EFFECTS OF MOTOR SKILL-BASED WHEELCHAIR PROPULSION TRAINING ON BIOMECHANICS, GROSS MECHANICAL EFFICIENCY, AND VARIABILITY IN OLDER ADULTS

by

Megan Kathleen MacGillivray

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BSc, St. Francis Xavier University, 2007

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Examining Committee:

Elizabeth Dean, Rehabilitation Sciences
Supervisor

Bonita Sawatzky, Orthopaedics
Supervisory Committee Member

Janice Eng, Rehabilitation Sciences
Supervisory Committee Member

Nicola Hodges, Kinesiology
University Examiner

Jill Zwicker, Rehabilitation Sciences
University Examiner

Abstract

Older adults are the largest cohort of manual wheelchair users (MWUs); yet, no studies have examined the effects of wheelchair propulsion training with this population. Various practice and training protocols have demonstrated mixed results related to biomechanics and efficiency when applied to younger able-bodied populations; however, their validity for older adult MWUs is unknown. Older adult MWUs are at risk of decreased participation, low confidence, and wheelchair abandonment; therefore, effective training strategies are needed for this population.

The objectives of this study were to: (1) examine the effectiveness of existing handrim wheelchair propulsion practice and training protocols; (2) determine the effect of motor skill-based wheelchair propulsion training in older adults on (i) wheeling biomechanics, (ii) gross mechanical efficiency (GME), and (iii) intercycle variability; and (3) determine the effect of motor-skill based wheelchair propulsion training for older adults with mobility disabilities.

Methods: Studies evaluating the effect of wheelchair propulsion practice or training protocols were systematically reviewed and meta-analyzed. The effect of motor skill-based training in able-bodied older adults compared to active (uninstructed practice) and inactive control groups was examined with a 3-arm RCT (*n*=34). The effect of motor skill-based training was compared to uninstructed practice in two individuals with mobility-related disabilities within a single subject research design study.

Results: Significant medium effects of practice and training protocols for pre-post design studies were observed for push angle, push frequency, and GME. The motor skill-based training resulted in increased push angle and decreased push frequency, which were transferable to over-ground wheeling and retained two-weeks post training. Although there were no improvements in GME, a trend towards increased work per push following training was observed. Intercycle variability did not change based on training; however, nearly all participants in the training group modified their wheeling pattern from the arc to semi-circular pattern. Lastly, both older adult participants with mobility disabilities increased their push angles and decreased their push frequencies and peak negative forces.

Conclusion: Motor skill-based wheelchair propulsion training is an effective means of improving handrim wheelchair propulsion biomechanics among novice older adult MWUs, which may help reduce overuse injuries in older MWUs.

Lay summary

Older adult manual wheelchair users are at risk of reduced participation in physical and leisure activity and may have low wheelchair-related confidence; however, most wheelchair propulsion research has excluded older adults. This thesis aimed to compile and summarize the current evidence for wheelchair propulsion training and apply those findings to our own wheelchair propulsion training for older adults. We tested our training among older adults without disabilities to examine how older adults with no prior wheeling experience might respond to the training compared to uninstructed practice or no practice. Lastly, we tested our training among two older adults with physical disabilities to examine how they responded to the training. Our training was effective in modifying movement patterns in both able-bodied participants and those with physical disabilities. Interestingly, the active control group showed no improvements, suggesting that unguided practice (i.e., experience) is not sufficient to improve wheelchair propulsion in older adults.

Preface

The research for this dissertation took place at the Blusson Spinal Cord Centre, Vancouver, British Columbia. The three studies and corresponding methods and analyses that comprise this dissertation were developed by the student (Megan Kathleen MacGillivray), in consultation with a supervisory committee, including supervisors (Elizabeth Dean and Bonita J. Sawatzky) and committee member (Janice J. Eng). Ethical approval was obtained from the Clinical Research Ethics Board at the University of British Columbia for chapters, 3, 4, and 5 (certificate #: H14-00253) and Vancouver Coastal Health Research Institute (certificate #: V14-00253) and from the Clinical Research Ethics Board at the University of British Columbia (certificate #: H16-01181) and Vancouver Coastal Health Research Institute (certificate #: V16-01181) for chapter 6. The protocol for the randomized controlled trial referred to in chapters 3, 4, and 5 was registered with the NIH Clinical Trials Database at clinicaltrials.gov (Identifier: NCT02123043).

A version of Chapter 2 and 3 have been submitted for publication in a peer-reviewed journal. Versions of Chapters 4, 5, and 6 will be submitted for publication. This statement is to certify that the work presented in this thesis was conducted, analyzed, written, and disseminated by Megan Kathleen MacGillivray.

MKM, BJS, and ED conceptualized the studies and developed the research designs. MKM completed the data collection, analyzed the data, and drafted the chapters/manuscripts. BJS supervised the research studies, contributed to interpretation of results and provided feedback on all chapters. ED contributed to study and concept formation and provided feedback and edited the chapters/manuscripts. JJE was involved in study and concept formation, provided guidance on statistical analyses, and provided feedback on all chapters.

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Glossary

Closed skill: Skills that are performed in stable or predictable environmental settings (Schmidt and Lee, 2005, p. 462).

Continuous skill: Skills that appear to have no recognizable beginning or end (Schmidt and Lee, 2005, p. 463).

Energy expenditure: The sum of the basal metabolic rate, the thermal effect of food, and the energy expended in physical activity. Energy expenditure is calculated using standard thermal equivalents of O_2 based on RER and $\dot{V}O_2$ values obtained during steady-state activity (Fox, 1989).

Feedback: Sensory information that results from movement (Schmidt and Lee, 2005, p. 464).

Fractional effective force: The ratio of effective (tangential) force and total force (expressed as a percentage) (de Groot, 2002).

Gross mechanical efficiency: Efficiency calculated as the mean power output divided by the energy expenditure and multiplied by 100.

Handrim propulsion: Forward propulsion of a manual wheelchair produced by using the hands to push the handrims (i.e., outer circular part of maneuvering wheel).

Knowledge of performance: Augmented feedback related to the nature of the movement produced (Schmidt and Lee, 2005, p. 465).

Knowledge of results: Augmented feedback related to the nature of the result produced in terms of the environmental goal (Schmidt and Lee, 2005, p. 465).

Manual wheelchair: A wheelchair that consists of two castor wheels, two drive wheels and does not rely on an external power source other than the person who is wheeling the chair.

Mechanical effectiveness: The efficiency of the movement based on kinetics described as the ratio between tangential force squared and resultant force squared. Mechanical effectiveness may be greater than one because the calculations do not consider the torque of the hand on the handrim (only the wheel) (Appendix C).

Mental imagery: Representations and the accompanying experience of sensory information (e.g., visual and kinesthetic imagery) without external stimuli (e.g., propelling a wheelchair).

Motor learning: A set of internal processes associated with practice or experience leading to relatively permanent changes in the capability for motor skill (Schmidt and Lee, 2005, p. 466).

Open skill: Skills that are performed in unpredictable, changing environmental settings (Schmidt and Lee, 2005).

Power output: Calculated as the torque around the wheel axel (Nm)*angular speed (rad/s).

Retention test: A performance test administered after a retention interval for the purpose of assessing learning.

Transfer: A change in the capability of performing one task (e.g., over-ground wheelchair propulsion) as a result of experience performing another task (e.g., treadmill wheelchair propulsion).

Variability in practice: A prediction of schema theory; transfer is predicted to be facilitated when goals are systematically varied from trial to trial during practice (Schmidt and Lee, 2005, p. 469).

Verbal feedback: Feedback provided via verbal descriptions.

Visual feedback: Feedback provided visually on select variables related to successful completion of a motor task often presented on computer screens.

Wheelchair propulsion pattern: One of the four categorical classifications (arc, single-looping over propulsion, double-looping over propulsion, semi-circular) defined by the kinematic wheeling trajectory of the third metacarpophalangeal joint (Appendix B).

Wheeling characteristics: Any biomechanical variables (kinetic, kinematic, temporo-spatial) that describes manual wheelchair propulsion.

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Dedication

To my family,

To my mom and dad who gave me everything they could.

To my sister, Tara, who provides endless support and friendship.

To my husband, Derrick, who keeps me grounded and loves me unconditionally.

To my daughter, Cedar, who has made life so much more interesting and meaningful.

1 Introduction

1.1 Impetus for this program of research

The impetus for this program of research arose after my MSc research, which examined differences in cutaneous reflex modulation between experienced manual wheelchair users (MWUs) and inexperienced able-bodied participants. Overall, no differences were observed in reflex modulation (i.e., we concluded that there were no apparent differences in neural pathway excitability). We anticipated that individuals naïve to wheeling would show greater excitation through decreased inhibition (1). Although we did not observe evidence of differences in the motor control of manual wheeling, we did identify kinetic and kinematic differences between these two groups in general (2) and over the duration of the wheeling trial (2). Specifically, experienced MWUs used a larger push angle and more force compared to able-bodied participants and adapted towards a more efficient wheeling pattern over the 10-minute trial.

While collecting data for other studies, I observed older adults that were physically capable of using optimal biomechanics, based on clinical practice guidelines, to propel their wheelchairs (3) use high braking forces and push frequencies in combination with wheeling patterns that are associated with large accelerations and decelerations. This led me to question why some individuals are more skilled at wheelchair propulsion and what methods of training are most effective for older adults. Despite the fact that older adults comprise the largest cohort of MWUs (4), they have been under represented in wheelchair propulsion studies. The definition of 'older adult' has been defined between 45 and 65 years of age depending on the location and context (5); for example, developing countries often define older age to be younger compared to developed countries. We have defined the term ‘older adult’ in our work as an individual aged 50 years and older.

1.1.1 Wheelchair use and the aging population

Nearly 5 million Canadians are over the age of 65 years and this number is projected to double over the next 25 years (6). Therefore, the number of older Canadians using manual wheelchairs may also double. As the population ages and the incidence of conditions limiting mobility increases, more individuals will need to rely on wheeled mobility. Currently, 21% percent of Canadians over the age of 65 years report having a mobility-related disability (7). As the population ages, the need for assistive mobility devices and related training will increase correspondingly.

The prevalence of individuals who rely on manual wheelchairs for mobility is increasing, with over 197, 560 Canadians (mean age 65 years, 61% female), of which 88% are over 45 years, and 1.5 million Americans living in private households reportedly using wheelchairs (4, 8). Individuals often use wheelchairs when ambulation is not possible for various reasons (e.g., loss of motor or sensory function, amputation, fatigue, pain, breathlessness). Moreover, manual wheelchair use can promote activity and participation (9) by improving mobility and potentially conserving energy (10, 11), thus enabling independent mobility. With more wheelchair users coinciding with the aging population, new users may benefit from wheelchair propulsion training aimed at promoting and preserving upper limb health and function. From here on, any mention of wheelchair propulsion or wheeling is specifically referring to handrim propulsion.

Although the largest cohort of wheelchair users in Canada and the United States consists of older adults (8, 12), most wheelchair-related research has been conducted on younger adult wheelchair users (18-50 years) (13-18) or able-bodied participants (18-25 years) (19-26). Interestingly, ninety percent of aging wheelchair users, within a sample of individuals with multiple sclerosis between the ages of 33-81 years (mean 55.3 years), were reported to use a wheeling pattern associated with high repetition (i.e., arc pattern) which could lead to overuse injury (27). Despite the poor wheeling biomechanics observed among older adults, only five studies to our knowledge have investigated some element of wheelchair propulsion biomechanics exclusively in older adults (28-32).

The entirety of the older adult wheelchair propulsion literature includes two studies on backrest angle, one study on weight and axle position, one study comparing biomechanics and energy expenditure to a younger cohort, and one study using a novel technique for classifying stroke pattern. Specifically, two related studies examined the impact of seat tilt and backrest angle (28, 30), which showed that a backrest recline of 10˚ improved fraction of effective force (FEF) (i.e., force contributing to forward motion/total force applied) by 10% and that there were no differences in shoulder loads based on seat tilt and backrest angle in older adults (28, 30). Furthermore, Cowan et al. examined the effect of wheelchair weight and axle position on propulsion biomechanics and reported that increased weight and posterior axle position resulted in larger peak resultant and tangential forces in adults over the age of 65 years (29). Aissaoui et al. applied fuzzy clustering to classify stroke patterns of older adults (31). Lastly, Hers et al. compared wheeling biomechanics and energy expenditure between younger and older able-bodied adult males (32). Compared with the younger cohort (19-40 years), older adults (65 years and older) had a lower mechanical effectiveness (i.e., 0.62 vs. 0.74) while wheeling at a comfortable speed and a lower peak power output (i.e., 126 vs. 225 W) during a 15 m wheelchair sprint test (32).

Although the energy demands of propelling a wheelchair have been explored since the early 1970s (33), only a few studies have delved into the energy demands of wheeling in older adult MWUs stemming from the early 1980s (34, 35). One such study that aimed to quantify metabolic variables associated with wheelchair propulsion identified that male MWUs had a lower peak power output, peak $\dot{V}O_2$, and maximum heartrate with advancing age, when a cohort of young males (20-30 years) was compared to middle aged (50-60 years) and elderly (80-90 years) cohorts (35). Limited information about the efficiency of wheelchair propulsion in older adults can be garnered from existing studies.

Aging is a multi-factorial process that incorporates physical, psychological, and social elements of change (36). The field of aging, in relation to wheeled mobility, has focused on psychological and social elements including self-efficacy and confidence (37-39). However, little attention has focused on the physical aspect of aging and how aging may relate to learning the skill of manual wheelchair propulsion (28, 29, 31, 34, 35, 40). Muscle strength, flexibility, cardiovascular fitness, and reaction time tend to decline with age (41, 42). In addition to the physiological declines associated with older age, there is evidence that the process of learning a new complex motor skill may slow with increasing age (43, 44).

Older adults acquire wheelchairs in various ways, therefore they do not always receive instruction or training (45). For example, family members may purchase mobility equipment for their aging relatives independently rather than with the assistance of a rehabilitation therapist. Thus, older adults may not be given the opportunity to learn through proper instruction. Little is understood about how effectively older adults wheel and whether motor skill-based wheelchair propulsion training can improve wheeling biomechanics and gross mechanical efficiency (GME), i.e., mean power output/energy expenditure*100.

1.1.2 Activity and participation in older adult wheelchair users

Activity and participation decline in the general population as individuals age (46) and this phenomenon is often exacerbated in individuals with physical disabilities (47). Wheelchair users face many barriers to participation including personal, interpersonal, and environmental barriers (e.g., illness; climate; weakness and deconditioning; lack of motivation, and the absence of ramps) (48). Sixty-three percent of women and 50% of men, aged 65-84 years, who use manual wheelchairs require assistance to move around (12). Older adults who require mobility assistance have been reported to have decreased independence, participation, and quality of life (47); therefore, maintaining or enabling independent mobility may help to improve participation and quality of life. Although wheelchairs may enable independent mobility, overall wheelchair use is a risk factor for reduced participation in physical and leisure activity among older adults (49).

1.1.3 Overview of manual wheelchair propulsion

The two primary components attributing to the energy requirements of manual wheelchair propulsion are overcoming the (1) inertia of the system and (2) friction (internal to the wheelchair and the friction between the castor and drive wheels of the wheelchair with the ground). The type of wheelchair (e.g., material and weight), configuration of the wheelchair, wheelchair user (weight, anthropometrics), as well as the surface with which the wheels are interacting, all play significant roles in the energy required to propel a wheelchair. Manual wheelchair propulsion is most efficient while wheeling on flat surfaces with little friction (e.g., smooth tile); however, these conditions are rarely encountered in the outdoor environment. In reality, wheelchair users experience carpet, asphalt and other surfaces with higher coefficients of friction, which require large forces to overcome the associated inertia and friction. When wheeling over any surface with friction in any wheelchair, assuming the presence of internal friction, an MWU must constantly cycle through phases of acceleration (push phase) and deceleration (recovery phase). On level surfaces or inclines, wheelchairs begin to decelerate immediately after the propelling force stops.

Wheelchair propulsion requires more energy compared to walking on surfaces with high friction such as carpet (50); however, wheelchair propulsion is often the more energetically efficient mobility choice for MWUs who have difficulty walking (51). In addition to overcoming inertia and friction, the muscle mass of the upper limbs is smaller, and the moment arm is generally shorter than the lower limbs; therefore, propulsion with a handrim requires high mechanical loading and is less mechanically advantageous than walking. Wheelchair propulsion has a GME of 2-11% (52-56), which is lower (less efficient) than using an arm crank (up to 15%) (57, 58), or lever propulsion system (up to 11%) (59). Leg cycling (bicycling) is much more efficient with a GME between 18-23% (60). This disparity in efficiency can be attributed to the braking that occurs during hand contact, the need to brake when maneuvering (turning, changing directions), and the lack of consistent force delivered from a drive train (e.g., cycling gear).

The initial acceleration phase of wheelchair propulsion is experienced anytime the user performs one of their approximately 90 bouts of daily mobility, totalling an average of 1.6 km over 54 minutes (61). Inertia and friction must be overcome with each bout of manual wheeling; thus, the weight, internal friction, and configuration of the wheelchair are important in optimizing propulsion. In summary, the internal friction of the wheelchair limits the efficiency of wheelchair propulsion through friction of the castor and drive wheels with the floor. Furthermore, the method in which the MWU propels the wheelchair can impact the amount of friction between the handrim and hands of the MWU.

Joint health may be preserved among MWUs by reducing repetition and joint forces and through improving efficiency of the system (3). Both GME and measures of propulsion effectiveness are important to optimize wheelchair propulsion and ultimately reduce fatigue and injury especially in aging populations (3). Gross mechanical efficiency refers to the ratio of mean power output to energy expenditure. Unlike GME, mechanical effectiveness ($F_{tangential}^2/ F_{total}^2$) and FEF ($F_{tangential}/F_{total}$) relate to the forces applied to the handrim of the wheelchair. Mechanical effectiveness is defined as the ratio of the handrim forces applied in a tangential direction compared to the force (calculated as a vector sum of F_x, F_y and F_z ($\sqrt{F_x^2 + F_y^2 + F_z^2}$)) applied to the handrim. Both variables, GME and mechanical effectiveness, are used to evaluate different but important constructs of wheelchair propulsion. The relationship between GME and mechanical effectiveness has not been well studied.

1.1.4 Relationship between wheeling biomechanics and injury

Manual wheelchair use is associated with overuse injuries, including the high prevalence of shoulder injury and pain. Upper extremity pain often occurs as a result of inflammation, joint degeneration, instability, nerve impingement, or rotator cuff tears (62-64). Moreover, injuries to the upper extremities may result from overuse, ineffective manual wheeling, poor transfer technique, and other activities of daily living (3). More than two-thirds of MWUs will experience upper limb pain or injury as a result of muscle fatigue or overuse injuries (65) that may reduce participation in activities of daily living (66). For those with spinal cord injury (SCI), duration of injury (64, 67-69), older age (70), and an increased body mass index (BMI) (71, 72) have been reported to contribute to the development of shoulder pathology and pain. Furthermore, the incidence of pain has been shown to increase with time since injury. For example, individuals with paraplegia who had their SCIs approximately 20 years ago were twice as likely to report shoulder pain compared to those who had their injury 5 years ago (64). Interestingly, Sawatzky et al. found that age of injury (i.e., age beginning wheelchair use) was more influential than duration of wheeling at predicting pain (73).

Manual wheelchair users are reliant on their upper extremities for mobility as well as other functional activities of daily living. Therefore, injuries to the upper extremities can further debilitate MWUs and contribute to their decreased independence. When people can no longer use a manual wheelchair, they can either use power mobility or they may become dependent on others for their mobility. Power mobility equipment can be expensive and difficult to obtain which leaves a caregiver (e.g., family member) to provide mobility for the MWU. Caregivers who care for older adults who can no longer independently propel their wheelchairs should have appropriate skills training to prevent injuries to themselves or the wheelchair user (74). The incidence of injuries to caregivers is high because they are often untrained family members (i.e., spouses who are also older adults) (74).

