armbewegingsfrequenties tijdens SYN en ASY hoepelrolstoelrijden. Gegeven het beperkte eerdere onderzoek rond hoepelduwfrequentie en de resultaten van hoofdstuk twee wordt hiermee een impuls gegeven aan verder inzicht in de relatie tussen mechanische efficiëntie en aandrijfstrategie. In overeenstemming met eerdere studies werd een kromlijnig verband gevonden tussen mechanische efficiëntie en duw- frequentie; dit suggereert dat een verschuiving in 'actieve' interne arbeid hiervoor verantwoordelijk is. Echter, in tegenstelling tot onze verwachting, waren mechanisch rendement en zuurstofopname niet optimaal op of rond de vrijgekozen bewegingsfrequentie (100%) en ontbraken statistisch significant verschillen in de lagere opgelegde duwfrequenties tussen 60 en 100% van de vrijgekozen bewegingsfrequentie. Ook werd er geen significant verschil gevonden tussen de aandrijfmodi, waarmee het grotere belang van bewegingsfrequentie voor de energiehuishouding onder de gegeven experimentele omstandigheden aannemelijk lijkt. Duwfrequenties op of onder vrijgekozen frequentie zijn gunstiger met betrekking tot zuurstofopname en mechanische efficiëntie. Er werd geconcludeerd dat de 'actieve' interne arbeid vergelijkbaar is voor beide voortbewegingsmodi onder de gegeven studierandvoorwaarden, ondanks de grote verschillen in de bewegingstaak zelf.

Hoofdstuk 4 was opnieuw een uitbreiding op het experiment van **hoofdstuk 3,** waarbij hoepelrolstoelervaring werd geïntroduceerd in de relaties tussen mechanische efficiëntie, duwfrequentie en aandrijfmodus. Psycho-fysiologische maten werden verder geïntroduceerd aan de hand van drie verschillende (perifere, centrale en algemene) schalen voor ervaren inspanning. De trends in de fysiologische data waren niet verschillend als gevolg van rolstoelervaring, ongeacht de manipulatie van armfrequentie en aandrijfmodus. Rolstoelervaring resulteerde evenwel in een aanzienlijk hogere mechanische efficiëntie over de range van duwfrequenties (% van vrijgekozen frequentie), de aandrijfmodi bij een hogere snelheid en uitwendig vermogen. Met uitzondering van hoepelrolstoelrijervaring (dus taaktraining) in het dagelijks leven blijven de onderliggende mechanismen voor de gevonden verschillen onduidelijk. De ervaring van hoepelrolstoelgebruik zal hebben geleid tot de ontwikkeling van een betere coördinatie, wat ondermeer in een verbeterde aandrijftechniek tot uiting komt, wat weer leidt tot een hogere efficiëntie en een verminderde zuurstofopname.

De ervaren inspanning volgde de trends in het energieverbruik en niet die van het mechanische rendement. De naar verwachting meer verfijnde bewegingspatronen van de ervaren rolstoelgebruikers verminderen de zuurstofopname, hetgeen resulteert in een betere efficiëntie in vergelijking met onervaren niet-rolstoelgebruikers. De scores voor ervaren inspanning werden gedomineerd door duwfrequentie; onder de gegeven testomstandigheden had rolstoelervaring geen effect op ervaren inspanning. Het onderzoek onderstreept ook dat verschillende maten voor ervaren inspanning kunnen helpen de gevonden fysiologische bevindingen in hoepelrolstoelrijden in beide deelnemende groepen te onderbouwen. De perifeer ervaren inspanning lijkt evenwel de dominante sensatie die personen tijdens uitoefening van deze rolstoeltaak als belastend waarnemen.