Researchers have described several approaches that aim to reduce upper extremity injuries and pain in MWUs. These approaches include examining biomechanics relating to wheelchair ergonomics, equipment (e.g., type of wheelchair and accessories, configuration, wheelchair maintenance), skill training, and physical capacity training (Appendix A). Strong, lightweight and fully customizable wheelchairs are recommended because they require less energy to propel and can be fitted to the user (75). In addition, lightweight wheels with pneumatic tires are recommended because they provide the least rolling resistance (i.e., coefficient of friction) (76).

Minimal specialized training that focuses on wheelchair propulsion technique, skills, and wheelchair configuration may result in positive biomechanical, physiological, and psychological changes. Focused wheelchair-related training can promote efficient wheeling patterns, reduce maximal force application, increase push angle, and enable specific skills that are important for independent mobility in the community (3, 75, 77). By optimizing wheelchair configuration and learning efficient wheeling strategies, energy consumption can be reduced, which may decrease fatigue. One study demonstrated that a 7-week low intensity wheelchair-training program resulted in significant improvements in wheeling biomechanics through increasing push time and decreasing push frequency (19), both of which are thought to optimize manual wheeling (3).

1.1.5 Role of biomechanics in preventing injuries associated with wheelchair use

Although there have been no longitudinal studies demonstrating causation of specific variables resulting in increased injury and pain associated with wheelchair use, several studies have shown that specific wheeling variables are correlated with injury. Wheelchair propulsion biomechanics of MWUs with upper extremity injuries have been compared to MWUs without upper extremity injuries in cross-sectional studies. These studies have demonstrated that individuals who exhibit poor wheeling biomechanics (e.g., high push frequency) had a higher incidence of nerve injury (78, 79) and shoulder abnormalities (71, 80). One study reported a relationship between body weight and function of the median nerve, where high weight-normalized forces corresponded with decreased nerve function (78). The investigators concluded that peak force should be minimized because force is directly related to weight, which can be accomplished through weight loss of the wheelchair user or using a lighter wheelchair. Additionally, higher push frequencies were related to lower median nerve amplitude (i.e., poorer nerve function) (78) and higher median nerve amplitude was related to greater wrist extension-flexion range of motion (79).

Four common wheeling patterns have been described in the literature based on the trajectory of the hand during the recovery phase of the wheeling cycle: (1) Arcing (arc); (2) Semi Circular (SC); (3) Double Loop Over Propulsion (DLOP); and, (4) Single Loop Over Propulsion (SLOP) (Appendix B). The arc strategy involves tracing the handrim with the hands (81) whereas the

SLOP strategy involves raising the hands above the handrim, the DLOP strategy involves raising the hands above the handrim and then dropping them below, and the semicircular strategy involves bringing the hands below the handrim in a circular motion (81, 82). The SC wheeling pattern has been associated with a lower push frequency, compared to other wheeling patterns when wheeling at the same speed, which suggests that it may be optimal for reducing median nerve injury (81, 82).

Recently, the association between variability of wheelchair propulsion and injury has been explored. Although there has been minimal wheelchair propulsion research on the implications of wheelchair propulsion variability, studies have found that both larger kinematic variability during the recovery phase and smaller shoulder joint force variability are associated with shoulder pain (83-85). Furthermore, variability is thought to play an important role in motor skill learning, whereby sensorimotor circuits learn, and initially high variability can enhance the learning process (86). The task relevant ‘noise’ observed in movement variability may allow for movement exploration, which is theorized to predict the rate at which someone learns a motor skill (86). Therefore, motor skill training should not necessarily focus on reducing variability.

1.1.6 Importance of gross mechanical efficiency, push frequency, wheeling pattern, and braking forces on optimizing wheelchair propulsion

There are generally two conflicting opinions regarding the benefit of wheelchair propulsion training. One school of thought argues in favor of decreasing the amount of energy required to propel the wheelchair by improving the GME. The other school of thought is concerned with improving mechanical effectiveness (See Appendix C). The major limitation and criticism of this method of calculating mechanical effectiveness is that the calculation is based on the torque applied to the handrim (which is calculated directly from the torque produced around the axle) and ignores the torque applied to the hand (21). This enables someone to wheel at more than 100% efficiency, which in reality is not possible. Mechanical effectiveness provides a good indicator of how much of the overall force is used to propel the wheelchair forward, although caution should be used when interpreting the data. The reliability and sensitivity of GME and mechanical effectiveness at low power outputs has not been well studied, therefore the sensitivity of these measures for capturing small changes at mild-moderate levels of exercise may not be ideal.

A larger GME is important for energy conservation and for reducing fatigue. Fatigue can negatively influence wheeling biomechanics (87). Rodgers et al. observed increased peak handrim forces and increased forward trunk lean following the onset of fatigue among MWUs with SCI (87). By improving the GME of manual wheelchair propulsion, MWUs may have more energy to spend on other aspects of their lives, which could result in increased activity and participation. Low push frequencies at a standardized power output are related to decreased heart rate and volume of oxygen consumption compared to high push frequencies (88), suggesting that wheeling patterns with lower push frequencies (81) could also be associated with greater GME. Manual wheelchair users may also exert braking forces by applying backward force to their handrims, thus wheeling patterns that are related to lower braking forces and lower push frequencies are optimal. Overuse injuries result from repetitive use; thus, decreasing the push frequency of wheeling will ultimately result in reduced repetitions which should help to reduce overuse injuries, as long as negative compensatory strategies are not used (e.g., exerting higher peak forces, hyperextending the shoulder). Non-optimal equipment and wheelchair configurations may also result in decreased GME. For example, wheeling with partially inflated tires will energy expenditure of wheelchair propulsion because the area between the tire and the ground is greater, which results in increased friction (53, 89).

Small modifications of a specific wheeling variable will not necessarily result in positive changes in other variables (16, 21). For example, only push distance and push frequency have been reported to be directly related when 10% changes in speed are compared to self-selected speeds (16). Likewise, when individuals are trained to increase their FEF, their GME decreased (21). The consequences of manipulating some wheeling variables on others are not well understood and may vary across populations of MWUs. From a motor learning perspective, movement efficiency is expected to improve with experience and practice when a person learns a novel skill (90-92). By training MWUs to reduce their negative acting (i.e., braking) forces and to adopt a wheeling pattern that is more circular and fluid (which prevents abrupt accelerations and decelerations of the upper limbs) may lead to improved GME of wheelchair propulsion.

1.1.7 Rationale that training may help to reduce overuse injuries resulting from wheelchair propulsion

The first longitudinal randomized trial to examine the impact of a wheelchair education program followed 37 new wheelchair users with SCI over one year (15). No differences in wheelchair set-up or selection, pain, satisfaction with life, and participation were identified between those users who received education and those in the control group (15). The authors reported that the education group demonstrated significantly lower push frequency on tile at discharge and significantly larger push angle on ramp at discharge, as well as 6 months and 12 months post discharge (15).

In addition to education, several studies focusing on wheelchair propulsion practice and motor skill-based training have observed improvements in wheeling biomechanics (13, 14, 19, 23, 93) and GME (94). One recent study reported that experienced MWUs had lower energy expenditures compared to novice and unpractised able-bodied participants (95). Decreased energy expenditure based on long-term wheeling experience (95) and seven weeks of wheeling practice (92) may be related to developing and learning a complex motor skill (92). If MWUs cannot change or modify their wheelchair (equipment), motor skill-based training may be the single fastest way to improve the efficiency of wheelchair propulsion while reducing biomechanical characteristics associated with injury. A recent study identified that individuals were able to significantly improve wheeling biomechanics following training even in a poorly configured wheelchair (96).

Limited conclusions about wheelchair propulsion biomechanics and GME in adults can be garnered from these individual studies. Collating the data together through a meta-analysis may provide an overall impact of wheelchair propulsion training on key variables, including push angle, push frequency, and GME. Thus, one of the questions to be explored in this thesis is to quantify the effect of wheelchair propulsion practice and training protocols through a meta-analysis of existing studies.

1.1.8 Evidence suggesting experienced wheelchair users do not always use effective wheelchair propulsion patterns

Handrim wheelchair propulsion performed by able-bodied and experienced MWUs has consistently been reported to result in low (less than 11%) GME (53-56, 94, 95, 97-99). Further, experienced MWUs exhibited negative wheeling attributes (e.g., high peak force and high braking force) as well as inefficient wheelchair propulsion patterns (81, 82). In one study, 14% of experienced MWUs used the ARC wheeling pattern which is thought to relate to poor biomechanics, whereas 16% used the SC pattern (81), which is thought to be associated with optimal biomechanics (3).

1.2 Application of the field of motor learning to wheelchair propulsion

Following motor skill training, the presence of motor learning is supported by lasting improvements in motor performance (e.g., kinetics and kinematics) that can be transferred to varying tasks or conditions (100). Furthermore, improvements in efficiency are often postulated to coincide with improvements in motor performance, which may result in an increased GME (90, 91, 101). Lastly following the Schema theory of motor learning, a reduction in noise (i.e., unnecessary movement) is believed to accompany improved motor performance (102). Therefore, motor performance (kinetics and kinematics), GME, and intercycle variability of biomechanics will be used to evaluate the wheelchair propulsion training and explore evidence for the presence of motor learning throughout this thesis.

1.2.1 Role of motor learning principles in training wheelchair propulsion

The field of motor learning has been inconsistently integrated into the research and clinical practice of rehabilitation science. Three theories that have evolved over the past 50 years that have had major contributions to the field of motor learning include: (1) Closed-loop theory (103); (2) Schema theory (102); and (3) Dynamic systems theory (104). Various theories have been integrated to provide four governing principles of motor learning: (1) Stage of learning; (2) Types of tasks; (3) Practice; and (4) Feedback. These principles have been extensively studied individually as well as in combination in both able-bodied and clinical populations. The majority of motor learning research, in particular sport-related, has been conducted on convenience samples of young and middle-aged adults. Pediatric and elderly populations have been less researched, thus the application of training based on motor learning principles to these populations is not as well understood. Motor learning consists of competing and evolving theories that make the application of motor learning theory to some areas of rehabilitation challenging for clinicians to apply in practice (105).

For the purpose of this research program, we focused on the two principles: *Practice* and *Feedback* because they can be manipulated in a clinical setting. Across our studies, we examined various stages of motor learning as established by Fitts and Posner (1967) including the *Cognitive stage* (declarative phase), *Associative stage* (generally involves implicit and explicit learning), and the *Autonomous stage* (procedural learning) (100), although the specific stage of motor learning was not the focus of this research program. The task of manual wheelchair propulsion is *continuous* with no distinct beginning and end to the movement (100). Manual wheelchair propulsion follows more of a *closed* task paradigm on the continuum between closed and open skills when performed in a laboratory setting because the environment is generally predictable and stable while lacking the distraction and complexity of wheeling in the community (100).

The goal of manual wheelchair propulsion involves contacting the hands with the handrims and pushing the wheels forward (push phase) immediately followed by letting go and bringing the hands backward (recovery phase) to contact the handrims for the next push. Manual wheelchair propulsion, unlike constrained movements often used in motor learning research, has degrees of freedom such that the less precise targets (i.e., handrims) allows the movement to be conducted in various ways. Manual wheelchair propulsion is similar to walking which has two defined phases (stance and swing) and bicycling with toe clips (push and pull); however, the balance component of the task is minimized and mainly limited to the trunk because of the four points of contact with the ground achieved with the drive and castor wheels.

The potential value of applying motor learning principles to wheelchair propulsion training has gained interest over the past decade. Several studies have evaluated various motor skill training protocols for wheelchair propulsion training in young adults. One of the most common applications of motor skill training used in wheelchair propulsion training has been visual feedback (13, 14, 21, 93, 106, 107). Studies have evaluated the impact of education on modifying wheelchair propulsion biomechanics of wheelchair users (15, 93). Education, which addresses the first stage of motor learning (cognitive stage), without incorporating physical practice or feedback, appears to be beneficial in decreasing push frequency while increasing push angle (15). Education delivered through an instructional video was found to be effective at decreasing the peak rate of rise of resultant force, decreasing push frequency, and increasing push angle (93). Other studies have examined motor skill training of wheelchair propulsion in the simple context of practicing the movement (i.e., repetition for the purpose of discovery learning) (20). Three weeks of practice resulted in decreased push frequency in able-bodied individuals (20). One study examined differences in manual wheelchair propulsion based on context (i.e., three groups each wheeled in a different environment). The authors reported that only percent push time was larger in the group that wheeled on a wheelchair ergometer compared to the over-ground and treadmill groups (25). Visual feedback, practice, and education all appear to have roles in the training of wheelchair propulsion.

One in-depth study compared the effect of variable practice (30% and 55% of maximal speed) with constant practice (one group at 30% and another at 55% maximal speed only) on the accuracy of wheeling at specific speeds. The accuracy of wheeling at those speeds (retention) as well as at 40% and 70% (transfer), indicated that the variable practice generally resulted in greater accuracy and participants in that group produced fewer errors (108). Additionally, a similar study reported that the variable practice group had better efficiency scores compared to the 30% constant practice group; however, there were no differences observed in propulsive timing (e.g., pushing time and recovery time) between the variable practice and constant practice groups (109).

Although several studies have examined various approaches to improving GME and mechanical effectiveness of manual wheelchair propulsion, the findings have been inconsistent (19-22, 24, 25, 54, 94, 110-117). Katajarvi et al. instructed participants to improve their FEF and found that in doing so, participants also increased velocity, decreased push frequency and increased push angle (107). Similarly, de Groot et al. observed increased FEF with a similar paradigm; however, they observed lower GME (21), indicating that FEF is not directly related to metabolic efficiency. These findings support the observations by Bregman et al, that increasing tangential force may come at a physiological cost (118).

Continuous real-time feedback can decrease learning and retention of motor skills if a learner becomes dependent on the feedback to perform a specific task (119-121). Therefore, to prevent individuals from becoming dependent on feedback for task performance, feedback should be limited to approximately three variables (14, 120). Additionally, sporadic feedback, whereby feedback is provided after an intermittent delay, can prevent reliance of the learner on feedback for executing the motor skill (122). Random and variable practice is generally superior to blocked and massed practice when a person learns a motor skill (100). Although practice in a research-setting cannot be completely random, the activities within a practice session can be variable. Massed practice can improve immediate performance but may limit retention (100).

Manual wheelchair propulsion has been the task of focus in some studies within the motor learning literature (108, 123, 124). Manual wheelchair propulsion is an interesting and feasible skill to explore from a motor learning perspective since most individuals are naïve to the motor skill. For example, one study within the field of motor learning compared internal visual imagery focusing on accuracy (i.e., completing a wheelchair slalom task) to external visual imagery with an external focus (i.e., on speed) (123). The authors observed that internal visual imagery was more effective than external for the planning of action in response to changes in a visual field and fewer errors were observed in the transfer condition, compared to the external visual imagery group.

1.2.2 Rationale for manual wheelchair propulsion training for older adults

The motor skill of wheelchair propulsion is likely the most feasible factor for a trainer or therapist to manipulate when attempting to improve a person's wheelchair propulsion efficiency (14, 19, 93, 107), especially in contexts where more ergonomically-adapted equipment is not accessible (e.g., in less-resourced settings). Properly fitted lightweight wheelchairs help to improve comfort and ergonomics of the wheelchair-user system (125); however, 50% of veterans post stroke who were fitted to a wheelchair reported difficulty with the motor skill of wheelchair propulsion (126). Although improving physical capacity and decreasing bodyweight may make wheelchair propulsion biomechanically and physiologically easier, they are both time consuming. A lightweight and well-fitted wheelchair will not improve the skill of the user; however, fitted wheelchairs may provide optimal positioning and posture unique to an individual's needs that can make wheelchair propulsion biomechanically and physiologically easier (e.g., improved posture can better enable breathing). Motor skill training, ideally with a customized ultralight manual wheelchair, may be the fastest and most economical approach for improving wheelchair propulsion efficiency in older adults. Similar improvements in wheeling biomechanics were observed following training with both optimally and sub-optimally configured wheelchairs (96).

Age-related factors can influence wheelchair propulsion. As individuals age, they often lose strength, muscle mass, range of motion, and cardiovascular fitness (42). Furthermore, older adults often experience a decline in sensitivity to sensory information (127). For example, older adults may have poor cutaneous sensation or reduced proprioception, which may impact how they contact the handrim of the wheelchair. Given decreases in strength, in addition to other physical disabilities, older adults may be at a greater disadvantage than young adults and may receive greater benefit from efficient wheelchair propulsion. Motor learning-based training, specifically involving practice, has resulted in improvements in biomechanical variables within short training periods for young populations (22, 23, 128).

As an individual learns a new task, the technique of performing that task also improves and the individual becomes more efficient. Improvements in metabolic efficiency have been observed for continuous skills such as rowing in as little as six training sessions each lasting 1 hour at 100 watt power output (92). Furthermore, in one study, experienced paraplegic wheelchair users were reported to expend less energy than novice or practiced (3 weeks of practice) able-bodied individuals (95). No differences in energy expenditure were observed between the novice and practiced able-bodied groups. This finding suggested that 3 weeks of wheelchair propulsion practice (without feedback) is not sufficient to improve GME (95).

Age-related functional changes need to be considered when older adults are taught new skills. Investigators in the field of motor learning have evaluated age-related differences with respect to how older adults learn new tasks. Although the findings are mixed, the general consensus is that older adults experience a greater timing-accuracy trade-off compared with younger adults (44). With increasing complexity of tasks, older adults take longer to successfully complete the task and are often less accurate (44).

1.2.3 Are there age-related differences in motor learning for wheelchair propulsion?

There is sparse literature that infers that older age may affect the acquisition of manual wheelchair propulsion; however, there is some evidence to suggest that the motor learning process could take more time, which has been reviewed by Voelcker-Rehage (44). Manual wheelchair propulsion is a complex and largely gross motor skill. Unlike some gross motor tasks (e.g., bicycling), manual wheelchair propulsion does require some degree of accuracy in reaching the handrim. Although many MWUs grasp the handrim with their fingers, others use the palm of their hand to contact and push the handrim. The grasping feature may introduce a fine motor skill component increasing the complexity of this motor task.

Although motor learning impairments have been associated with aging in some studies (44, 129, 130), the current literature may not be applicable to wheelchair propulsion. Researchers have reported that accuracy with practice in a task involving tracing with a stylus was not achieved in an older population to the same extent as a younger population (129); however, wheelchair propulsion does not require the same degree of accuracy as the tracing task. Investigators have postulated that aging may reduce working memory resources (i.e., resources available for formation of strategies) (129), which could have implications for wheelchair propulsion, especially among those with neurological conditions affecting cognitive functioning. Although the ability to achieve performance gains for fine motor skills appears to decrease in older adults, this does not seem to be the case for gross motor skills (44). Overall, the age-related decline in motor learning appears to be task-specific and is not observed in all situations (44). Another study that compared the capacity of older adults to learn sequences versus adapt to sensorimotor changes, within the same joystick aiming task paradigm, reported that older adults demonstrated impairments in their ability to modify movements to adjust for changes in sensory input or motor output (130). The investigators hypothesized that cerebellar-mediated motor skills are impaired with age based on the differences in sensorimotor adaptations (130). These findings could have implications for training manual wheelchair propulsion because environmental conditions and the demands of the task change with varying surfaces or situations.

1.2.4 Considerations for motor skill-based wheelchair propulsion training for older adults with pathology

Physical limitations associated with older age may require special considerations and modifications when providing wheelchair propulsion training. Older adults may have a smaller range of motion (decreased flexibility), decreased strength, and potentially decreased endurance (42). Other physical disabilities in addition to potential age-related decline can provide further physical limitations. A push angle of approximately 100 degrees has been associated with reduced push frequency and therefore has been recommended for wheelchair users (3); however, older adults with limitations in flexibility may not be physically capable of performing a push angle of 100°. Therefore, individual improvements in outcome variables may be more important to consider when training older adults because the recommendations that have been established for the general population of MWUs may not be applicable (3). Although individuals with joint pathologies or pain will be excluded from our randomized controlled trial, participants may demonstrate differences in physical capacity due to age.