Hoofdstuk 5 is uitgevoerd op basis van de bevindingen in **hoofdstuk 3 en 4** en is tevens een uitbreiding op het werk van de Groot et al. [21]. Zo werd het effect van oefenen met al dan niet opgelegde bewegingsfrequentie tijdens asynchroon hoepelrolstoelrijden onderzocht op het bruto mechanisch rendement, de timing en de sub-maximale belasting. Asynchrone rolstoelaandrijving is een nieuw element in het rolstoelonderzoek rond oefeneffecten en de mechanische efficiëntie en techniek van hoepelrolstoelrijden. De toevoeging van het wel en niet vrijlaten van bewegingsfrequentie zou de leertheorie ook verder kunnen helpen uitbouwen en de vraag helpen beantwoorden welke strategie meer optimaal is. Oefenen bevordert de mechanische efficiëntie van rolstoelrijden, terwijl de optimale bewegingsfrequentie in de natest het dichts ligt bij die frequentie waarop ook geoefend werd. Verbeteringen waren zichtbaar in de afname van de bewegingsfrequentie met oefenen, terwijl de vrijgekozen bewegingsfrequentie na het oefenen voor zowel de opgelegde als de niet-opgelegde oefengroep meer en meer overeenkwam met de frequentie waarop ook daadwerkelijk geoefend was. Ondanks de significante verschillen in bewegingsfrequentie tussen de oefengroepen met de opgelegde en niet-opgelegde bewegingsfrequentie, was de mechanische efficiëntie na het oefenen niet verschillend tussen de groepen. Evenals in de hoofdstukken 3 en 4 werd gezien, is er onder de gegeven experimentele omstandigheden een range van bewegingsfrequenties waar de mechanische efficiëntie min of meer optimaal blijft op groepsniveau.

Hoofdstukken 6 en 7 onderzochten de krachtleverantie en haar effectiviteit tijdens hoepelrolstoelrijden in afhankelijkheid van duwstrategie (zowel bewegingsfrequentie als –modus) om zo de veranderingen in mechanisch rendement verder te helpen begrijpen. De resultaten zouden zo inzicht geven in de relatie tussen krachtleverantiekenmerken en de duwstrategie enerzijds en de mechanische efficiëntie anderzijds. Een hogere bewegingsfrequentie resulteerde in het algemeen in een vermindering van de absolute krachtparameters met uitzondering van snelheid van krachtsopbouw in de duw. Deze bevindingen lijken belangrijk in het licht van blessure- en overbelastingsproblematiek van het bovenlichaam. De effectiviteit van de kracht bleef min of meer onveranderd over de condities en lijkt tesamen met de andere krachtparameters niet geassocieerd met de gevonden trends in de mechanische efficiëntie. Duwfrequentie beïnvloedt de krachtcomponenten zo dat de effectieve (tangentiële) kracht proportioneel aan de totale kracht vector verandert, tesamen met veranderingen in duwhoek en –tijd. Hoewel de krachtcomponenten en haar effectiviteit niet direct geassocieerd zijn met mechanische efficiëntie, is er wel een relatie met bewegingsfrequentie. De resultaten ondersteunden opnieuw eerdere bevindingen dat in ongetrainde deelnemers bewegingsfrequenties op of onder de vrijgekozen bewegingsfrequentie dicht bij het optimale energieverbruik en efficiëntie liggen. Rond identieke duwfrequenties werden in de asynchrone modus significant hogere krachten (en de snelheid van krachtsopbouw) gezien dan in de synchrone modus; dit is opnieuw van belang voor de preventie van blessures en overbelasting. Asynchroon of synchroon voortbewegen bij eenzelfde armfrequentie lijkt van invloed op krachtleverantiekenmerken, terwijl bewegingsmodus en –frequentie tezamen dan van invloed zijn op mechanische efficiëntie. Hoe mensen kracht leveren tijdens verschillende strategiën van hoepelrolstoelrijden is belangrijk om te begrijpen, zodat interventies kunnen worden ontwikkeld die de belasting van rolstoelgebruik op armen en schouders en de kans op blessures kunnen helpen verminderen, terwijl tevens de efficiëntie van voortbewegen wordt geoptimaliseerd.

Hoofdstuk 8 vormt de algemene discussie. Geconcludeerd wordt dat het gebruik van verschillende maten voor mechanisch rendement bijdraagt aan het verklaren van de rol van interne en externe arbeid in hoepelrolstoelrijden. Vooral ook kunnen resultaten van mechanisch rendement foutief worden geïnterpreteerd als de definities van de verschillende maten voor efficiëntie niet eenduidig worden meegenomen. Met de vergelijking van de verschillende maten voor efficiëntie is het mogelijk om een meer volledige beschrijving van de energiehuishouding te geven. Vervolgens kan onderzoek gericht worden op de verdere verklaring van de relatief lage efficiëntie die bij hoepelrolstoelrijden wordt gezien. Binnen de beperkingen van de gepresenteerde studies in dit proefschrift is het duidelijk dat de wijze van aandrijving (SYN vs. ASY) van de hoepelrolstoel van minder invloed is op het mechanisch rendement. Duwfrequentie daarentegen is een sleutelfactor, waarbij een bewegingsfrequentie op 100% van de vrijgekozen bewegingsfrequentie of lager optimaal lijkt in termen van mechanische efficiëntie. Vervolgonderzoek zal zich daarbij alsnog moeten richten op verschillende snelheids- en vermogenscondities. Ervaring met hoepelrolstoelrijden is ook belangrijk, waarbij oefenen met opgelegde en niet-opgelegde bewegingsfrequenties beide tot significante verbeteringen in efficiëntie leidt. Het patroon van krachtleverantie en krachtopbouw bij verschillende bewegingsfrequenties geeft een aanvullend beeld omtrent de risico's van overbelasting en blessures en kan helpen om adequate bewegingsstrategiën en -techniek te adviseren. Bij de beperkingen van het onderzoek wordt aandacht besteed aan de thema's deelnemergroepen, experimentele opzet, -uitvoering en -protocol, alsook de maten voor mechanisch rendement en ervaren inspanning. Tot slot worden praktische implicaties van het onderzoek en de toekomstige onderzoeksrichtingen gepresenteerd.

References

1 de Groot S, Veeger DHEV, Hollander AP, van der Woude LHV. Wheelchair propulsion technique and mechanical efficiency after 3 wk of practice. Med Sci Sports Exerc 2002b; 34: 756–766.

2 van der Woude LHV, de Groot G, Hollander AP, Ingen Schenau GJ van, Rozendal RH. Wheelchair ergonomics and physiological testing of prototypes. Ergonomics 1986; 29: 1561–1573.

3 van der Woude LHV, Veeger HEJ, Dallmeijer AJ, Janssen TWJ, Rozendaal LA. Biomechanics and physiology in active manual wheelchair propulsion. Med Eng Physics 2001; 23: 713–733.

Acknowledgements

There have been many 'challenging' times during my research work and there are many people who have played a part in the completion of this thesis. Firstly I would like to thank my Dad for his love, support and belief in me throughout and always being on hand to give advice during the difficult times. Special thanks also go to Debbie my wonderful wife for having to put up with me; "I know I've not been the easiest person to get along with during periods of my research work but without your love and belief in me, I don't know what I would have done".

I am most grateful to the members of my supervisory team who have helped me along this journey. Prof. Lucas van der Woude for providing me with the opportunity to undertake and complete my PhD, Lucas has not only been a mentor to me and my research but importantly a friend from whom I have learnt so much from as he has shared his vast depth of knowledge into hand-rim wheelchair propulsion. I can only hope to continue to work with Lucas in the future on research projects and benefit from his expertise. Dr. Vicky Tolfrey for her continued support throughout the process as I continue to learn under her leadership at Peter Harrison Centre for Disability Sport, School of Sport, Exercise & Health Sciences, Loughborough University and involvement in research projects into disability sport. I would also like to thank Prof. Neil Fowler for his support and advice throughout.