1.2.5 Does novel motor skill training improve wheelchair propulsion biomechanics and energy expenditure?

Given the potential for motor skill training to enhance wheelchair propulsion biomechanics, this thesis explored the effect of wheelchair propulsion training, compared to uninstructed practice and no practice, on wheelchair propulsion (1) biomechanics, (2) energy expenditure, and (3) intercycle variability of biomechanics among able-bodied older adults with no prior wheelchair propulsion experience (Chapters 2, 3, and 4, respectively). Furthermore, we applied the uninstructed practice and novel training to individuals with physical disabilities who may be candidates for wheeled mobility (Chapter 5). This final study explored wheelchair propulsion biomechanics, energy expenditure, and variability through a single-subject research design.

1.3 Conclusions

Manual wheelchair propulsion can result in pain and overuse injuries in the upper extremities. Older MWUs may experience age-related physical decline in addition to their disabilities, or in some cases older adults may use a manual wheelchair as a result of their age-related physical decline. The motor skill of wheelchair propulsion may be the most feasible factor to manipulate when improvements in wheelchair equipment or configuration are not possible. Fitted wheelchairs alone may not be sufficient for enabling wheelchair propulsion since more than half of older adults with fitted wheelchairs expressed difficulty with the motor skill of basic wheelchair propulsion (126). Therefore, efficient 'equipment' will not improve the motor skill of manual wheelchair propulsion without proper training. Training protocols based on motor learning principles have been shown to be effective for modifying some biomechanical variables that have been associated with upper limb health (14, 15, 93). Improvements in wheelchair propulsion biomechanics and GME may decrease pain, overuse injuries, and fatigue and, in turn, prolong independence and participation. Despite the fact that older adults comprise the largest cohort of wheelchair users in Canada and the United States, no studies have examined the feasibility and effectiveness of motor skill training on wheelchair propulsion biomechanics and GME in older adults (8, 12).

1.4 Research purpose

In summary, the goals of this thesis were to (1) identify wheelchair propulsion training protocols, and their theoretical underpinnings where possible, and meta-analyze the literature accordingly, and (2) evaluate the newly developed motor skill training protocol (informed by goal 1 above) among able-bodied older adults and older adults with physical disabilities. Testing specific motor learning principles was not the specific focus of this work, but rather we applied these principles to the training protocol. To identify whether the training resulted in learning the motor skill of wheelchair propulsion, we examined whether there were (1) lasting improvements in motor performance (i.e., wheelchair propulsion biomechanics) and evidence of skill transfer, (2) lasting improvements in physiological variables including GME, and (3) decreased movement variability.

Older adults have been under-represented in wheelchair propulsion research, therefore the benefits of motor skill training for this population warrants elucidation. Such training could offer a feasible means of improving wheelchair propulsion biomechanics and GME for older adults, which may in turn improve independent mobility and help to prevent overuse injuries associated with manual wheelchair propulsion. High quality and ecologically valid studies are needed to determine whether older adults benefit from motor skill training for wheelchair propulsion because they are at risk of decreased leisure and physical activity (49) as well as wheelchair abandonment (131).

2 Can motor skill practice or training enhance acquisition of wheelchair propulsion? A systematic review and meta-analysis

2.1 Introduction

Over two-thirds of manual wheelchair users (MWUs) experience upper limb pain or injury as a result of muscle fatigue or overuse injuries (65), which may reduce their participation in activities of daily living (66). Upper extremity pain often occurs as a result of inflammation, joint degeneration, instability, nerve impingement, or rotator cuff tears (62-64). Wheelchair propulsion is a highly repetitive cyclical gross motor skill that involves a propulsion phase followed by a recovery phase. To reduce the prevalence and severity of overuse injuries resulting from manual wheelchair propulsion, established Clinical Practice Guidelines (3) recommend a circular trajectory of the hands to reduce push frequency (Hz) (frequency of full cycles each consisting of a propulsion and recovery phase) and increase push angle (degrees) (angle that the hand is in contact with the handrim during the propulsion phase of the wheeling cycle); both are thought to improve biomechanical efficiency and economy (3). Thus, the objective of wheelchair propulsion training is to reduce repetition while improving force application and gross mechanical efficiency (GME) (mean power output/ energy expenditure * 100). Improvement in GME is thought to accompany learning as an individual improves their efficiency by reducing unnecessary movement and noise (90-92).

The application of motor learning principles into the design of training protocols in the rehabilitation context may be effective for motor skill training (132, 133) (See Chapter 1, pages 14-18). Motor learning is defined as "a set of internal processes associated with practice or experience leading to relatively permanent changes in the capability for motor skill" (100) (p. 466). In order to learn a motor skill, one should engage in practice with the amount of practice depending on the complexity of the motor skill. Wheelchair propulsion is considered to be a *locomotion on object* task which lies towards the complex side of the simple-complex spectrum (134). Biomechanical variables (e.g., push angle) have been shown to improve with as few as 1000-2700 wheeling cycles during propulsion training that involved sporadic verbal feedback in a population of MWUs (135). In addition to the number of repetitions, the distribution of practice (e.g., massed versus distributed practice), and task variability are important when designing training interventions. Variable practice was observed to be superior over constant practice in the acquisition of wheelchair propulsive speeds and propulsive efficiency (108, 109). This is attributed to the theory that variable practice introduces novel variations of the skill, which builds stronger schemas that can be retrieved at a later time (136). Based on the motor learning literature, multiple training sessions that incorporate variable practice (e.g., changes in speed or objective) is theoretically more effective than constant practice when learning motor skills. The consensus regarding this theory has yet to be determined in relation to wheelchair propulsion training.

Another key motor learning principle that has been applied in the rehabilitation setting involves the incorporation of augmented feedback into training. The relative frequency of augmented feedback has also been shown to have an effect on motor skill acquisition. Providing the learner with augmented feedback after every trial is not optimal for learning, as it places a reliance on the feedback (136). The literature suggests that reducing the frequency of augmented feedback prevents dependency and pushes the learner to associate task-intrinsic feedback with the skill being performed (136). Although wheelchair propulsion studies have examined the use of augmented feedback presented on a computer screen via data obtained through an instrumented wheel (e.g., SmartWheel (Three Rivers Holdings, Mesa, AZ, USA) or OptiPush (Max Mobility, LLC, Antioch, TN, USA)) (13, 14, 16, 21, 93, 107, 137, 138), optimal use of feedback (i.e., type and schedule) has not been well documented for wheelchair propulsion training, particularly across cohorts of MWUs.

Basic wheelchair propulsion is the most fundamental skill for people who use their hands to propel their wheelchair and is a prerequisite to perform many successive skills on the Wheelchair Skills Test (e.g., wheeling up ramps) (139). Specific elements of propulsion that can be transferred to successive skills on the Wheelchair Skills Test involve timing of hand contact and release, positioning of the hands at contact and release, and force application to the handrims. Given the repetitive nature of wheelchair propulsion, in which the average MWU performs approximately 2,500 pushes per day (140) or 90 bouts per day over 1.6 km (61), the importance of optimizing this movement becomes evident for both energy conservation and injury prevention. The intended goals of motor skill training and rehabilitation, with respect to wheelchair propulsion, are similar in that skilled arm movement must be consistent (repeatable), flexible (transferable), and metabolically and biomechanically efficient (133).

The lack of expert consensus on training strategies for wheelchair propulsion makes it challenging to apply evidence-based research in a clinical setting. The purpose of this systematic review and meta-analysis was to identify practice and training strategies that have been applied to wheelchair propulsion and to summarize the evidence that supports the effectiveness of implementing these strategies. We hypothesized that a motor skill training program that incorporates motor learning principles is effective in improving wheelchair propulsion biomechanics (push angle and push frequency) and GME in populations with varying amounts of wheeling experience compared to baseline measures or control groups within 1-week following training.

2.2 Method

This review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (141). A review protocol was not registered for this study. See Appendix D for the PRISMA checklist.

2.2.1 Data sources

A systematic review of six established electronic databases (CINAHL, Medline, EMBASE, PsycINFO, ERIC, and SportDiscus) was conducted of articles published prior to July 2016 using keywords and subject headings; search limits included human-based research. An updated search was performed on December 6, 2016 and final hand searching occurred on October 2017. Truncation was used to make the search as inclusive as possible and proximity (i.e., 'adj' adjacent to) was used to further focus the search. For example, the following search strategy was used for EMBASE (Ovid) (1) Wheelchair* adj4 (instruct* or practice* or train* or learn*), (2) Wheelchair, (3) Teaching, (4) Learning, (5) Skill retention, (6) Transfer, (7) Motor performance, (8) or 3-7, (9) 8 and 2, (10) 9 or 1. Numbers (2) through (7) represent subject headings used in the search. Subject headings for each database can be found in Appendix E and an example search strategy can be found in Appendix F.

2.2.2 Inclusion and exclusion criteria

We reviewed peer-reviewed journal articles written in English that met the following criteria: (1) apply practice or training strategies, based on motor learning principles, to the skill of manual wheelchair propulsion; and (2) evaluate at least one biomechanical variable related to manual wheelchair propulsion (e.g., speed, push angle). Articles were excluded from the review if they met any of the following criteria: (1) examine training designs with an emphasis on physical capacity training only (e.g., strength or endurance training); (2) involve training of healthcare professionals regarding how to instruct wheelchair propulsion; and (3) report editorials, commentaries, and other non-systematic reviews of the literature, or conference proceedings.

2.2.3 Article selection process

All titles were screened by the first author (MKM) and those that did not relate to the research question were removed. Remaining titles and abstracts were reviewed, and articles were identified for review in full text format by the first author. References of included articles were examined to identify those that may have been missed in the original search. Additional hand searching (i.e., checking journal indices and reference lists) was performed to ensure that all relevant articles were included. A second author (BJS) verified the included articles and performed a secondary hand search.

Relevant data relating to practice and training strategies from articles selected for review were transcribed in a data extraction form. Data were organized based on the format of the practice or training protocol (i.e., single day versus multiple days), schedule and conditions of practice, types of feedback provided, and use of transfer and retention to demonstrate motor skill learning.

2.2.4 Methodological quality assessment

Methodological quality of the included studies that used *independent groups* (e.g., randomized controlled trials and randomized comparative trials with no distinct control group) were evaluated with the PEDro scale (max score 10) (142), which was adapted from the Delphi list for quality assessment of randomized controlled trials by Verhagen et al. (143). This scale, that evaluates both internal validity and statistical criteria (142), has been used to evaluate methodological quality in other wheelchair-related reviews (144). Although there are no standardized categories based on the PEDro scale, we categorized the scores into: Poor quality (0-3) Fair quality (4-6), and High quality (7-10) (145). The first author (MKM) scored articles based on methodological quality and for available articles the PEDro website was consulted.

2.2.5 Evidence level

The quality assessment tool from the University of Oxford's Centre for Evidence Based Medicine's "Levels of evidence" was used to determine the level of evidence of the articles that applied motor learning principles to manual wheelchair propulsion (146). This scale ranges from level 1 (systematic review of randomized controlled trials (RCTs) with homogeneity) to level 5 (expert opinion). The first author (MKM) determined the evidence level for all articles.

2.2.6 Effects of practice and training strategies

Effect sizes (ESs) (i.e., standard mean difference) were calculated for push angle, push frequency, and GME between baseline and the first post-test evaluation from the included articles where applicable. Due to the small numbers of included studies, the calculated ESs combined various types of training protocols. Findings related to transfer conditions and retention testing were described descriptively, as we anticipated there would be insufficient data to perform further sub-analyses. Effect sizes and 95% confidence intervals were computed using Cohen's *d* estimate with a Hedge's *g* adjustment for sample size (147). Effect sizes were calculated for studies that used independent groups (e.g., non-RCTs and RCTs) by determining the change in the variable of interest (e.g., push angle, push frequency, GME) between baseline and post-testing for both groups and dividing the difference in the mean changes (between groups) by the weighted pooled standard deviation of both groups. Effect sizes were calculated for the pre-post design studies by determining the change between the pre- and post- values and dividing it by the weighted average standard deviation of pre- and post- values. Study designs were analyzed separately because of the inflated values observed in pre-post study designs (148). Calculated ESs and standard errors were used in fixed effects or random effects models (Comprehensive Meta-analysis, Software version 3) for each of the variables of interest. Random effects models were computed if the heterogeneity statistic I^2 value exceeded 50%, which indicates moderate heterogeneity; otherwise fixed effects models were used. Statistical heterogeneity was evaluated with the I^2 value to identify the magnitude of effect estimates that relate to heterogeneity between studies with a larger number representing greater heterogeneity (149). Additionally, the Q-value was identified to indicate variance among ESs. A statistically significant sum of squares for each ES about the weighted mean (Q) implied heterogeneity.

2.3 Results

Our search of six electronic databases yielded 2423 articles, of which 1632 remained after duplicates were removed. An additional six articles were found by hand searching and one article was found in the updated search on December 6, 2016. Upon review of the titles and abstracts, 1568 were deemed to be unrelated to the research question (e.g., involved training of healthcare professionals regarding how to instruct wheelchair propulsion) and met the exclusion criteria, leaving 70 articles that were reviewed in full (including one found in the updated search). A total of 44 articles were not eligible based on full review (see Figure 2.1 for reasons for excluding articles). In total, 26 articles met eligibility criteria; these were conducted in the Netherlands (*n*=13), the United States (*n*=10), the United Kingdom (*n*=2), and Canada (*n*=1).

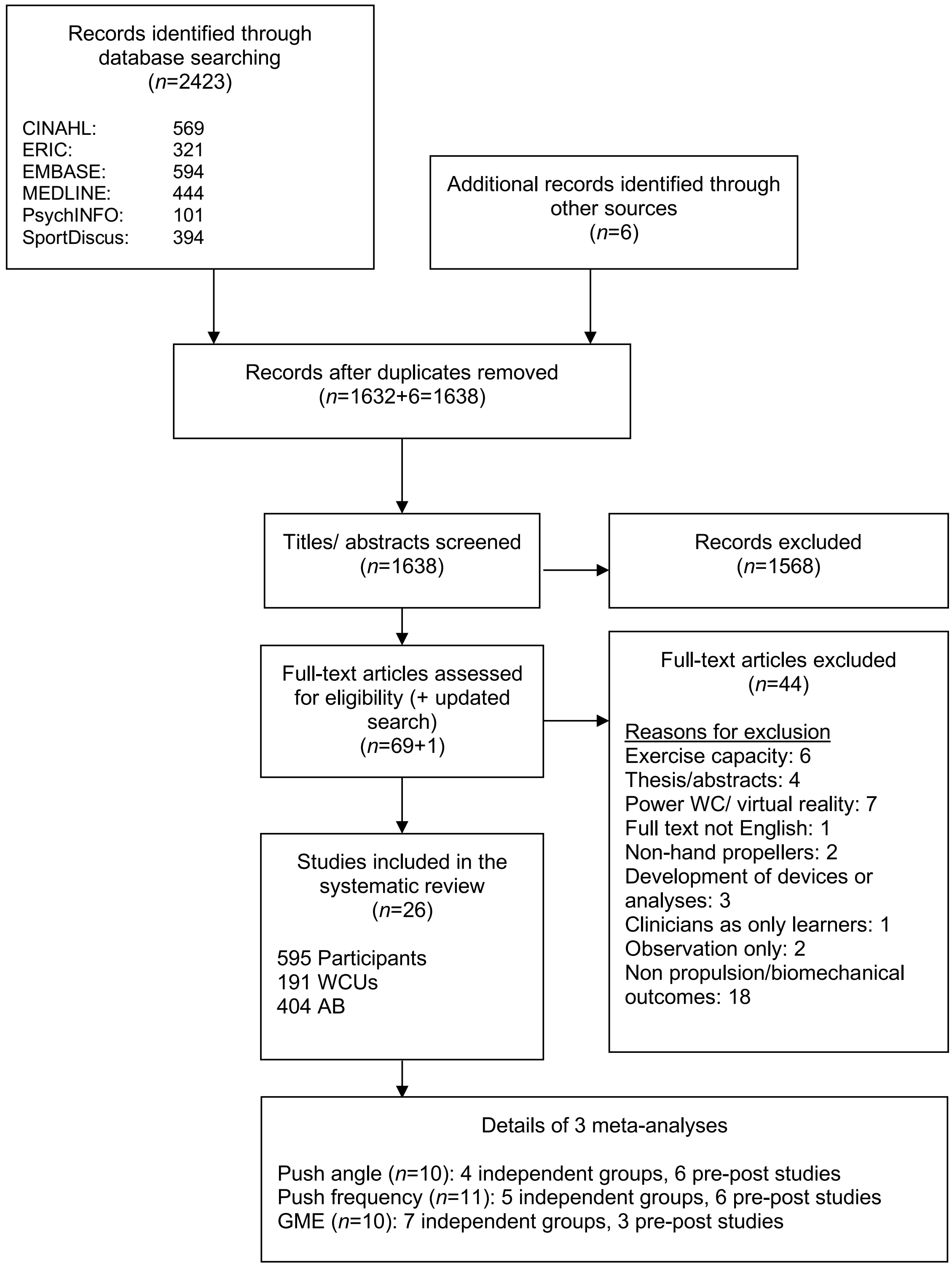


Figure 2.1. PRISMA flow diagram illustrating the search, screening, and selection of articles. Of the 26 included articles, 15 were included in the meta-analyses (push angle = 10, push frequency = 11, and GME = 10)

Abbreviations: AB: able-bodied; GME: gross mechanical efficiency; WC: wheelchair; WCUs: wheelchair users

2.3.1 Participants

The included articles reported data from 595 participants; however, there may be overlap among the reported participants because some authors appeared multiple times and may have presented data from the same cohort in multiple articles. The participant population was predominantly composed of male participants (84%) with approximately 480 men and 94 women (participant's sex was not reported in all cases). Most articles (*n*=15; 58%), which present data from 404 participants, examined able-bodied individuals with no prior manual wheeling experience. Eleven articles (42%), which present data from 191 participants, examined wheelchair users; eight of these examined experienced MWUs and three examined novice inexperienced MWUs (one was based in a rehabilitation setting whereas the other two were based in the community setting). Out of the 11 articles that examined MWUs, eight articles included samples of individuals with spinal cord injury exclusively, and the remaining three articles included samples of individuals with mixed mobility disabilities and conditions. Able-bodied individuals tended to be younger (18-41 years) with an average age of 22.7 years (mean of reported study means), whereas wheelchair users included a wider age range (13-69 years) with an average age of 36.9 years (mean of reported study means). Table 2.1 shows a summary of the participant groups as well as the timeline of the practice or training protocol and environmental factors related to training for each of the included articles.

Table 2.1. Study characteristics of the 26 studies included in the review that evaluated wheelchair propulsion practice and training protocols

	Study				Participants				Other		
	Year	Level of evidence	PEDro score	Groups	N	Age (yrs) mean (SD)	Sex (m/f)	Sample	Timeline of practice or intervention	Surface	Type of WC used
Single day protocol (*n*=10)	Blouin et al. 2015 [159]	IV Case series		(1) all received intervention	18	42.4 (11.6)	16/2	SCI	1 day	ergo	Invacare Ultralight A4
	de Groot et al. 2003[1] [22]	IV Case series		(1) all received intervention	9	24 (4.8)	9/0	AB	1 day	ergo	WC simulator
	de Groot et al. 2003[2] [23]	IV Case series		(1) all received intervention	9	24 (4.8)	9/0	AB	1 day	ergo	WC simulator
	DeGroot et al. 2009 [13]	IV Case series		(1) all received intervention	9	36.8 (7.1)	7/3	WCU	1 day	rollers	own
	Dysterhelft et al. 2015 [154]	IV Case series		(1) all received intervention	10	15.8 (1.6)	7/3	WCU	1 day	OG	own
	Kotajarvi et al. 2006 [107]	IV Case series		(1) all received intervention	18	38 (9)	16/2	SCI	1 day for 0.15 W/kg, 1 day for 0.25 W/kg	dyna	lightweight sport

	Richter et al. 2011 [16]	IV Case series		(1) all received intervention	31	34.1 (9.5)	27/4	WCU	1 day	tread	own
	Vegter et al. 2014[1] [128]	IV Case series		(1) all received intervention	70	22.8 (3.6)	70/0	AB	1 day	tread	Double Performance BV
	Vegter et al. 2014[2] [138]	IV Case series		(1) received intervention (4 types- types are not explored in this paper)	39	22.9 (3.2)	39/0	AB	1 day or 3 wks	tread	Double Performance BV
	Vegter et al. 2015 [155]	IV Case series		(1) all received intervention	15	27.4 (11.9)	8/7	AB	1 day	tread	Double Performance BV
Multiple day protocol (*n*=16)	De Groot et al. 2002[1] [20]	II RCT	6/10	(1) experimental (2) no practice control	20	exp: 21.7 (2.2); control: 21.3 (2.4)	20/0	AB	3 wks	ergo	WC simulator
	de Groot et al. 2002[2] [21]	II RCT (single-blinded)	6/10	(1) experimental (2) no practice control	20	exp: 21.6 (2.4); control: 21.7 (2.2)	20/0	AB	3 wks	ergo	WC simulator

de Groot et al. 2005 [25]	II RcoT	4/10	(1) ergometer practice (2) treadmill practice (3) track practice	30	ergo: 21.7 (2.2); tread: 22.1 (1.2); track: 19.8 (1.5)	30/0	AB	3 wks	ergo	WC simulator
de Groot et al. 2008 [19]	II RCT	5/10	(1) experimental (2) no practice control	21	exp: 23.5 (3.5); control: 22.7 (2.6)	21/0	AB	7 wks	tread	Quickie Triumph
Goosey-Tolfrey et al. 2011 [156]	III non-RCT	5/10	(1) 125 beat/min tempo music (2) 170 beat/min tempo music (3) no practice control	22	exp low: 19.6 (0.9); exp high: 20.4 (0.5); control: 20.2 (2.4)	NS	AB	3 wks	ergo	basketball
Lenton et al. 2010 [152]	III non-RCT	5/10	(1) un-paced (2) paced to 80% of freely chosen frequency (3) no practice control	25	22 (4)	25/0	AB	4 wks	ergo	basketball
Leving et al. 2015 [137]	III non-RCT	5/10	(1) feedback (2) natural learning	32	exp: 22.9 (2.9); control: 22.8 (3.9)	32/0	AB	3 wks	tread	Double Performance BV

Leving et al. 2016 [151]	III non-RCT	6/10	(1) variable practice (2) no practice control	23	exp: 20.2 (2.0); control: 20.7 (1.4)	9/14	AB	7 wks	tread	Kuschall K4
Morgan et al. 2017 [153]	IV case series		(1) all received intervention	6	38 (17.5)	4/2	SCI	3-5 wks	dyna	own
Rice et al. 2010 [14]	IV Case study		(1) all received intervention	1	45.6	1/0	SCI	3 wks	dyna	own
Rice et al. 2013 [93]	II RCT	4/10	(1) feedback (2) instruction only 3) no practice control group	27	same day: 40.0 (13.4); long term: 42.3 (13.6)	24/3	SCI	3 wks	dyna	own
Rice et al. 2014 [15]	II RCT (single blinded)	5/10	(1) intervention-education on clinical practice guidelines (2) standard therapy	37	38.3 (15.9)	28/9	SCI	during rehab	NA	own
van der Scheer et al. 2015 [150]	II RCT	6/10	(1) experimental (2) no practice control	29	median: 57	22/7	SCI	16 wks	tread	own
Will et al. 2015 [135]	IV SSRD		(1) all received intervention	5	39 (30)	3/2	SCI	5-9 wks	dyna	own

Yao et al. 2009 [108]	II RcoT	4/10	(1) 30% max speed (2) 55% max speed (3) variable speed (both 30 and 55%)	36	range: 20-41	18/18	AB	10 wks	rollers	Quickie GPV
Yao et al. 2012 [109]	II RcoT	4/10	(1) 30% max speed (2) 55% max speed (3) variable speed (both 30 and 55%)	33	range: 20-35	15/18	AB	12 wks	rollers	Quickie GPV

The grey background indicates single day interventions and the white background represents multiple day interventions. AB: able-bodied; dyna: dynamometer; ergo: ergometer; exp: experimental; FB: feedback; FEF: fraction effective force; GME: gross mechanical efficiency; ME: mechanical effectiveness; MEF: mechanical effective force; NA: not applicable; non-RCT: non-randomized controlled trial; OG: over-ground; RCT: randomized controlled trial; RcoT: randomized comparative trial, SCI: spinal cord injury; sig: significantly; SSRD: single subject research design; tread: treadmill; WCU: wheelchair user; wks: weeks

2.3.2 Schedule of practice and feedback

Table 2.2 shows the practice and training protocols, including their schedules and conditions of practice as well as the types of feedback provided, where applicable. The training protocols involved in the 26 articles ranged from 1 day to 16 weeks and involved 1 to 36 sessions. Ten articles examined the impact of a single session of training ranging from 12-80 minutes in propulsion duration. Only 13 articles included the use of a control (n=10) or comparative group (n=3) to evaluate the practice and training protocols' effectiveness; only nine studies involved randomization. Comparator groups were identified when there was no defined control group. Twenty-one articles included feedback (i.e., nine articles exclusively included feedback focusing on task maintenance, eight exclusively included feedback with the goal of improving the task, and three articles incorporated feedback focusing on task maintenance and improvement) while the other five articles focused on repetition of movement in promoting motor skill learning (19, 128, 138, 150, 151). Eleven articles exclusively used visual feedback (e.g., variables shown on a screen mounted to a treadmill or a computer screen) while six articles exclusively used auditory feedback. Three articles used combined visual and auditory feedback and one used combined haptic and visual feedback. Visual biofeedback on a computer screen was provided throughout the movement in the form of lines or bars to provide knowledge of performance in 13 articles. Two other articles that examined mixed modality feedback used a mirror and an audio-visual representation of a metronome to provide visual feedback (152, 153).

Table 2.2. Conditions of practice and feedback for the included studies that evaluated practice and training protocols

	Study	Training		Feedback				Findings	
	Year	Dosage (min)	Conditions of practice	FB variables (visual)	FB variables (other types)	Conditions of FB (spontaneous, continuous)	Goal of FB	Gross Mechanical Efficiency (mean PO/ energy expenditure)	Biomechanics
Single day (*n*=10)	Blouin *et al.* 2015 [159]	5 x 3 min tot: 15	variable	Computer screen: velocity-target ±2 SD	Haptic FB: 5, 10, 15, 20, 25% of participant's max voluntary propulsive moment (increased perception of resistance when pushing)	Visual = continuous, Haptic = continuous	Visual: maintenance of task (velocity), Haptic: improve mechanical effective force	Not evaluated	MEF ($Ftan^2/Ftot^2$) pattern was modified towards target in post-testing in 8 of 18 participants. MEF increased by up to 12.4% on the left side and 15.7% on the right side.
	De Groot *et al.* 2003[1] [22]	3 x 4 min tot: 12	block	Computer screen: left and right velocity and target velocity of 1.11 m/s		Continuous	Maintenance of task (velocity)	No change	Frequency and percent push time sig decreased over time. Work per cycle increased sig over time and was associated with higher peak torque. Peak torque also increased sig over time.
	De Groot *et al.* 2003[2] [23]	3 x 4 min tot: 12	block	Computer screen: velocity to keep target velocity of 1.11 m/s		Continuous	Maintenance of task (velocity)	Not evaluated	Frequency sig decreased over time. Medio-lateral distance between shoulder and elbow got smaller over time but the medio-lateral distance between the elbow and hand sig increased. Some muscles increased muscle activity during the push phase, recovery phase, and some showed increased co-contraction.

DeGroot *et al.* 2009 [13]	NS	NS	Computer screen: push length, push force, frequency	Verbal FB: propulsion (earlier verbal instructions)	Visual = continuous, verbal = spontaneous (terminated when decided sufficient training had occurred)	Visual: improve wheeling biomechanics, Verbal: improve wheeling biomechanics	Not evaluated	Push angle, peak force, and average force sig increased while frequency sig decreased immediately following training (on the treadmill only).
Dysterhelft *et al.* 2015 [154]	NS	NS		Verbal FB: 'basic feedback' given	NS	Improve wheeling biomechanics	Not evaluated	Push angle and peak total force sig increased while frequency sig decreased on the carpet and tile surfaces over time. Push angle sig increased and frequency sig decreased in the velocity controlled concrete trial over time.
Kotajarvi *et al.* 2006 [107]	4 x 10 min tot: 40	variable	Computer screen: FEF, velocity, power output, during push phase of propulsion		Continuous	Improve wheeling biomechanics (fraction of effective force)	Not evaluated	Frequency was sig lower and push angle and velocity were sig higher in the feedback trials. At the higher intensity, both trials (with and without FB) resulted in a sig improvement in FEF compared to the lower intensity.
Richter *et al.* 2011 [16]	10 x 1.5 min tot: 15 max	variable	Computer screen: braking moment, cadence, push angle, peak force, push distance, smoothness		Continuous (stroke by stroke). 6 variables presented individually	Improve wheeling biomechanics	Not evaluated	Participants improved all biofeedback (biomechanical) variables except smoothness (from 11-25%) for 9 of the 11 conditions. Push angle resulted in the tightest control while smoothness and force appeared to be more difficult to modify.

	Vegter *et al.* 2014[1] [128]	3 x 4 min tot: 12	block					GME sig increased with each successive block for the three 4-min blocks.	Push time, cycle time, work per push, and push angle sig increased over time. Frequency, mean force, and negative work per cycle sig decreased.
	Vegter *et al.* 2014[2] [138]	10 x 8 min tot: 80 (sessions separated by 30 min or 48 hrs)	block and variable	Computer screen: braking moment, cadence, push angle, peak force, push distance, smoothness, impact		Continuous (stroke by stroke). 7 variables presented individually	No instruction related to visual feedback (unclear of purpose). Improvements in wheeling were assumed to result from practice.	GME increased by at least 10% after 80 min of training in 26 of 39 participants. These fast improvers had a sig higher GME compared to the initially slow learners at post-test. No data presented representing all participants.	Initially fast learners (26 of 39) benefited to a greater extent from the practice indicated by higher push angle and lower frequency. They also had sig higher intra-individual variability for most variables.
	Vegter *et al.* 2015 [155]	3 x 4 min tot: 12	block					GME sig increased over practice. There was a significant increase from block 1 (first block) to block 3 (final block).	Push time, cycle time, work per push, mean fraction effective force, and push angle sig increased over time. Frequency sig decreased over time. Increased load on shoulder (higher shoulder forces), and higher net moment on the glenohumeral joint was also observed.
Multiple day (*n*=16)	de Groot *et al.* 2002[1] [20]	3/ wk x 8 min tot: 72	variable	Computer screen: left and right velocity, target velocity of 1.11m/s, symmetry		Continuous	Maintenance of task	GME sig increased between trial 1 and trial 9 in the exp group. GME was sig higher at higher external power outputs.	Frequency and negative power deflection sig decreased in the exp group compared to the control group. Work per cycle, push time and cycle time sig increased in the exp group compared to the control group.

De Groot et al. 2002 [21]	3/ wk x 8 min tot: 72	variable	Computer screen: velocity and FEF	Continuous	Maintenance of task	GME was sig lower in the exp group compared to controls at trial 8 (the 9th practice session). GME was sig higher at higher external power outputs in both groups. The difference between groups was larger at higher power outputs.	Exp group showed higher FEF at trial 8 (the final trial). There was no correlation between FEF and ME. Fz was sig lower in the exp group for trial 8 and Fy was directed inward in the exp group rather than outward (also sig).
de Groot et al. 2005 [25]	3/ wk x 8 min tot: 72	variable	Computer screen: left and right velocity and target velocity of 1.11m/s (erg group only); Speedometer: speed (for track and tread)	Continuous *The erg group was the only to have FB provided on the screen during training	Maintenance of task	GME did not change over time in any of the training groups. Erg showed a 1.3% higher GME than tread (sig). Track showed a 0.9% lower ME than tread (sig).	Percent push time decreased sig more in the erg group compared to the tread group. Improvements over time were shown for frequency, push time and cycle time in all 3 groups. Velocity was sig lower in the erg group compared to the others. Work per cycle was sig lower in the erg group compared to tread.
De Groot et al. 2008 [19]	3/ wk x 70 min tot: 1470	block				GME increased sig more in the exp group compared to the control group (relative increase = 30%). Metabolic cost decreased sig more in the exp group compared to the control group (relative decrease = 21%).	Push time sig increased and frequency sig decreased in the exp group compared to the control group. The exp group mainly used DLOP and the control group mainly used SLOP.

Goosey-Tolfrey *et al.* 2011 [156]	3/ wk x 8 min tot: 72	block		Auditory FB: Participants in the intervention groups were paced to various tempo music (either 125 or 170 beats/ min)	Continuous- the music was played throughout the training for the intervention groups.	Maintenance of task	GME sig increased in the low tempo group compared to the control group after controlling for pre-practice differences. There was no difference between high temp and control groups.	There were no sig differences in biomechanical variables over time.
Lenton *et al.* 2010 [152]	3/ wk x 16 min tot: 192	block	Audio-visual metronome was used for pacing arm frequency	Auditory FB: audio-visual metronome used to cue the paced group	Continuous (for paced groups)	Maintenance of task	GME sig improved by 21% in the un-paced group and the paced groups improved by 17%. Increases in GME were most evident at higher frequencies of wheeling. Additionally, heart rate, submax VO_2, blood lactate and rating of perceived exertion decreased sig in the exp groups.	Self-selected (freely chosen) frequency sig decreased in both practice groups over time. Work per cycle sig increased for both groups over time in the freely chosen frequency trial.

Leving *et al.* 2015 [137]	2 x 12 min; 7 x 8 min tot: 80	variable	Computer screen: push frequency, braking moment, push angle, peak force, push distance, smoothness, FEF		Continuous (8 mins FB per variable)	Instructed to use as much variability as possible to increase motor exploration (specific variable was not disclosed)	GME sig improved in the natural practice (control) group overtime compared to the FB group. The FB group did not improve.	Power output sig decreased over time in the FB group but not the natural practice group. Both groups sig increased push angle and sig decreased frequency. The natural learning group sig improved smoothness, FEF, and braking moment. The FB group showed greater intra-individual variability while practicing.
Leving et al. 2016 [151]	7 x 60 min tot: 420	variable (standardized WC skills and uninstructed WC basketball)					GME sig improved in the variable practice group (intervention) between baseline and post-testing compared to the control group.	Wheeling frequency sig decreased and push angle sig increased between baseline and post-testing in both groups (no difference between groups).
Morgan et al. 2017 [153]	9 x 20 min tot: 180	variable	Reflection in mirror	Verbal FB: Set A focused on longer push strokes and set B focused on dropping hands down towards the axle	Visual = continuous, Verbal = spontaneous (more at the beginning and decreased over time)	Verbal: Improve wheeling biomechanics (longer push angle and dropping hand toward axle)	Not evaluated	Push loop area, speed, and push effectiveness (m/cycle) sig increased while the slope of force and the distance between the 3rd metacarpal and the wheel axle sig decreased. Participants modified their propulsion pattern from pre- to post-testing.

Rice et al. 2010 [14]	3 x 12 min tot: 36	variable	Computer screen: velocity, frequency, push angle		Spontaneous (intermittent)	Maintenance of velocity/ improve wheeling biomechanics	Not evaluated	The participant increased push angle, and reduced frequency, mean resultant force, and peak rate of rise in self-selected and velocity-matched trials.
Rice et al. 2013 [93]	3 x 11 min tot: 33	variable	Computer screen: velocity, frequency, push angle		Spontaneous (intermittent)	Maintenance of velocity/ improve wheeling biomechanics	Not evaluated	Both exp groups showed a sig increase in push angle and a sig decrease in frequency. The FB group showed sig larger push angle and sig lower frequency compared to the instruction only group 3 months post baseline.
Rice et al. 2014 [15]	no specific practice	NA		Therapists were instructed to give external/ augmented FB (e.g., move patients hand through wheelchair stroke)	Spontaneous-manual said to decrease amount of FB after participants learned proper technique	Improve wheeling biomechanics	Not evaluated	Frequency was sig lower in the exp group on tile at discharge compared to the active control group. Push angle was sig longer on ramp at all time points compared to the active control group.

Van der Scheer et al. 2015 [150]	2/ wk x ~30min tot: 924	block					Not evaluated	No sig effects of training. Only peak force change was sig larger in the intervention group for block 2 compared to the control.
Will *et al.* 2015 [135]	9 x 20 min tot: 180	variable		Verbal FB: Set A cued participants to lengthen time hand was in contact with handrim and Set B cued to drop hand toward wheel axle	Spontaneous-individualized for each participant	Improve wheeling biomechanics (longer push angle and dropping hand toward axle)	Not evaluated	All participants improved their propulsion biomechanics in at least 1 variable at dosage 1 (1000-2700 repetitions), changes were also seen at dosage 2 and 4. There was a lot of variability between participants. Most improvements occurred within 2-3 sessions.
Yao *et al.* 2009 [108]	3/ wk x 30 min tot: 900	block or variable		Verbal FB: speed (if speed varied +/- 0.1 km/h off target	Continuous when speed was not achieved based on +/- 0.1 km/h (training sessions only)	Maintenance of task	Not evaluated	All groups sig improved accuracy in performing wheelchair propulsive speeds. For post training data, sig main effect of speed and training group. Variable group produced sig lower absolute error scores than the 30% only group at novel speeds and the 55% group only at 70% speed.

Yao *et al.* 2012 [109]	3/ wk x 30 min tot: 1080	block or variable		Verbal FB: speed (if speed varied +/- 0.1 km/h off target	Continuous when speed was not achieved based on +/- 0.1 km/h (training sessions only)	Maintenance of task	Not evaluated	All groups sig improved propulsive efficiency, timing, and intercycle variability following training. The variable practice group improved propulsive efficiency to a greater extent. For post-test, both 40% (novel) and 55% speeds had better efficiency scores (speed/energy expenditure) compared to the 30% and 70% (novel) speeds.

The grey background indicates single day interventions and the white background represents multiple day interventions. WC: wheelchair; exp: experimental; FB: feedback; FEF: fraction effective force; Ftan: Force tangential to handrim; Ftot: total force; Fy: force in y-direction; Fz: force in z-direction; GME: gross mechanical efficiency; hrs: hours; km/h: kilometers per hour; m/s: meters per second; ME: mechanical effectiveness; MEF: mechanical effective force; min: minutes; NA: not applicable; NS: not stated; SD: standard deviation; sig: significantly; tot: total, wk: week

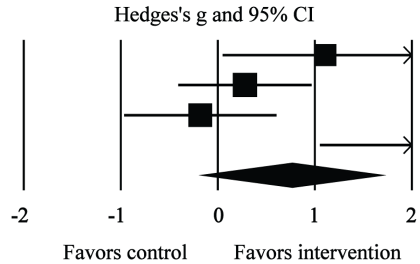
2.3.3 Effects of practice and training protocols

Articles that reported sufficient data at baseline and following training to calculate ESs for push angle (*n*=10), push frequency (*n*=12), and GME (*n*=10) were included in the meta-analyses. Overall, the meta-analyses involved 15 of the 26 articles included in the review. Post-testing occurred within the same day (i.e., immediately following training) for all pre-post design articles while post-testing occurred immediately following (*n*=4) and within 1 week (*n*=4) for the studies that used *independent groups*. Only four articles evaluated retention (a post post-test), of which only one article reported retention data; therefore, a meta-analysis to examine retention was not feasible.

Push Angle: Five of the single day practice or training protocols (13, 107, 128, 154, 155) and five of the multi-day practice or training protocols (14, 15, 93, 137, 151) reported that some format of training was effective in increasing push angle. The weighted mean ES was homogeneous for the pre-post studies (Q_5=0.70, *P*=0.98, I^2=0.00) and was heterogeneous for the studies that used independent groups (Q_3=13.16, *P*=0.004, I^2=77.21). The weighted ESs for push angle were 0.67 (SE=0.12; 95% CI 0.43-0.92; *z*=5.43; *P*<0.001) for the pre-post studies and 0.77 (SE=0.47; 95% CI -0.16–1.70; *z*=1.63; *P*=0.10) for the studies that used independent groups (Figure 2.2). This reflects a statistically significant medium effect in favor of training for the pre-post model. Articles that evaluated push angle included both able-bodied participants and MWUs.