The research studies in this thesis were supported financially by the Manchester Metropolitan University for which I am most appreciative alongside the technical support which was made possible by the time and efforts of Tom Mckee, Garry Pheasey and Rob Perkins. Particular thanks go to Tom for his continuous support and technical expertise in the development of the wheelchair ergometer software. Many thanks go to RGK Wheelchairs, in particular Russ Simmons for loan of the wheelchairs and Bromakin Wheelchairs for the wheelchair roller ergometer used throughout the research.

Finally, a sincere 'thank you' to all the participants and athletes who gave up their time to partake in the studies, my friends both past and present, that have helped on my PhD journey and shared my experiences.

Dedication

This thesis is dedicated to the memory of two very special people. Firstly, my mum Lorraine Lenton who passed away in October 1992 after losing her battle with breast cancer. "Mum I miss you so very much, I will love you always and hope that you're proud of me. It's been a difficult journey but I have developed as a person both professionally and personally with new skills and learnt so much throughout my journey". Secondly is Dr. Graham Nicholson who was tragically killed in a motorcycle accident, August 2006. Graham was an exceptional individual who I was fortunate to have known and worked alongside. In doing so I gained a special friend who is dearly missed but not forgotten, so if you're listening Graham "thanks for everything".

I would like to share with everyone a reading that has helped me through the most difficult time in my life when coping with the passing of mum, Lorraine – "Remembered Tenderly, Loved Completely."

Death is nothing at all,
I have only slipped away into the next room.
I am I and you are you.
Whatever we were to each other,
That we are still!
Call me by my old familiar name.
Speak to me in the easy way you always used.
Put no difference into your tone,
Wear no forced air of solemnity or sorrow.
Laugh as we always laughed,
At the little jokes we always enjoyed together.
Play, smile, and think of me. Pray for me.
Let my name be ever the household word that it always was.
Let it be spoken without effort,
Without the ghost of a shadow in it.
Life means all that it ever meant.
It is the same as it ever was,
There is absolute unbroken continuity.
What is death but a negligible accident?
Why should I be out of mind?
Because I am out of sight!
I am waiting for you for an interval,
Somewhere very near,
Just around the corner….
All is well.
Nothing is past; nothing is lost
One brief moment and all will be as it was before.
How we shall laugh at the trouble of parting when we meet again!

Canon Henry Scott-Holland, 1847-1918, Canon of St Paul's Cathedral.

Publications

Publications

Lenton, JP, van der Woude LHV, Fowler NE, Nicholson G, Tolfrey K, Goosey-Tolfrey, V.L. Hand-rim forces and gross mechanical efficiency at various frequencies of wheelchair propulsion. Int J of Sports Med. 2012 Aug 23 [Epub ahead of print]

Sindall P, Lenton JP, Tolfrey K, Cooper RA, Oyster M, Goosey-Tolfrey VL. Wheelchair tennis match-play demands: effect of player rank and result. Int J Sports Physiol Perform. 2012 Aug 1. [Epub ahead of print]

Leicht CA, Tolfrey K, Lenton JP, Bishop NC, Goosey-Tolfrey VL. The verification phase and reliability of physiological parameters in peak testing of elite wheelchair athletes. Eur J Appl Physiol. 2012 Jun 21. [Epub ahead of print]

Mason B, van der Woude L, Lenton JP, Goosey-Tolfrey V. The Effect of Wheel Size on Mobility Performance in Wheelchair Athletes. Int J Sports Med. 2012 May 16. [Epub ahead of print]

Mason BS, Van Der Woude LH, Tolfrey K, Lenton JP, Goosey-Tolfrey VL. Effects of wheel and hand-rim size on submaximal propulsion in wheelchair athletes. Med Sci Sports Exerc. 2012; 44(1):126-34.