Independent groups studies

	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Goosey-Tolfrey, 2011^	1.110	0.540	0.292	0.052	2.168	2.056	0.040
Leving, 2015	0.280	0.350	0.123	-0.406	0.966	0.800	0.424
Leving, 2016	-0.180	0.400	0.160	-0.964	0.604	-0.450	0.653
Rice, 2013*^	2.150	0.560	0.314	1.052	3.248	3.839	0.000
Random effects	0.769	0.473	0.223	-0.157	1.696	1.628	0.104



Pre-Post studies

	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
de Groot, 2003[2]	0.360	0.450	0.203	-0.522	1.242	0.800	0.424
Dysterhelft, 2015*	0.720	0.440	0.194	-0.142	1.582	1.636	0.102
Kotajarvi, 2006*	0.630	0.330	0.109	-0.017	1.277	1.909	0.056
Morgan, 2015*	0.780	0.550	0.303	-0.298	1.858	1.418	0.156
Vegter, 2014[1]	0.730	0.170	0.029	0.397	1.063	4.294	0.000
Vegter, 2015	0.600	0.360	0.130	-0.106	1.306	1.667	0.096
Fixed effects	0.674	0.124	0.015	0.431	0.917	5.430	0.000

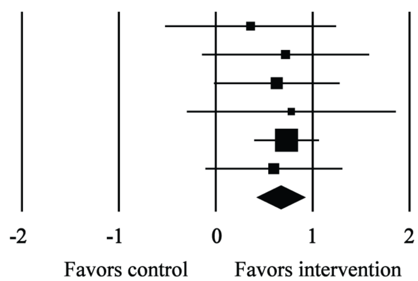


Figure 2.2. Meta-analyses of practice and training protocols indicating a significant medium effect of pre-post design studies on push angle

The solid squares represent the corresponding ESs of the independent samples studies (above) and the pre-post studies (below). The corresponding diamonds represent the weighted ES for the study type. The * denotes studies with MWUs and the ^ denotes studies with more than 2 groups. In these cases, the control group was evaluated with the 'intervention' of focus (i.e., Goosey-Tolfrey, 2011: control and low tempo, Rice, 2013: control and feedback).

Push Frequency: Seven of the single day practice or training protocols (13, 22, 23, 107, 128, 154, 155) and nine of the multi-day practice or training protocols (14, 15, 19, 20, 25, 93, 137, 151, 152) reported that some format of training was effective in decreasing push frequency (Hz). The weighted mean ES was homogeneous for the pre-post study studies (Q_5=2.21, P=0.82, I^2=0.00) and heterogeneous for the studies that used independent groups (Q_5=34.96, P<0.001,

I^2=85.70). The weighted ESs for push frequency were 0.59 (SE=0.13; 95% CI 0.35-0.84; *z*=4.73; *P*<0.001) for the pre-post studies and 1.19 (SE=0.53; 95% CI 0.16-2.22; *z*=2.26; *P*=0.024) for the studies that used independent groups (Figure 2.3). This reflects a statistically significant medium effect in favor of training for the pre-post model and a large effect in favor of training for the independent groups model; however, after removing the outlying study (93) with an effect size of 4.29, the model of independent groups studies was no longer significant 0.65 (SE=0.38; 95% CI -0.10-1.41; *z*=1.70; *P*=0.089). The effect size was calculated from adjusted mean values averaged across three surface types in the outlying study, which may have inflated the change following training. Articles that evaluated push frequency included both able-bodied participants and MWUs.

Independent groups studies

	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
de Groot, 2002[1]	0.860	0.450	0.203	-0.022	1.742	1.911	0.056
Goosey-Tolfrey, 2011^	2.330	0.650	0.423	1.056	3.604	3.585	0.000
Lenton, 2010^	0.810	0.490	0.240	-0.150	1.770	1.653	0.098
Leving, 2015	0.110	0.350	0.123	-0.576	0.796	0.314	0.753
Leving, 2016	-0.320	0.400	0.160	-1.104	0.464	-0.800	0.424
Random effects	0.652	0.384	0.147	-0.100	1.405	1.700	0.089

Pre-Post studies

	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
de Groot, 2003[1]	0.800	0.470	0.221	-0.121	1.721	1.702	0.089
Dysterhelft, 2015*	1.000	0.450	0.203	0.118	1.882	2.222	0.026
Kotajarvi, 2006*	0.300	0.330	0.109	-0.347	0.947	0.909	0.363
Morgan, 2015*	0.410	0.540	0.292	-0.648	1.468	0.759	0.448
Vegter, 2014[1]	0.560	0.170	0.029	0.227	0.893	3.294	0.001
Vegter, 2015	0.780	0.370	0.137	0.055	1.505	2.108	0.035
Fixed effects	0.591	0.125	0.016	0.346	0.836	4.725	0.000

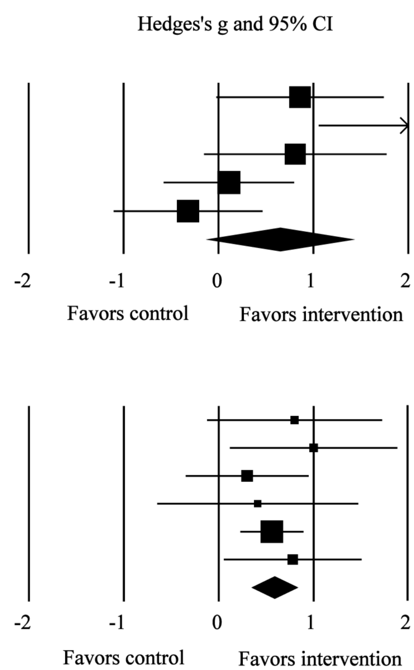


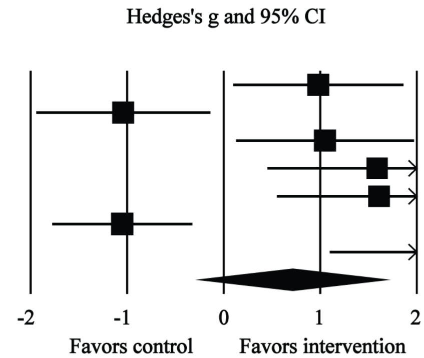
Figure 2.3. Meta-analyses of practice and training protocols indicating a significant medium effect of pre-post design studies on push frequency

The solid squares represent the corresponding ESs of the independent samples studies (above) and the pre-post studies (below). The corresponding diamonds represent the weighted ES for the study type. The * denotes studies with MWUs and the ^ denotes studies with more than 2 groups. In these cases, the control group was evaluated with the 'intervention' of focus (i.e., Goosey-Tolfrey, 2011: control and low tempo, Lenton, 2010: control and 80% FCF tempo, Rice, 2013: control and feedback).

Gross Mechanical Efficiency*:* Two of the single day practice or training protocols (128, 155) and six of the multi-day practice or training protocols (19, 20, 137, 151, 152, 156) reported that some format of training was effective in improving GME. The weighted mean ES was homogeneous for the pre-post studies (Q_2=4.72, I^2=0.00) and heterogeneous for the studies that used independent groups (Q_6=49.00, P<0.001, I^2=87.76). The weighted ESs for GME were 0.53 (SE=0.15; 95% CI 0.24–0.81; z=3.62; P<0.001) for the pre-post studies and 0.72 (SE=0.51; 95% CI -0.28–1.72; z=1.40; P=0.16) for the studies that used independent groups (Figure 2.4). This reflects a significant medium effect in favor of training for the pre-post model. Articles that evaluated GME included able-bodied participants exclusively.

Independent groups studies

	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
de Groot, 2002[1]	0.980	0.450	0.203	0.098	1.862	2.178	0.029
de Groot, 2002[2]	-1.040	0.460	0.212	-1.942	-0.138	-2.261	0.024
de Groot, 2008	1.050	0.470	0.221	0.129	1.971	2.234	0.025
Goosey-Tolfrey, 2011^	1.590	0.580	0.336	0.453	2.727	2.741	0.006
Lenton, 2010	1.610	0.540	0.292	0.552	2.668	2.981	0.003
Leving, 2015	-1.050	0.370	0.137	-1.775	-0.325	-2.838	0.005
Leving, 2016	2.080	0.500	0.250	1.100	3.060	4.160	0.000
Random effects	0.717	0.511	0.261	-0.284	1.719	1.403	0.160



Pre-Post studies

	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
de Groot, 2003[1]	0.110	0.450	0.203	-0.772	0.992	0.244	0.807
Vegter, 2014[1]	0.610	0.170	0.029	0.277	0.943	3.588	0.000
Vegter, 2015	0.420	0.360	0.130	-0.286	1.126	1.167	0.243
Fixed effects	0.527	0.145	0.021	0.242	0.812	3.621	0.000

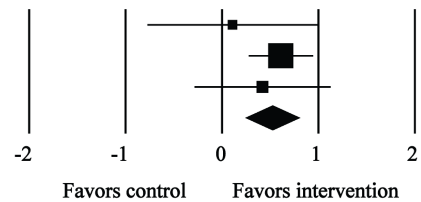


Figure 2.4. Meta-analyses of practice and training protocols indicating a significant medium effect of pre-post design studies on GME

The solid squares represent the corresponding ESs of the independent samples studies (above) and the pre-post studies (below). The corresponding diamonds represent the weighted ES for the study type. The * denotes studies with more than 2 groups. In these cases, the control group was evaluated with the 'intervention' of focus (i.e., Goosey-Tolfrey, 2011: control and low tempo).

Training involving feedback generally resulted in positive effects in many articles; however, some articles reported that the group that did not receive feedback actually performed better (Table 2.2). Lenton et al. reported that the 'unpaced' group improved GME to a greater extent than the paced intervention group, which received feedback via an audio-visual metronome with the purpose of maintaining pace (152). Additionally, Leving et al. reported that the natural learning group (i.e., active control group) that did not receive biofeedback showed improvements in GME; whereas, the experimental group (i.e., visual feedback group that was instructed to manipulate propulsion variables to maximize variability and then optimize in a prescribed direction) did not improve (137); both studies implemented continuous feedback.

2.3.4 Evidence of skill learning

Table 2.3 shows the four articles that evaluated retention (i.e., whether a training effect outlasted the intervention) and the ten articles that identified transfer (i.e., whether participants improved on a different task resulting from their experience on the intervention task). The most common transfer tests involved over-ground wheeling such as the SmartWheel Clinical Protocol (157) or the Wheelchair Propulsion Test (158). The Wheelchair Propulsion Test only involves wheeling on smooth level ground, whereas the SmartWheel Clinical Protocol involves wheeling on tile, carpet, and ramp surfaces.

Table 2.3. Studies that included and evaluated retention and transfer

	Study	Evaluation of motor learning		Evidence for motor learning	
	Year	**Transfer**	**Retention**	**Transfer**	**Retention**
Transfer & retention (*n*=3)	Rice *et al.* 2010 [14]	OG testing	3 months post baseline	Participant increased push angle, and reduced frequency, mean resultant force, and peak rate of rise in self-selected and velocity-matched trials.	Improvements (decreased frequency and increased push angle) were observed 3 months post-baseline (~70 days post training).
	Rice *et al.* 2013 [93]	OG testing (ramp, tile, carpet)	3 months post baseline	The results were not Influenced by surface type so surfaces were collapsed. Short- and long- term effects on push angle and frequency and short-term effects on peak force and rate of rise of force.	Controlling for several variables, improvements were observed in the short-term and 3 months post-baseline (~70 days post training) in push angle and frequency in the FB group compared to the instruction only group.
	Rice et al. 2014 [15]	SmartWheel Clinical Protocol (tile, ramp, carpet)	6 months and 1 year post discharge (training)	The intervention group propelled with a sig lower frequency and a sig greater push angle on ramp.	The intervention group propelled with a sig lower frequency on tile at discharge (this effect was not maintained) and a sig greater push angle on ramp at all time points (this effect was maintained).
Transfer only (*n*=6)	DeGroot *et al*. 2009 [13]	SmartWheel Clinical Protocol (tile, ramp, carpet)		Improvements in push length, frequency, peak force, and average force were observed on rollers, but no improvements were observed OG on tile (no transfer).	
	de Groot *et al.* 2005 [25]	Track and tread groups tested on ergometer (different from their training setting)		The erg group showed a 1.3% higher ME than tread and the tread showed a 0.9% higher ME than track. Erg group decreased push time sig more than tread.	

	Dysterhelft *et al.* 2015 [154]	Wheelchair propulsion was tested on multiple different surfaces and in different environments including carpet, tile, and concrete (velocity controlled outdoor trial). The practice surface in the intervention is not stated. It is assumed that they did not practice the testing tasks.		Carpet and tile trials resulted in sig increases in push angle and peak total force with a sig decrease in frequency. The velocity controlled concrete trial resulted in a sig increase in push angle and sig decrease in frequency. Transfer is difficult to infer because practice surface is unknown.	
	Morgan *et al.* 2017 [153]	Wheelchair Propulsion Test (*may have wheeled OG in skill practice which was in addition to propulsion practice)		Based on the wheelchair propulsion test, the recovery item (bringing hand below handrim) was sig improved. Speed sig increased between pretest 2 and the post-test.	
	Yao *et al.* 2009 [108]	Tested speeds that were not practiced (40, 70)		The variable practice group had lower absolute error scores than the 30% only group at novel 'transfer' speeds (40 and 70%) and the 55% only group at 70%.	
	Yao *et al.* 2012 [109]	Tested speeds that were not practiced (40, 70)		Both 40% (transfer) and 55% speeds had better efficiency scores compared to the 30% and 70% (transfer) speeds at post-testing.	
Retention only (*n*=1)	van der Scheer *et al.* 2015 [150]		42 week retention testing (26 weeks post intervention)		No retention (no initial impact of training either).

The grey background indicates single day interventions and the white background represents multiple day interventions. erg: ergometer; FB: feedback; ME: mechanical effectiveness; OG: over-ground; sig: significant

2.3.5 Evidence level and methodological quality

Table 2.1 reports evidence level and methodological quality. All single day studies had low evidence (IV: *n*=10) based on the Oxford's Centre for Evidence Based Medicine's "levels of evidence", while the multiple day studies generally had higher evidence (IV: *n*=3, III: *n*=4, and II: *n*=9). All single day observational studies used a case series design, while the multiple day studies used a variety of designs, including independent groups designs (e.g., RCTs and non-RCTs), a case series design, a case study, and another single subject research design. Overall, nine of the 26 included articles involved a randomized design. Although this study design has higher evidence, most studies were not blinded and only two were single-blinded. Additionally, only one study used concealed allocation (150) and only one study used a blinded assessor (15). Of the 13 articles that included more than one group, PEDro scores ranged from 4/10 to 6/10, with a mean (SD) score of 5.0 (0.8), indicating that the included articles were of fair quality (see Appendix G).

2.4 Discussion

Although motor learning principles have been applied to training protocols for wheelchair-related tasks for over two decades (123), there has been no previous synthesis of the literature. Our review supports that wheelchair propulsion motor skill practice and training protocols improve wheelchair propulsion biomechanics based on pre-post design studies. This is consistent with established clinical practice guidelines (3). However, these improvements may only be short-term. The clinical meaningfulness of these improvements warrants further elucidation as there are no published MCID values for wheelchair propulsion variables. Only four of 26 articles evaluated retention and nine of 26 articles evaluated transfer; therefore, we could not discern whether motor learning occurred.

Improvements in wheelchair propulsion characteristics were found following practice or training based on our meta-analyses. Although there was insufficient data to analyze retention, three articles noted long-term improvements following training (14, 15, 93). The findings of the meta-analyses demonstrated different ESs of practice and training protocols dependent on the corresponding study designs. The meta-analyses of studies that used independent groups did not identify statistically significant effects of training. All except one (153) of the pre-post design studies involved a single day intervention, while the RCTs consisted of multiple day interventions; therefore, training effects may not be sustained over time.

2.4.1 Motor learning principles

The articles included in this review consisted of diverse practice and training protocols, which incorporated various motor learning principles. The shortest practice or training protocols were 12 minutes for able-bodied participants (22, 23, 128, 155), and 15 minutes for MWUs (16, 159), which involved variable practice with feedback. The longest practice or training paradigms were 1470 minutes for able-bodied participants and 924 minutes for MWUs, both of which involved blocked practice designs (19, 150). Interestingly, the longest paradigms involved blocked practice and did not include feedback. The 924-minute intervention was not effective for improving wheelchair propulsion biomechanics among MWUs; however, the longer protocol by de Groot et al. was effective for improving biomechanics and GME among able-bodied participants (19).

Feedback is important and can facilitate motor skill acquisition. The type, frequency, delivery, schedule (continuous or variable), and focus of the feedback can markedly impact its effectiveness in clinical settings (132, 133). In the articles included in the present review, 21 of the 26 articles incorporated extrinsic feedback into their training. Twelve studies used feedback to maintain the task, while 11 studies used feedback with the goal of eliciting change; three studies incorporated feedback with both goals. Visual biofeedback delivered on a screen presenting biomechanical variables was the most common type of augmented feedback used. Two of the 21 studies did not provide 'bio' feedback, but rather used auditory or visual cueing to maintain a pace or tempo (152, 156). Sixteen studies used continuous feedback (13, 16, 20-23, 25, 107-109, 137, 138, 152, 153, 156, 159), which may have been detrimental if participants became dependent on the feedback.

Retention and transfer were used to support the presence of motor learning in few studies. Retention was considered a second post-test used to determine if changes following training were sustained or 'learned' on a more permanent basis. We observed short-term effects in studies with pre-post designs, which mainly incorporated single day interventions; however, no pre-post design studies evaluated retention. Of the 16 multiple day intervention studies, only four evaluated retention. Increased push angle and decreased frequency were observed in three of the four articles that examined retention (14, 15, 93). One study reported no evidence of retention, nor an initial effect of training (150).

2.4.2 Study samples

Wheelchair users may have less capacity for optimizing wheeling technique than their able-bodied counterparts. Specifically, they may be at a different stage on the non-linear continuum of learning where their improvement gains are smaller (133). Hence, propulsion training should be delivered as early as possible to prevent inefficient propulsion patterns from being formed. Interestingly, no articles examined GME in MWUs. The articles that evaluated GME used convenience sampling of young adult male able-bodied participants from a university population, which precludes inferences about the general population of MWUs. Future research needs to examine GME following training in MWUs.

Examining young men may be representative of the first mode of the bimodal spinal cord injury distribution based on age; however, they are not representative of the broad population of MWUs. The fastest growing cohort of MWUs is aging adults in the United States and Canada (8, 12); therefore, future studies need to explore more representative populations so that training protocols can be better applied to the spectrum of MWUs. Furthermore, many of the standardized speeds and power outputs used in the interventions may not be appropriate or feasible for an older population. Future training protocols need to be designed to be more inclusive of the broad population of MWUs.

2.4.3 Study design implications

Although motor skill training may be an efficient and cost-effective means of improving wheelchair propulsion, wheelchairs must be properly configured to optimize usability (160). The included articles in this review often used one wheelchair (20-23, 25, 107-109, 128, 137, 138, 151, 152, 155, 156, 159) for all participants and did not acknowledge whether they specifically fitted participants to the lab wheelchairs. Using a poorly configured wheelchair may negatively impact motor skill acquisition of wheelchair propulsion.

The ESs of pre-post design studies are on average 61% larger compared to independent groups studies (randomized and non-randomized), even when evaluating the same treatment areas (148). Furthermore, meta-analysis of studies including independent groups that have not been randomized results in slightly smaller ESs than studies including independent groups that have been randomized. Similarly, studies including independent groups with higher methodological quality results in slightly larger ESs compared to those of lower quality (148). Studies with small sample sizes also introduce bias, especially when they have five or fewer participants per group (148). Due to both our small number of included studies and the studies' small sample sizes, our meta-analyses were underpowered and the results of one of the included studies would have severely influenced our overall findings. Although there was minimal data that could be incorporated into the meta-analyses and the results are limited, this review provides insight into the effectiveness of motor skill practice and training protocols. Future research should improve the quality of study designs to build on the findings of this meta-analysis.

2.4.4 Limitations

We included search terms such as 'teaching', 'learning', retention' 'transfer' and 'motor performance' to capture articles that focused on learning or teaching wheelchair propulsion. We may have missed articles involving motor learning; however, if we could not explicitly extrapolate whether a practice or training protocol based on motor learning principles had been evaluated, we did not include the article. Another limitation of this review lies in the difficulty of synthesizing and interpreting the data. The results of the review may contain geographical bias, related to the involvement of affluent Western countries that have greater access to light-weight and efficiently-designed wheelchairs, as all articles came from the United States, Canada, and Europe. The meta-analyses may be influenced by the positive results publication bias and by the under-reporting of variables demonstrating negative results, as well as the small number of articles. Moreover, limiting the search to articles published in English only, may have introduced further geographical and cultural bias.

The articles included in the meta-analyses of independent groups studies demonstrated moderate to high heterogeneity. The larger magnitude of heterogeneity may be a result of including studies with various participant populations, studies that did not match their testing and training environments (e.g., trained on a treadmill but testing was performed over-ground), or studies with varying timelines of post-testing (e.g., ranging from immediately post to 1-week post training). Additionally, the diversity of control groups may have impacted the findings considering that control groups varied from a traditional 'no intervention' control group to an active dosage matched or 'natural learning' control group. The specific motor learning principles which had greatest impact and the effect of training duration could not be discerned from this review. Furthermore, we note that the overall quality and evidence of the included articles was fair and several of the studies lacked methodological rigor.

2.5 Conclusion

The included articles from the meta-analyses provided evidence that wheelchair propulsion motor skill training is effective in improving wheeling biomechanics and GME in pre- post design studies. However, the meta-analyses of studies including independent groups did not show significant effects of practice and training protocols. There were insufficient data to conduct further analyses to examine whether retention and transfer had occurred; therefore, the presence of motor learning could not be identified. Given that the included studies were not representative of the spectrum of MWUs, future research should focus on older adults to determine the impact of wheelchair propulsion training based on motor learning principles.

The application of motor learning principles to training wheelchair propulsion is in its infancy; therefore, all articles that examined motor skill practice or training in adults were included in the systematic review. Although the focus of the thesis is on older adults, no prior research has investigated wheelchair propulsion training in this population, thus the results of the systematic review and meta-analyses may have limitations when applied to older adults. The initial purpose of the review was to determine the effect of specific motor learning principles to inform the design of our training protocol; however, due to the limited literature and poorly described training protocols, the impact of select motor learning principles could not be discerned. We collapsed various practice and training protocols together for the meta-analyses; therefore, the results of this review can only provide a summary of the effectiveness of the protocols evaluated in the literature. The inclusion of uninstructed practice protocols may be up for debate; however, since many articles observed improvements with this fundamental principle of motor skill acquisition, we decided to include it in the review.

Overall, we observed that pre-post design studies identify immediate improvements in motor performance for push angle, push frequency, and GME; however, studies that evaluate independent groups did not identify significant effects. Moreover, the training involved in pre-post design studies may not have been capable of providing long-term results; however, this cannot be discerned due to the lack of studies that included retention testing. These findings may be a consequence of the poor-quality study designs frequently used within the field of wheelchair propulsion. Well-designed randomized controlled trials that evaluate interventions with theoretical underpinnings are needed to progress the field of wheelchair propulsion training. To enhance the ecological validity of prospective studies, older adults should be the target study population as they comprise the largest growing cohort of MWUs (8, 12).

3 Effects of motor skill-based training on wheelchair propulsion biomechanics in older adults: A randomized controlled trial

3.1 Introduction

Older adults comprise the largest and fastest growing cohort of manual wheelchair users (MWUs) (8, 12); however, they are frequently under-represented in the literature. Most published research involving older adults has examined the impact of various wheelchair configurations on wheeling biomechanics (29-31). Cowan et al. observed that adding weight to a wheelchair resulted in lower velocities and higher peak forces, and moving the axle forward resulted in lower peak forces among older adults novice to wheelchair propulsion (29). To our knowledge, there are only five studies that have focused on wheelchair propulsion biomechanics among older adults to date, (28-32) none of which has examined the effect of training. Therefore, interventions targeted at optimizing wheeling biomechanics in this population warrant study given they could minimize overuse injuries as well as optimize wheelchair propulsion biomechanics.

Manual wheelchairs can enhance independent wheelchair mobility; however, they are also a risk factor for reduced participation in physical and leisure activities (49). Older MWUs experience more environmental barriers than younger MWUs (161). Moreover, access to an appropriate custom-fit wheelchair does not ensure that a manual wheelchair is used to its potential. One study reported that half of older adults who received a fitted wheelchair, and had access to an unspecified clinician, reported difficulty with the basic motor skill of wheelchair propulsion (126). Over 30% of older adult MWUs experience falls and 14% experience related injuries

(162). This prevalence may be due to the fact that many MWUs receive their wheelchairs through various means (e.g., not exclusively through a health service) (45), therefore may not receive appropriate wheelchair propulsion training. These factors, coupled with other barriers such as low confidence in using their wheelchairs (163), may further limit participation (39).

Young males have demonstrated improvements in manual wheelchair propulsion biomechanics with nominal (i.e., approximately 12 minutes) practice or motor skill training (22, 23, 128, 155). Furthermore, interventions based on motor learning principles consistently lead to immediate improvements in push angle and frequency among MWUs following training (107, 153, 154, 156). Although several articles have focused on motor performance, very few have evaluated whether improvements, observed in a laboratory environment, are lasting and transferable to other tasks and environments (e.g., over-ground wheeling or wheeling up an incline) to support the presence of motor learning. A larger push angle and lower push frequency results in fewer repetitions, which could theoretically help reduce overuse injuries. A recent systematic review of wheelchair propulsion training and practice protocols identified that only eight of the twenty-six articles included individuals over 50 years of age; none of which exclusively examined older adults (Chapter 2). Therefore, the potential benefits of manual wheelchair propulsion motor skill training for older adults are not well understood.

Older adults may face challenges when learning the motor skill of wheelchair propulsion. Releasing the handrim during the recovery phase of wheeling may not be intuitive for older adults because continuous contact with the handrim may feel safer. These speculations are supported by the fact that older adults often use short arc-shaped pushes and exert negative forces on the handrim as they trace their hands backwards during the recovery phase of wheeling (27). How older age affects motor learning (i.e., “a set of internal processes associated with practice or experience leading to relatively permanent changes in the capability for motor skill” (100) (p. 466)) has not been widely studied. Previous literature has found that, compared to younger adults, older adults may rely more on vision (164), learn at a slower rate (165), and exhibit greater decline in physical performance (166) when learning a gross motor skill.

To date, no studies have examined training interventions aimed at improving wheeling biomechanics in an older adult cohort. Studying able-bodied older adults who have had no wheelchair experience allows researchers to examine the entirety of the learning process beginning with initial skill acquisition. One of the challenges of examining learning among experienced MWUs is the fact that everyone has a different level of wheelchair experience and thus may be on different learning trajectories, which may confound or bias findings. Wheelchair-naïve able-bodied older adults may be more homogeneous in terms of strength and flexibility, compared to a sample of MWUs, and thus may provide a better baseline understanding of the effect of handrim propulsion training in older adults.

The purpose of this study was to identify whether training based on select motor learning principles (e.g., variable practice and sporadic feedback) improves wheeling biomechanics in novice older adults and whether transfer (adaptability) or retention (persistence) occurs, which would support the presence of motor learning. We hypothesized that the wheelchair propulsion training is superior to practice (active control) and no practice (inactive control) with respect to improving performance (i.e., wheelchair propulsion biomechanics), and that practice (active control) is superior to no practice (inactive control). Furthermore, we hypothesized that improvements in wheelchair propulsion biomechanics are persistent (i.e., improvements are observable two weeks post training) and transferable to over-ground wheeling tasks.

3.2 Method

This study adhered to the Consolidated Standards for Reporting Trials (CONSORT) (167-169). Ethical approval was obtained from the University of British Columbia's Clinical Research Ethics Board and the participating hospital ethics board. All participants provided informed consent. See Appendix H for the CONSORT checklist.

3.2.1 Trial design

A three-arm randomized controlled trial with a randomized block design based on age (50-64 years and ≥65 years) and sex was used. Participants were blinded to the purpose of the study; however, the assessor was only blinded during the first of the three testing sessions (pre-randomization) because she also conducted the training, therefore could not be blinded for the remaining testing sessions.

3.2.2 Participants

Able-bodied adults 50 years of age and older with no wheeling experience, deemed ready to participate in physical activity based on the PARQ+ (170) (Appendix I), and residing in the community were invited to participate. Participants were excluded if they scored below 23 on the Mini Mental State Examination (171) (Appendix J), were over 113 kg (maximum weight for instrumentation), or had insufficient English proficiency to read, write, and understand the requirements of the study or questionnaires.

3.2.3 Intervention

The intervention consisted of six training sessions. Each session included two 5-minute blocks of active wheeling that were separated by a 5-minute inactive break involving instruction and discussion related to wheelchair propulsion. The primary investigator, who was experienced in the training procedures and had over 10 years of experience teaching wheelchair skills, served as the trainer. Training focused on increasing push length, decreasing push frequency, decreasing negative braking forces, using a circular wheeling strategy, and using smooth pushes (i.e., matching the speed of the hand with the handrim before contact). The speed used during the training varied by ±0.1 m/s of the participant's self-selected speed. Although the variation was small, ±0.1 m/s was selected so that it would be achievable by a heterogeneous population. Consistent quantities of pseudo sporadic feedback, related to specific variables, were provided to maintain consistency across training. Feedback could not be truly sporadic within the standardized training. The inactive break between wheeling blocks had different foci each session (e.g., identifying positive and negative features of videos demonstrating poor vs. effective wheeling techniques, using visual imagery to reflect on effective wheeling characteristics, and having participants describe how they would teach someone how to wheel). Each week, the training had a different focus beginning with developing a declarative knowledge of wheelchair propulsion, which aimed to guide participants to focus on their intrinsic feedback (e.g., position and sensation of arms when contacting the handrim). The final week of training focused on the consolidation of wheelchair propulsion and emphasized positive feedback related to performance. Details of the training procedures appear in Appendix K.

3.2.4 Control groups

Two control groups participated in this RCT. The unguided practice group (active control) received dose-matched uninstructed wheelchair propulsion experience (i.e., participants received the same amount of wheeling (60 minutes) as the training group) (Appendix L). This group did not receive instruction nor feedback related to wheeling from the trainer. Rest breaks were devoid of discussion about wheelchair propulsion. The control group (inactive control) received no form of training and only participated in the testing sessions.

3.2.5 Outcome variables

Descriptive variables (measured at baseline): A short demographic questionnaire asked participants' age, sex, education, and exposure to manual wheelchairs by family members or friends (Appendix M). Grip strength, upper limb joint angles for the purpose of identifying bilateral discrepancies, and weight were evaluated. Body mass index (BMI) was calculated from self-reported heights of each participant (Appendix N).

Primary outcome variable (measured at baseline, post-training, and 2 weeks after post-testing): The primary biomechanical outcome variable was push angle because past research has demonstrated that it is responsive to motor skill-based training protocols and push angle is a key focus of the motor skill-based training intervention used in the current study.

Secondary outcome variables (measured at baseline, post training, and 2 weeks after post testing): Secondary biomechanical variables included push frequency, mean and peak tangential forces, mean and peak total forces, as well as peak negative force. All biomechanical variables were measured with the SmartWheel (Out-Front, Mesa, AZ). The tile and ramp components of the SmartWheel Clinical Protocol were used to identify changes that transferred from treadmill training to over-ground wheeling (157). The SmartWheel Clinical protocol has a moderate to very high intrasession reliability and low to very high intersession reliability for able-bodied individuals, depending on the outcome variable (172). Furthermore, this tool requires little time and space and has established minimal detectable change values for both able-bodied individuals and MWUs (172).

3.2.6 Sample size calculation

Sample size for the RCT (Chapters 3, 4, and 5) was calculated based on the biomechanical variable, push angle (Appendix O). To achieve an effect size of 0.26, a sample size of 10 participants were needed in each of the three groups. Assuming a 15% drop out rate, the target recruitment goal was 12 participants in each of the three groups.

3.2.7 Randomization

Participants were assigned using a randomized block design based on age (50-64 years, ≥65 years) and sex. Participants were then randomly assigned to one of the three groups: training (intervention), practice (active control), control (inactive control) in a block design for each stratum by a statistician. Group allocation was provided in opaque concealed envelopes and was assigned after baseline testing. The statistician created four groups of sequentially numbered envelopes divided based on age and sex categories, which were drawn by the assessor in order of enrolment.

3.2.8 Blinding

The tester was blind only to the group allocation pre-randomization and became aware of participants' concealed allocation after opening the concealed envelope following each participant's first testing session.

3.2.9 Study protocol

Participants completed demographic questionnaires and physical measurements immediately before the first testing session. The SmartWheel was placed on participants' dominant side with an inertia-matched wheel placed on the other side. Participants were fitted to a laboratory wheelchair (Elevation™, PDG Mobility, Vancouver, BC) to ensure their elbows formed a 90-110° angle when their hands were centered at the top of the handrim. This wheelchair and corresponding configuration, with the specialized wheels, was used for all testing and practice or training sessions where applicable. Participants wheeled over-ground for two to three minutes to ensure a comfortable fit and to become familiar with the wheelchair, at which time they were not provided any instruction except to propel the wheelchair by pushing the handrim (i.e., not pushing the tire) with their hands. The adjusted wheelchair configurations were maintained for each participant and tire pressure was inflated to 100 psi (i.e., 689.5 kPa) for all testing and training or practice sessions. Once participants were comfortable, the fitted wheelchair was attached to the treadmill (Max Mobility, Nashville, Tennessee) with safety straps looped above the castor wheels to prevent the wheelchair from rolling off the back of the treadmill. Participants wheeled on the treadmill for two minutes to familiarize themselves with the treadmill (e.g., stopping and starting) and to select a comfortable speed that they could maintain over the 5-minute wheeling trial.

During the 5-minute wheeling trial, kinetic and spatial-temporal data were collected with the instrumented wheel. Additionally, participants completed the SmartWheel Clinical Protocol on tile and ramp surfaces (157) to identify transfer of the learned skill to over-ground environments. If participants indicated they wanted to continue the study following the first testing session, an opaque envelope with the randomized group allocation (e.g., training, practice, control) was opened. Participants' awareness was not drawn to the differences between the training and practice groups; they were only informed that they were in 'one of the training groups', so that those assigned to the practice group would not anticipate that they would not improve.

If randomized to the practice or training groups, participants scheduled six sessions (2-3 per week). The second testing session was scheduled two to seven days following the last training session and the third testing session was scheduled two weeks later. The three data collection time points illustrated in Figure 3.1 were scheduled over six weeks (T1: baseline, T2: within one week post-training or practice, and T3: within two weeks post-training or practice). Participants randomized to the control group completed all three testing sessions at the same time intervals but received no training or practice.

This RCT was registered with the NIH clinical trials database (identifier NCT02123043). A full copy of the study protocol is available at: https://clinicaltrials.gov/ct2/show/NCT02123043 There was no financial support for this trial.

3.2.10 Data analysis

The 24-inch SmartWheel, weighing 4.9 kg, was positioned on the participant's dominant side of the wheelchair. Five minutes of data, collected at a sampling frequency of 240Hz, were wirelessly transmitted to a data collection laptop. The previously filtered data were analyzed using proprietary software to allow for direct comparison to other published studies. Biomechanical data from the final minute of the 5-minute wheeling trial were averaged and used in the analyses to represent steady-state. Steady-state data (excluding the first three pushes) from the SmartWheel Clinical Protocol were analyzed for the tile and ramp transfer conditions.

3.2.11 Statistical analysis

Differences in baseline data were examined with one-way ANOVA for continuous variables or a chi-square test for categorical variables (SPSS Version 24.0, IBM Corp. Armonk, NY). Longitudinal data were analyzed with the statistical software R (version 3.0.2, R Foundation for Statistical Computing, Vienna, Austria) and the nlme package [Jose Pinheiro, Douglas Bates, Saikat DebRoy, Deepayan Sarkar and the R Development Core Team (2013). nlme: Linear and Nonlinear Mixed Effects Models. R package version 3.1-111.]. Generalized linear mixed-effects models (GLMMs) were used to assess the main effect of group (training, practice, control) and time (T1, T2, T3) on the biomechanical outcome variables. Time was treated as a categorical variable (i.e., T1, T2, T3). Each model was adjusted for age and sex, along with BMI, and participant identifier was included as a random effect. A sample of the R code can be found in Appendix P. A model was created for each independent variable. An example of the model and outputs can be found in Appendices Q and R. The models assumed that within-group errors were not correlated (i.e., no correlation between participants in each group) and followed an uncorrelated covariance structure. If there was a significant effect of training for a given biomechanical variable, the variable was further examined to determine if the effect of training was transferred to wheeling over-ground, on tile or up a ramp, using a similar GLMM for the transfer data.

Generalized linear mixed-effect models were identified as the most appropriate analysis because they provide less biased estimates, can handle imbalances in the number of repeated measures for each participant, and consider the interdependence of repeated measures. Because the GLMM provides standard error and not standard deviation for each variable, Cohen's d effect sizes were estimated by approximating standard deviations to compare effect sizes within our study. This approximation method ignores the correlation structure of the data, as well as the uncertainty associated with the random effects. Moreover, because standard errors are affected by the number of predictors, effect sizes should not be compared to other studies and caution should be used when interpreting the results of the approximated effect sizes.

The false discovery rate method was used to control for the proportion of rejected null hypotheses that are false (e.g., type 1 error) (173). Adjustments were made for the six comparisons for each of the 26 variables from Chapters 3 (7 variables), 4 (11 variables), and 5 (8 variables). An adjustment was applied to comparisons within each chapter, except for further statistical analysis involving the transfer conditions. Although there were several comparisons, the quantity of comparisons is largely driven by comparing across three groups and three time points. The majority of existing wheelchair propulsion literature compares two groups across two time points. This RCT was created with more comparison groups because the study was exploratory in nature with no prior literature on older adults to draw further hypotheses. The study design allowed us to determine if there was an effect of the training compared to practice and whether practice had an effect, similar to the literature on younger populations.

3.3 Results

3.3.1 Participants

Participants were recruited between January 2014 and February 2017 and enrolled between November 2014 and February 2017. Sixty-two individuals expressed interest in the study, and 35 participants met the inclusion criteria. Thirty-four participants (14 controls, 10 practice, and 10 training), who were all right-hand dominant, completed the study (Figure 3.1). One participant, who was randomized to the practice group, was excluded because they did not achieve steady-state criteria. Participants' ages ranged between 50-86 years (mean±SD: 62.2±9.2 years) and were evenly distributed by sex (18 females, 16 males). Participants were not evenly distributed across each age-sex stratum (females<65: n=12, females≥65: n=6, males<65: n=11, males≥65: n=5); see Table 3.1 for baseline comparisons between group demographics.