Goosey-Tolfrey VL, West M, Lenton JP, Tolfrey K. Influence of varied tempo music on wheelchair mechanical efficiency following 3-week practice. Int J Sports Med. 2011; 32(2):126-31.

Goosey-Tolfrey VL, Lenton JP, Goddard J, Oldfield V, Tolfrey K, Eston R. Regulating Intensity Using Perceived Exertion in Spinal Cord-Injured Participants. Med Sci Sports Exerc 2010; 42(3): 608-613.

Lenton JP, Van Der Woude LH, Fowler NE, Goosey-Tolfrey V. Effects of 4-weeks of asynchronous hand-rim wheelchair practice on mechanical efficiency and timing. Disabil Rehabil. 2010; 32(26):2155-64. Erratum in: Disabil Rehabil. 2011; 33(6):537.

Croft L, Dybrus S, Lenton J, Goosey-Tolfrey V. A comparison of the physiological demands of wheelchair basketball and wheelchair tennis. Int J Sports Physiol Perform. 2010; 5(3):301-15.

Lenton JP, van der Woude L, Fowler N, Goosey-Tolfrey V. Effects of arm frequency during synchronous and asynchronous wheelchair propulsion on efficiency. Int J Sports Med. 2009; 30(4):233-9.

Lenton JP, Fowler NE, van der Woude L, Goosey-Tolfrey VL. Wheelchair propulsion: effects of experience and push strategy on efficiency and perceived exertion. Appl Physiol Nutr Metab. 2008; 33(5):870-9.

Lenton JP, Fowler N, van der Woude L, Goosey-Tolfrey VL. Efficiency of wheelchair propulsion and effects of strategy. Int J Sports Med. 2008; 29(5):384-9.

Goosey-Tolfrey VL, Lenton JP. A comparison between intermittent and constant wheelchair propulsion strategies. Ergonomics. 2006; 49(11):1111-20.

Submitted for publication

Lenton JP, van der Woude LHV, Fowler NE, Nicholson G, Tolfrey K, Goosey-Tolfrey VL. Hand-rim forces and gross mechanical efficiency in asynchronous and synchronous wheelchair propulsion: a comparison

Croft L, Lenton JP, Tolfrey K, Goosey-Tolfrey VL. Energy expenditure of wheelchair propulsion at fixed power outputs: effect of experience.

Croft L, Lenton JP, Tolfrey K, Goosey-Tolfrey VL. Energy expenditure of wheelchair propulsion in novice individuals after 3 weeks practice

Sindall PA, Whytock K, Lenton JP, Tolfrey K, Oyster M, Cooper RA, Goosey-Tolfrey VL. Criterion validity and accuracy of global positioning satellite and data logging devices for wheelchair tennis court movement

Conference communications

Lenton JP, Fowler NE, van der Woude LHV, Goosey-Tolfrey VL. Mechanical efficiency of asynchronous hand-rim wheelchair propulsion after 4-weeks of practice. 4th International state-of-the-art Congress 'Rehabilitation: Mobility, Exercise & Sports'. Amsterdam, the Netherlands, 7-9 April 2009.

Lenton JP, Wilson L, Goosey-Tolfrey VL. Wheelchair tennis fan drill test: A predictor of anaerobic performance? Feasibility study with able-bodied participants. BPA sports science and medicine conference. Loughborough, United Kingdom, 4-5 March 2009.

Lenton JP, Goosey-Tolfrey VL. Physiological support: GB wheelchair tennis in Florida 2007. BPA sports science and medicine conference. Loughborough, United Kingdom, 5-6 March 2008.

Goosey-Tolfrey VL, Lenton JP, Fowler NE, van der Woude LHV, Nicholson G. The influence of push frequency on force application during steady-state manual wheelchair propulsion. BPA sports science and medicine conference. Loughborough, United Kingdom, 2-3 March 2007.