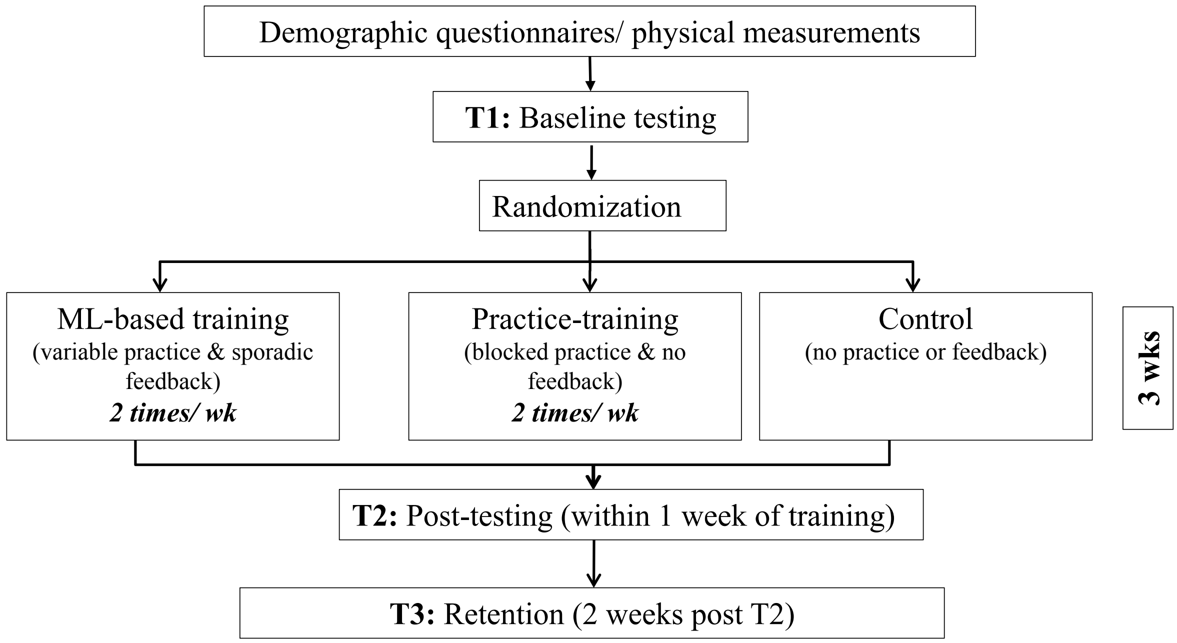


Figure 3.1 Testing and training timeline for the RCT

The three testing time points are illustrated in Figure 3.1. The testing time points were conducted for all participants and only those randomized to the practice and training groups underwent the additional training or practice sessions.

Table 3.1 Demographic data at baseline categorized by group (mean (SD))

	Training Group (*n*=10)	**Practice Group (*n*=10)**	**Control Group (*n*=14)**	**p-value**
Age (years)	58.8 (7.7)	64.5 (12.2)	62.9 (7.5)	0.37
Sex	6f, 4m	4f, 6m	8f, 6m	0.62
Body mass index (kg/m^2)	25.8 (6.2)	25.6 (3.7)	26.8 (3.7)	0.77
Grip strength:				
Left hand (kg)	29.7 (10.5)	35.7 (10.7)	27.4 (8.3)	0.13
Right hand (kg)	31.2 (11.2)	37.8 (11.4)	29.4 (8.3)	0.14

Abbreviations: f: female; m: male; kg: kilogram, m^2: meter squared

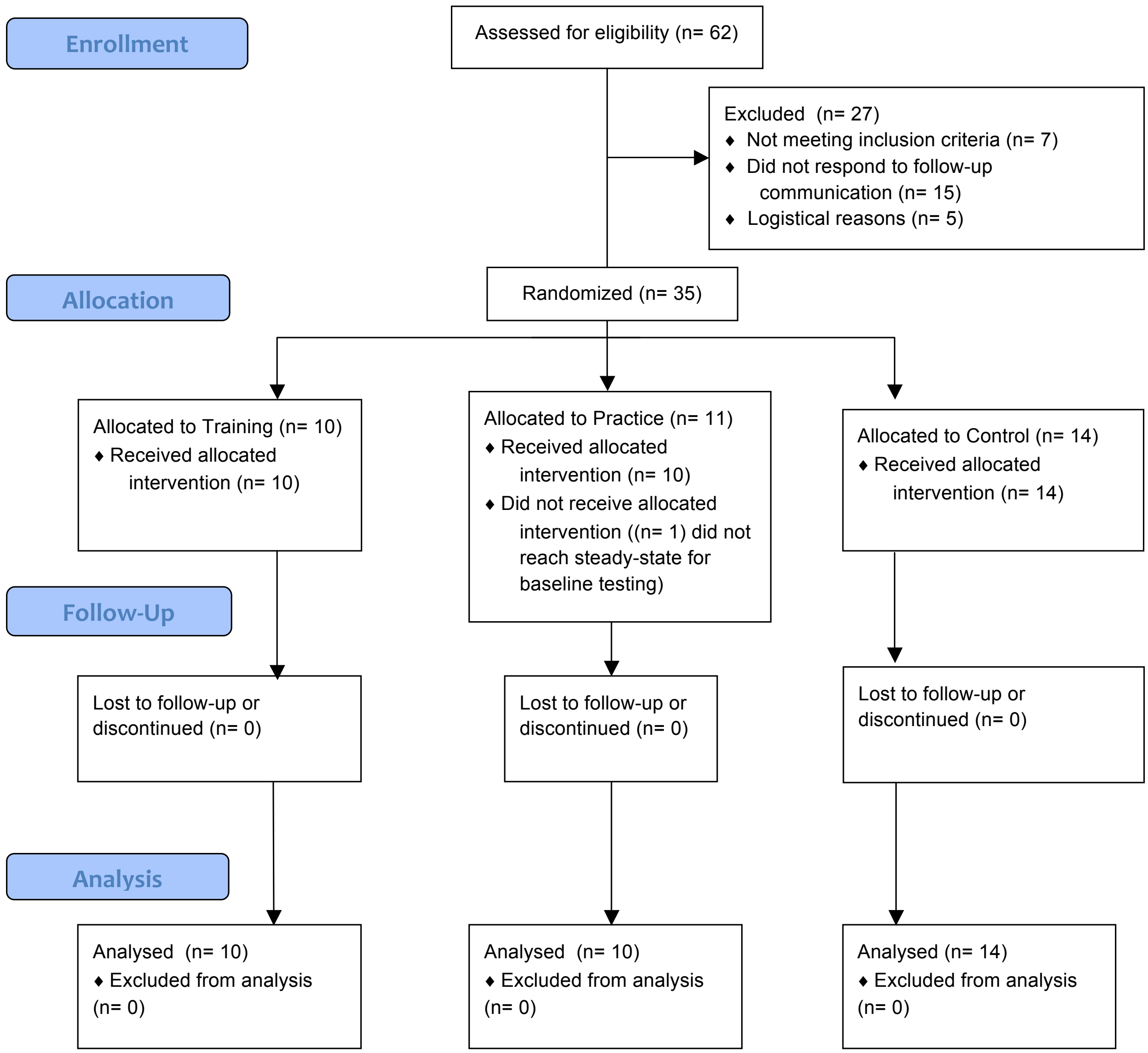


Figure 3.2 Consort flow diagram of participants through the 3-arm RCT

The consort flow diagram for the 3-arm RCT shows interested participants assessed for eligibility, the randomization process, and those who were included in the analysis.

Adherence to intervention: Training sessions were attended by all participants (i.e., 100% adherence to the intervention) with only two testing sessions being missed (T2: n=1, T3: n=1) due to medical or family emergencies. Other missing data occurred due to technical errors (e.g., data not saving properly, treadmill malfunction).

3.3.2 Baseline data

The three groups did not differ by age, sex, BMI, or grip strength (Table 3.1). Overall, groups did not differ based on baseline biomechanics during the final minute of the 5-minute wheeling trial, with the exception of peak negative force that was larger in the training group compared with the control group (-6.0 N vs. -3.9 N; p=0.04). Table 3.2 shows the baseline averages across groups for wheeling biomechanics over the final minute of the 5-minute wheeling trial. There were no differences in biomechanical variables from the transfer conditions at baseline (i.e., tile and ramp) (Table 3.3).

Table 3.2 Baseline wheelchair propulsion biomechanical data categorized by group (mean (SD))

	Training group (*n*=10)	**Practice group (*n*=10)**	**Control group (*n*=13)**	**p-value**
Self-selected speed	0.5 (0.1)	0.6 (0.1)	0.5 (0.2)	0.51
Push angle (°)	40.8 (16.0)	43.8 (11.1)	47.2 (16.5)	0.60
Push frequency (Hz)	1.1 (0.4)	1.0 (0.2)	0.9 (0.2)	0.32
Mean force tangential (N)	22.1 (6.8)	24.1 (4.7)	24.6 (8.1)	0.68
Mean force total (N)	29.3 (9.3)	32.2 (6.2)	31.4 (9.2)	0.73
Peak force tangential (N)	29.6 (10.4)	33.2 (6.7)	34.3 (13.1)	0.58
Peak force total (N)	36.0 (13.4)	42.2 (8.3)	41.7 (13.7)	0.45
Peak negative force (N)*	-6.0 (2.2)	-5.4 (2.0)	-3.9 (1.6)	0.04

Abbreviations: Hz: Hertz; N: Newtons *p<0.05

Table 3.3 Baseline SmartWheel Clinical Protocol (tile and ramp transfer conditions) data categorized by group (mean (SD))

Tile	**Training group (*n*=10)**	**Practice group (*n*=10)**	**Control group (*n*=14)**	**p-value**
Self-selected speed (m/s)	1.0 (0.3)	1.1 (0.3)	1.0 (0.2)	0.53
Push angle (°)	48.9 (12.7)	51.4 (16.0)	53.4 (16.8)	0.78
Push frequency (Hz)	1.0 (0.2)	1.0 (0.2)	0.9 (0.2)	0.37
Mean force total (N)	38.5 (14.2)	39.8 (13.8)	39.1 (15.4)	0.98
Peak force total (N)	52.2 (21.7)	54.2 (20.4)	53.9 (21.6)	0.97
Peak negative force (N)	-7.3 (5.4)	-6.8 (2.6)	-5.8 (3.7)	0.66
Ramp	**Training group (*n*=10)**	**Practice group (*n*=7)**	**Control group (*n*=12)**	**p-value**
Self-selected speed (m/s)	0.8 (0.2)	1.0 (0.2)	0.8 (0.2)	0.06
Push angle (°)	58.4 (10.1)	65.1 (12.2)	58.7 (15.5)	0.52
Push frequency (Hz)	1.1 (0.2)	1.2 (0.2)	1.1 (0.2)	0.51
Mean force total (N)	74.0 (25.6)	91.0 (19.8)	72.4 (16.9)	0.16
Peak force total (N)	102.4 (40.9)	122.9 (29.4)	99.8 (24.5)	0.30
Peak negative force (N)	-9.0 (5.0)	-9.5 (3.5)	-7.9 (4.5)	0.71

Abbreviations: m/s meters per second; Hz: Hertz; N: Newtons *$p<0.05$

3.3.3 Comparison of groups over time

Generalized linear mixed effects models were used to analyze the outcomes of interest. Models included a random-effect for participants while adjusting for the age, sex, and BMI. Group and time point were included as ordinal between-subject factors. No outliers were identified and no violations of the homoscedasticity or normality assumptions (174) were observed. Centering was not done on age or BMI as they were confounders and not the explanatory variables of interest. Group means and standard deviations of all variables at all time points for the treadmill testing are presented in Table 3.4. See Appendix Q for detailed GLMM outputs with adjusted p-values for the false discovery rate.

Table 3.4 Effect of motor skill training on wheelchair propulsion biomechanical categorized by group and time point (mean (SD))

	Training group			Practice group			Control group		
Variable	**T1** *n*=10	**T2** *n*=9	**T3** *n*=9	**T1** *n*=10	**T2** *n*=9	**T3** *n*=9	**T1** *n*=13	**T2** *n*=12	**T3** *n*=13
Push angle (°)	40.8 (16.0)	79.1 (17.3)	76.6 (15.7)	43.8 (11.1)	42.4 (14.8)	45.5 (13.4)	47.2 (16.5)	44.2 (14.5)	41.0 (14.2)
Push frequency (Hz)	1.1 (0.4)	0.5 (0.1)	0.5 (0.1)	1.0 (0.2)	1.0 (0.3)	1.0 (0.3)	0.9 (0.2)	1.0 (0.3)	1.0 (0.2)
Mean tangential force (N)	22.1 (6.8)	24.5 (10.2)	23.9 (10.3)	24.1 (4.7)	23.9 (6.7)	24.7 (4.6)	24.6 (8.1)	23.6 (7.3)	22.1 (8.0)
Mean total force (N)	29.3 (9.3)	36.6 (15.9)	35.8 (17.0)	32.2 (6.2)	31.8 (8.9)	33.1 (6.9)	31.4 (9.2)	32.8 (11.9)	30.1 (11.3)
Peak tangential force (N)	29.6 (10.4)	35.9 (15.9)	35.2 (16.9)	33.2 (6.7)	32.7 (10.5)	34.2 (7.7)	34.3 (13.1)	32.9 (11.2)	30.4 (12.7)
Peak total force (N)	36.0 (13.4)	50.4 (21.5)	48.1 (24.7)	42.2 (8.3)	40.9 (13.1)	43.1 (10.2)	41.7 (13.7)	43.1 (17.4)	38.9 (16.0)
Peak negative force (N)	-6.0 (2.2)	-2.6 (1.2)	-2.4 (0.9)	-5.4 (2.0)	-4.8 (1.7)	-4.4 (1.6)	-3.9 (1.6)	-4.5 (2.7)	-4.5 (1.8)

Abbreviations- Hz: Hertz; N: Newtons; T1: time point 1; T2: time point 2; T3: time point 3

Push angle: The training group increased their push angles compared to the practice group ($p=0.03$) and control group ($p<0.01$). There was no difference between the practice group and control group ($p>0.05$). Push angle showed improvement following training (T2: $p=0.05$, T3: $p=0.05$); there was no difference between time points T2 and T3 ($p>0.05$).

Push frequency: The training group decreased their push frequencies compared to the practice group ($p=0.05$) and control group ($p=0.04$). There was no difference between the practice group and control group ($p>0.05$). Push frequencies improved following training (T2: $p=0.05$, T3: $p=0.04$); however, there was no difference between time points T2 and T3 ($p>0.05$).

Mean force (tangential and total): There were no observed effects of training on mean tangential force compared to the practice group ($p>0.05$) and control group ($p>0.05$). Similarly, there were no effects of training on mean total force compared to the practice group ($p>0.05$) and control group ($p>0.05$).

Peak force (tangential and total): There were no observed effects of training on peak tangential force compared to the practice group ($p>0.05$) and control group ($p>0.05$). Similarly, there were no effects of training on peak total force compared to the practice group ($p>0.05$) and control group ($p>0.05$).

Peak negative force There were no observed effects of training on peak negative force compared to the practice group ($p>0.05$) and control group ($p>0.05$), but there was an effect of time between time points T1 and T3 ($p=0.03$) with peak negative force increasing over time.

3.3.1 Effect size estimations

The GLMMs produced regression coefficients for each model's main effects (see Appendix Q); in addition to the model results, estimates for Cohen's *d* were also approximated (see Appendix R).

3.3.2 Transfer conditions

Group means and standard deviations of all transfer variables at all time points for the over-ground tile and ramp conditions are presented in Table 3.5.

Tile: The training group increased push angle compared to the practice group ($p=0.05$) and control group ($p=0.04$). There were no differences between the practice group and control group ($p>0.05$). Push angle increased following training (T2: $p=0.01$, T3: $p=0.01$); no difference between time points T2 and T3 ($p>0.05$) was observed. The training group decreased their push frequency compared to the practice group ($p=0.03$) but not the control group ($p>0.05$). Push frequency decreased following training (T2: $p=0.04$, T3: $p=0.02$); however, no difference between time points T2 and T3 ($p>0.05$) was observed.

Ramp: The training group increased their push angle compared to the control ($p=0.04$) group, but not the practice group ($p>0.05$). Push angle improved following training (T2: $p<0.01$, T3: $p<0.01$); no difference between time points T2 and T3 ($p>0.05$) was observed. Push frequency was lower in the training group compared to the practice group ($p=0.03$).

This intervention resulted in no adverse events.

Table 3.5 Effect of motor skill training on wheelchair propulsion biomechanics on tile and ramp categorized by group and time point (steady-state pushes only): evidence for transfer (mean (SD))

	Training group			Practice group			Control group		
Tile	**T1** *n*=10	**T2** *n*=10	**T3** *n*=9	**T1** *n*=9	**T2** *n*=9	**T3** *n*=9	**T1** *n*=14	**T2** *n*=13	**T3** *n*=14
Self-selected speed (m/s)	1.0 (0.3)	1.1 (0.3)	1.2 (0.3)	1.2 (0.3)	1.1 (0.3)	1.2 (0.4)	1.0 (0.2)	1.1 (0.2)	1.1 (0.3)
Push angle (°)	48.9 (12.7)	70.7 (9.0)	67.8 (13.5)	51.3 (17.0)	50.9 (12.0)	52.7 (10.6)	53.4 (16.8)	54.4 (13.7)	53.5 (9.7)
Push frequency (Hz)	1.0 (0.2)	0.7 (0.2)	0.7 (0.3)	1.0 (0.3)	1.0 (0.2)	1.0 (0.2)	0.9 (0.2)	0.9 (0.2)	0.9 (0.2)
Mean total force (N)	38.5 (14.2)	44.1 (15.1)	46.9 (17.2)	40.6 (14.3)	38.6 (12.8)	40.0 (11.5)	39.1 (15.4)	43.9 (14.9)	44.0 (15.3)
Peak total force (N)	52.2 (21.7)	64.9 (26.2)	67.6 (26.0)	55.6 (21.1)	54.4 (18.1)	54.5 (17.3)	53.9 (21.6)	60.5 (21.6)	61.2 (22.0)
Peak negative force (N)	-7.3 (5.4)	-3.8 (2.5)	-5.7 (5.1)	-7.1 (2.6)	-7.0 (3.2)	-7.9 (4.2)	-5.8 (3.7)	-6.1 (3.4)	-7.2 (4.8)
Ramp	**T1** *n*=10	**T2** *n*=10	**T3** *n*=9	**T1** *n*=6	**T2** *n*=8	**T3** *n*=7	**T1** *n*=12	**T2** *n*=12	**T3** *n*=13
Self-selected speed (m/s)	0.8 (0.2)	0.9 (0.3)	0.8 (0.2)	1.0 (0.2)	1.0 (0.2)	0.9 (0.3)	0.8 (0.2)	0.8 (0.2)	0.8 (0.2)
Push angle (°)	58.4 (10.1)	80.9 (11.4)	76.2 (12.2)	65.7 (13.2)	65.8 (12.8)	61.1 (11.5)	58.7 (15.5)	64.2 (13.6)	61.7 (11.6)
Push frequency (Hz)	1.1 (0.2)	0.9 (0.2)	0.9 (0.2)	1.2 (0.2)	1.2 (0.3)	1.2 (0.2)	1.1 (0.2)	0.8 (0.2)	1.1 (0.3)
Mean total force (N)	74.0 (25.6)	80.8 (27.9)	74.3 (18.8)	91.0 (21.6)	91.2 (22.9)	86.7 (22.4)	72.4 (16.9)	76.7 (14.6)	77.9 (16.6)
Peak total force (N)	102.4 (40.9)	115.3 (45.3)	106.8 (30.8)	124.5 (31.8)	125.9 (36.9)	114.8 (31.6)	99.8 (24.5)	107.6 (22.2)	106.7 (23.8)
Peak negative force (N)	-9.0 (5.0)	-5.00 (4.4)	-5.8 (4.2)	-9.3 (3.7)	-10.4 (3.7)	-8.3 (2.1)	-7.9 (4.5)	-7.1 (3.2)	-7.8 (5.0)

Abbreviations: m/s: meters per second; Hz: Hertz; N: Newtons; T1: time point 1; T2: time point 2; T3: time point 3