Goosey-Tolfrey VL, Lenton JP, Fowler NE, van der Woude LHV, Nicholson G, Batterham A. The Influence of push frequency on force application during steady-state hand-rim wheelchair propulsion. ACSM 53rd annual conference. Colorado, USA, 31 May – 4 June 2006.

Lenton JP, Fowler NE, van der Woude LHV, Goosey-Tolfrey VL. Effect of push frequency on gross mechanical efficiency during asynchronous and synchronous manual wheelchair propulsion. BPA sports science and medicine conference. Loughborough, United Kingdom, 3-4 February 2006.

Lenton JP, van der Woude LHV, Fowler NE, Goosey-Tolfrey VL. Effect of push frequency on gross mechanical efficiency during asynchronous and synchronous manual wheelchair propulsion. BASES annual conference. Loughborough, United Kingdom, 4-7 September 2005.

Goosey-Tolfrey VL, Lenton JP. Push frequency and sequential push strategy variations during synchronous wheelchair propulsion on economy. BASES annual conference. Loughborough, United Kingdom, 4-7 September 2005.

Lenton JP, Fowler NE, van der Woude LHV, Goosey-Tolfrey VL. Effects of push frequency and sequential push strategy variations during synchronous wheelchair propulsion on economy BASES annual conference. Loughborough, United Kingdom, 4-7 September 2005.

Lenton JP, Fowler NE, van der Woude LHV, Goosey-Tolfrey VL. Efficiency of synchronous and asynchronous wheelchair propulsion at two selected speeds. 3rd International Congress: Restoration of (wheeled) mobility in spinal cord injury rehabilitation: state of the art III. Amsterdam, the Netherlands, 19-21 April 2004.

Goosey-Tolfrey VL, Lenton JP, Slater C. Peak physiological responses to asynchronous and synchronous wheelchair exercise. 3rd International Congress: Restoration of (wheeled) mobility in spinal cord injury rehabilitation: state of the art III. Amsterdam, the Netherlands, 19-21 April 2004.

Curriculum Vitae

Curriculum Vitae

John Lenton was born on the 15th August 1980 in Whiston, Knowsley, England. He finished high school at Great Sankey in 1996. Thereafter he studied Sports Studies, Maths, Biology and Chemistry at A-Level before leaving for university, September 1999. Attending the Manchester Metropolitan University, he studied Sport and Exercise Science obtaining his BSc in 2002. Continuing with his studies he went on to complete an M.PhiL. "Mechanical efficiency of push strategies during manual hand-rim wheelchair propulsion" in 2008 at the Institute for Biophysical & Clinical Research into Human Movement, Department of Exercise & Sport Science, *the* Manchester Metropolitan University, England.

During his study he worked voluntarily from 2001-2005 with the England Amputee Football Squad assisting in sports science support and coaching practices to international players. From 2007-2009 he worked as an applied sport scientist to Great Britain Wheelchair Tennis, attending the Beijing 2008 Paralympic Games. Continuing to work in the area of disability sport he was appointed as a Research Assistant (Sports Science) in the Peter Harrison Centre for Disability Sport, Loughborough University in 2009. During which he alongside the excellent guidance of Dr. Vicky Tolfrey established a cutting-edge laboratory to work with wheelchair athletes and other athletes with disability to provide Sports Science Support and conduct important research projects. In June 2010 John registered to complete his PhD studies in the Centre for Human Movement Sciences, University Medical Centre at the University of Groningen. Throughout the process he was supervised by Professor Lucas van der Woude (Centre for Human Movement Sciences, University Medical Centre at the University of Groningen), Dr. Vicky Tolfrey (Peter Harrison Centre for Disability Sport, SSEHS, Loughborough University) and Professor Neil Fowler (Department of Exercise & Sport Science, the Manchester Metropolitan University). Currently, John is still working at the Peter Harrison Centre for Disability Sport in Loughborough, where he will continue his research and support work focussing on hand-rim propulsion in laboratory and field-based environments.