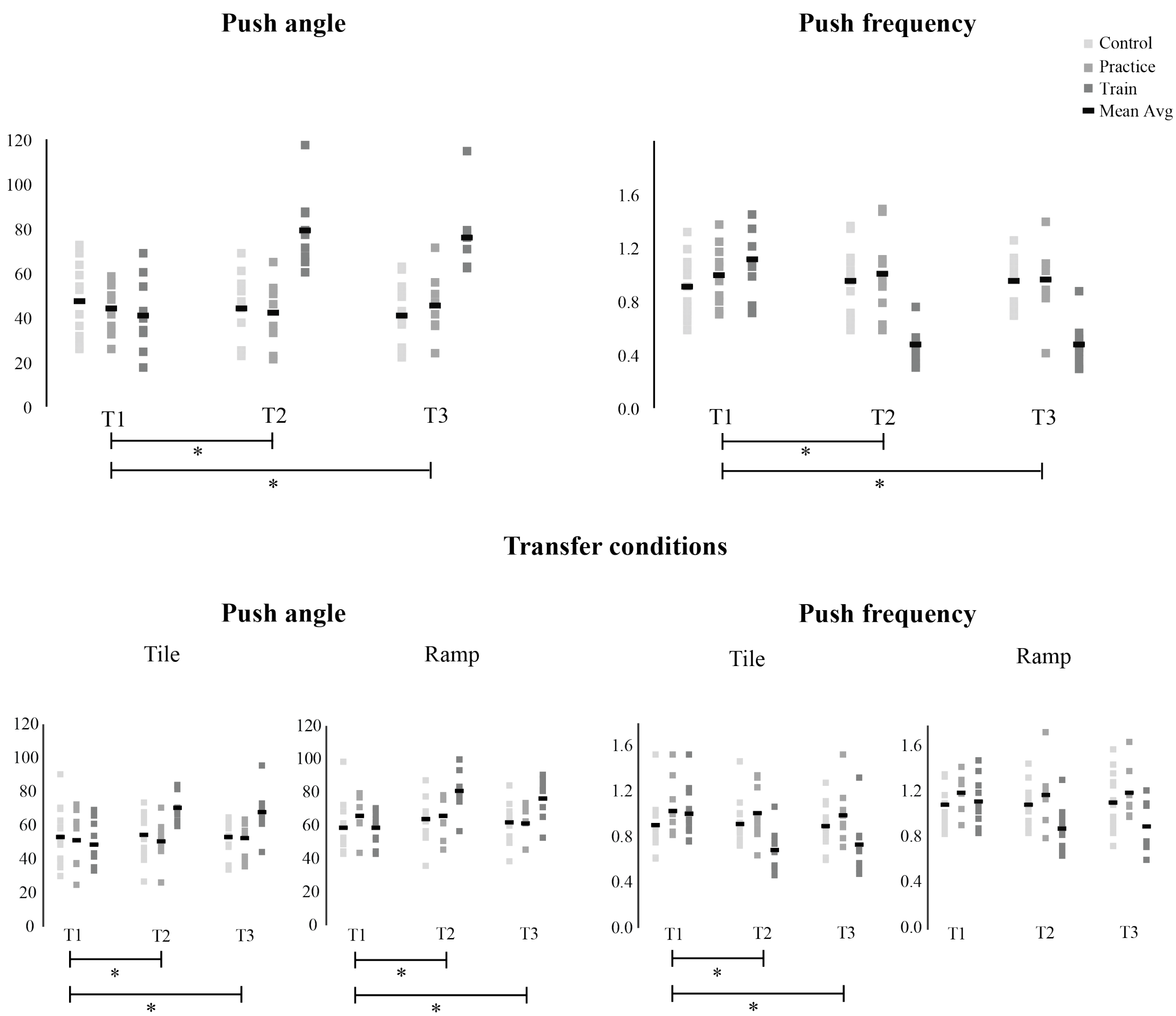


Figure 3.3 Treadmill testing and transfer results for push angle and push frequency for the training, practice, and control groups

Light grey boxes represent the control group, medium grey boxes represent the practice group, and dark grey boxes represent the training group. The black rectangles represent the mean value for each group. The * represents a significance level of $p<0.05$ between time points.

3.4 Discussion

This is the first wheelchair propulsion training study that exclusively focused on older adults. We observed that the training group significantly increased push angle and decreased push frequency compared to the practice and control groups. Interestingly, there were no differences in wheeling biomechanics between the practice group and the control group. Our hypotheses were only partially supported as we had expected that the practice group would show improvements compared to the control group.

Unguided practice alone does not appear to elicit improvements in wheeling biomechanics among older adults; however, improvements following practice are frequently observed in younger populations (22, 23, 128, 137, 155). The lack of improvement following blocked practice in older adults may be associated with low wheelchair-related confidence (163), which could affect older adults' exploration of movement during wheeling. Older adults have been reported to have less confidence in exploring walking compared to younger adults because of the increased likelihood of falling (175). Similar to gait, older adults may be less likely to explore and modify their wheeling biomechanics without direction, which may prevent the identification of a more effective technique without training.

Our baseline biomechanical data were consistent with the findings of past studies. Hers et al. examined able-bodied males (mean age 70.9 years) wheeling at pre-selected speeds of 0.83 or 1.11 m/s (32). Similar to our study, Hers et al. found that older adults used short push angles (mean: 45.1°) compared to our 44.2° and high frequencies (mean: 1.05 Hz) compared with our 1.00 Hz at baseline (32). Cowan et al. also reported that older adults novice to wheelchair propulsion (mean age 73.6 years) performed speeds of 1.03-1.09 m/s, push angles of 54.8-55.9°, and push frequencies of 1.17-1.19 Hz over tile using various unweighted wheelchair configurations (29). Furthermore, increased age has been correlated with lower wheeling velocities among MWUs (176).

The improvements observed in push angle and push frequency by the training group exceed the established minimal detectable change values for the SmartWheel Clinical Protocol (172). Lui et al. established that the minimal detectable change for able-bodied people wheeling on tile was 21-31° for push angle and between 0.22-0.25 Hz for push frequency, depending on the number of trials used (172). The differences in mean values over time observed in the current study far exceeded the minimal detectable change values from the SmartWheel Clinical Protocol. Unfortunately, there are no published minimal detectable change values for 5-minute wheeling trials and the minimal clinically important differences for the biomechanical variables are not yet known. Although the findings related to push angle and push frequency are statistically significant, their significance to older adult MWUs is unknown.

Transfer (i.e., adaptability) and retention (i.e., persistence) must be evaluated to differentiate motor learning from initial skill acquisition (i.e., performance curves that may reflect performance variables rather than learning) (100, 136). Thus, we sought to determine if improvements based on our intervention were maintained and if they transferred from treadmill wheeling to over-ground wheeling on tile and ramp. We observed that most improvements were retained two weeks post-training. Some studies have identified retention at 70 days (14, 93) and up to one year following training (15). Our training protocol appeared to transfer better to the over-ground tile condition rather than the ramp condition, likely because both conditions involved a relatively flat surface. This could be expected because the biomechanics of wheeling up an incline differ from wheeling on a flat surface (17, 177). The lack of transfer to the ramp condition supports the need to train propulsion in a variety of environmental conditions and to look at ramp versus level wheeling as distinct skills, as suggested in the Wheelchair Skills Program (178).

3.4.1 Limitations

The use of able-bodied participants may not be representative of the population of MWUs. Some technical errors (e.g., data not saving properly) occurred which may have impacted the completeness of our data. Participants were not evenly distributed across each age-sex stratum because the majority of males and females who volunteered to participate in this study were under 65 years of age. Participants self-selected lower speeds for the treadmill trial (treadmill mean speed: 0.56 m/s) than they used for the over-ground conditions (tile mean speed: 1.06 m/s), potentially because of the differing lengths of the trials. The speeds selected in the current study are lower than what has been reported in the literature. Karmarker et al. observed an average speed of 0.64 m/s at home and 0.76 m/s during the National Veterans Wheelchair Games among MWUs (mean age: 63 years) (176). Many participants were apprehensive to select a speed that they were unable to maintain for the 5-minute trial, thus may have self-selected a slower speed than what they would realistically perform in a natural setting. The slower selected speeds may have affected the outcomes of the training intervention; however, the self-selected speeds were similar across groups at baseline. The participants enrolled in our study were diverse in age, self-reported fitness, and physical abilities (e.g., grip strength), thus provided a heterogeneous sample of older adults. Participants that volunteered for this study may have had a vested interest (e.g., a family member or friend whom they wanted to share what they learned) and therefore may not be representative of the general population.

In terms of study design, only minimal blinding was achieved with the assessor blinded to the participant's group during baseline testing (i.e., pre-randomization). Having more study personnel would have allowed for the tester and trainer to be different people. Although the tester could not be blinded for T2 and T3 testing timepoints, the data collected was not up for interpretation; however, participants in the training group may have performed the testing session in a favourable manner (e.g., they may have wanted to please the trainer).

Although we observed positive effects of the motor skill-based wheelchair propulsion training, the training protocol incorporated several principles of motor learning; therefore, the components of the training that resulted in the observed changes cannot be discerned. The training may have been longer or incorporated more sessions than necessary; however, the training was sufficient to elicit change across a heterogeneous population of older adults. Individualized training may have been more effective and less resource intensive; therefore, future research should compare different training protocols to determine the most effective components (e.g., verbal feedback).

3.5 Conclusion

This study is the first to examine the effect of wheelchair propulsion training based on motor learning principles (e.g., variable practice, sporadic feedback) in older adults. Overall, we concluded that six training sessions are effective for improving some biomechanical variables (e.g., push angle and push frequency); however, the training had little effect on modifying forces. Interestingly, there were no differences between the practice group and the control group, which supports that practice alone may be insufficient to improve wheeling biomechanics among older adults. These findings are relevant given older adults are the largest cohort of MWUs and may be prone to wheeling injuries in the absence of preventive strategies, such as effective training to reduce undue biomechanical stress. Furthermore, whether improved wheeling biomechanics is more energetically economical warrants further study in this cohort.

In summary, older able-bodied adults do not appear to modify their wheelchair propulsion biomechanics based on uninstructed practice, which is contrary to much of the literature on younger able-bodied populations. Furthermore, only certain biomechanical variables (e.g., push angle, push frequency) improved following training, which indicates that the training protocol may not be effective for influencing force-related variables. Importantly, the training resulted in significant improvements in push angle and push frequency among a population of able-bodied older adults, which exceeded the minimal detectable change (172), persisted over time, and transferred to over-ground wheeling. The biomechanical findings from this RCT are partially consistent with the findings of the meta-analyses (Chapter 2), where we identified a significant medium effect of practice and training protocols on push angle and push frequency among pre-post design studies. Although the motor skill training resulted in changes in motor performance (i.e., wheelchair propulsion biomechanics), the consequences of manipulating the movement pattern on physiological variables (e.g., energy expenditure and gross mechanical efficiency) should also be considered.

4 Effects of motor skill-based wheelchair propulsion training in older adults: A comparison of gross mechanical efficiency and mechanical effectiveness

4.1 Introduction

Manual wheelchair propulsion is an inherently inefficient form of mobility due to its dependence on the arms. Instead of using muscles with large cross sections (i.e., muscles of the legs) to support and carry the body's weight, the smaller cross sections of the arm muscles are responsible for overcoming the inertia and rolling resistance of the wheelchair-user system. Furthermore, the arms can move in multiple degrees of freedom, which may result in greater wasted energy expenditure compared to the legs. The relative wheeling efficiency (i.e., gross mechanical efficiency (GME) (average power output/ energy expenditure * 100)) of wheelchair propulsion has been reported to be less than 10% (179, 180), which is much lower than the 20% efficiency observed in gait (181, 182). For individuals who rely on the smaller muscles of the arms for everyday mobility, it is essential that their wheelchair propulsion be as efficient as possible to reduce overuse injuries and unnecessary energy expenditure.

Efficient mobility is paramount for older adults who have decreased muscle strength and endurance. Muscle atrophy, associated with aging, may further compromise muscular endurance and strength because of the loss of overall muscle fibres (183) and the atrophy of type II muscle fibres (184). In addition to the loss of muscle fibres, muscle properties also change with aging (185) and connective tissues (e.g., collagen and elastin) degenerate, which has been reviewed by Holland and colleagues (186)). Changes in motor unit control (187) and increased coactivation associated with aging may also contribute to decreased strength and force production (188). Therefore, improving wheeling efficiency and reducing energy expenditure is of great importance for older adults.

In addition to decreased muscular strength and endurance, older age is also associated with decreased exercise capacity (189). Researchers have sought to identify differences in wheeling capacity based on increased age. One study, which evaluated three age groups (20-30 years, 50-60 years, 80-90 years) of manual wheelchair users (MWUs) with a variety of conditions, found that heart rate, maximal oxygen consumption, and maximal power output decreased with older age based on a maximal wheelchair ergometer propulsion test (35). Many MWUs with spinal cord injuries experience mobility-related pain and fatigue (3), which may negatively affect activity and participation (190, 191). Therefore, conserving energy expended during wheelchair propulsion may help to reduce fatigue and improve quality of life.

Importantly, efficiency should be considered from multiple perspectives including GME, which incorporates biomechanical data (used in the calculation of power output) and metabolic data (used in the calculation of energy expenditure), as well as a purely mechanical perspective (mechanical effectiveness). Mechanical effectiveness is the proportion of applied force acting in a forward direction (i.e., tangential to the handrim) compared to the total force applied to handrim (i.e., $\sqrt{F_x^2 + F_y^2 + F_z^2}$) (192). Although mechanical effectiveness is not a direct measure of efficiency, it may help to identify 'wasted' force applied to the handrim that does not contribute to forward motion. Moreover, identifying and negating braking forces may help to improve GME. The relationship between GME and mechanical effectiveness is not well understood with respect to manual wheelchair propulsion training.

Manual wheelchair propulsion training has shown promising, but inconsistent, improvements in GME in adult populations. Increased GME has long been thought of as an indicator of motor skill learning, with a reduction in metabolic cost attributed to improved control and decreased variability (90, 91, 101). Although several studies have shown large positive effects of wheelchair propulsion training on GME (19, 20, 151, 152, 156), some studies have reported that the training group became less efficient compared to the natural learning (control) group (21, 137). A systematic review of wheelchair propulsion training and practice studies found a significant medium effect in favour of training within pre-post design studies, but no significant effect for studies including independent groups (Chapter 2). Interestingly, all studies in the systematic review that evaluated GME exclusively included able-bodied participants.

Most wheelchair propulsion motor skill-training studies focus on either practice or specific training based on the recommendations described in the clinical practice guidelines (3). Although the clinical practice guidelines were developed to help reduce overuse injuries by recommending long, smooth pushes at a lower push frequency, they may not necessarily result in an increased GME (24). One study observed that able-bodied adults demonstrated the highest GME when using the 'arc' wheeling pattern (24), which is the most commonly observed pattern among inexperienced able-bodied adults (2). This finding may relate to the concept of self-optimization reviewed by Sparrow (101), where people select the most efficient rate of movement, which may be easier to determine with the smaller and more basic movement of the arc pattern compared to other wheeling patterns. The arc pattern may be the most efficient wheeling pattern, in some contexts, at the cost of high repetition. In contrast, studies of experienced MWUs have most commonly observed patterns where the hand goes above the handrim (i.e., single looping over propulsion) (81, 193) The arc pattern is not recommended by the clinical practice guidelines because it is associated with a short push angle, high frequency, high braking forces, and abrupt directional changes of the shoulder (3).

The purpose of this study was to identify whether motor skill-based wheelchair propulsion training is effective in improving GME and mechanical effectiveness in older adults and whether retention (persistence) occurs. We hypothesized that motor skill-based training is superior in improving GME compared to practice (active control) and no practice (inactive control), and that practice (active control) is superior over no practice (inactive control). We also wished to explore whether GME and mechanical effectiveness appeared to be related at baseline.

4.2 Method

This chapter is part of the larger randomized controlled trial (RCT); therefore, we highlight the differences from Chapter 3. Detailed methods following the Consolidated Standards for Reporting Trials (CONSORT) can be found in Chapter 3, pages 72-80). Ethical approval was obtained from the University of British Columbia’s Clinical Research Ethics Board and the participating hospital ethics board. All participants provided informed consent.

4.2.1 Trial design

This chapter is part of the larger three-arm RCT described in Chapter 3, page 71.

4.2.2 Participants

The same cohort of able-bodied older adults described in Chapter 3, page 71-72 was recruited to participate in this study.

4.2.3 Intervention

The intervention is described in Chapter 3 page 72. Details of the training procedures appear in Appendix K.

4.2.4 Control groups

The control groups are described in Chapter 3 page 73. Details of the uninstructed practice (i.e., active control group) appear in Appendix L.

4.2.5 Outcome variables

Calculated outcome variables derived from SmartWheel data (Out-Front, Mesa, AZ) included mechanical effectiveness, mean power output (Watts), relative power output (PO) (Watts/ kg), work (Joules/push), and sprint PO (Watts). Sprint PO was evaluated with the 15 m sprint test to determine the peak momentary PO, which can be used as an estimation for a Wingate-like sprint test (194).

Outcome variables derived from metabolic data included $\dot{V}O_2$ (ml/min/kg), respiratory exchange ratio ($\dot{V}CO_2/\dot{V}O_2$), $\dot{V}_E$ (l/min), and heart rate (bpm). Energy expenditure (Watts) was calculated with the following equation: ($\dot{V}O_2$ (l/min) * conversion factor (Kcal/l O_2)) * (4184/60).

The primary outcome measure, GME, was derived from both SmartWheel and metabolic data: (mean PO (Watts)/ energy expenditure (Watts) * 100).

Perceived exertion: Participants reported their perceived exertion following each wheeling block based on Borg's scale of perceived exertion ranging from 6-20 (195). This variable was used to confirm testing parameters for descriptive purposes only.

4.2.6 Randomization

The randomization procedures can be found in Chapter 3, page 74-75.

4.2.7 Blinding

The blinding procedures can be found in Chapter 3, page 75.

4.2.8 Study protocol

After providing informed consent, participants completed a demographics questionnaire that included participants' age, sex, BMI and perceived level of physical fitness. Participants were then fitted to either a 16- or 17-inch-wide lightweight laboratory wheelchair (Elevation™, PDG Mobility, Vancouver, BC). Seat height and backrest position were adjusted to create a comfortable fit with the elbow creating an optimal angle (degree range: 90-110°) when their hands were centered at the top of the handrim. Participants spent two to three minutes becoming familiar with the wheelchair and set-up and were not provided any instruction except to propel the wheelchair by pushing the handrim (i.e., not pushing the tire) with their hands. The adjusted wheelchair configurations were maintained for each participant and tire pressure was inflated to 100 psi (i.e., 689.5 kPa) for all testing and training/practice sessions. An instrumented wheel (SmartWheel - Out-Front, Mesa, AZ) was placed on the dominant side and an inertia-matched dummy wheel was placed on the opposite side.

Once participants were comfortably fit, the wheelchair was fastened to safety straps on the wide-belt treadmill (Max Mobility, Nashville, Tennessee). Participants selected a comfortable speed that could be maintained for the 5-minute wheeling trial, and then spent two minutes becoming familiar with the treadmill (e.g., stopping and starting). Participants were fitted with a heartrate monitor (Polar H7, Kempele, Finland) and headpiece for metabolic testing to evaluate ventilation and expired gases (TrueOne® 2400, Parvo Medics, Sandy, Utah). The metabolic system was calibrated according to the manufacturer's instructions for each test approximately 15 minutes prior to the testing procedure. Baseline (i.e., resting state) data were collected to ensure that participants were breathing normally and that their respiratory exchange ratio (RER) was appropriate (less than 0.9). Once baseline data were stable, the treadmill was adjusted to participants' pre-determined self-selected speed and the 5-minute trial began when the treadmill reached the participant's self-selected speed. After completing the 5-minute trial, participants completed the 15 m sprint test to determine maximum power output (194). If participants wanted to continue the study after completing the first testing session, an opaque envelope with the randomized group allocation (e.g., training, practice, control) was opened. Participants' awareness was not drawn to the differences between the training and practice groups; they were only informed that they were in 'one of the training groups', so that those assigned to the practice group would not anticipate that they would not improve.

If randomized to the practice or training groups, participants scheduled six sessions (2-3 /week). The second testing session was scheduled two to seven days following the last training session and the third testing session was scheduled two weeks later. The three data collection time points illustrated in Figure 1 were scheduled over six weeks (T1: baseline, T2: within one week post-training/ practice, and T3: within two weeks post-training/ practice). Participants randomized to the control group completed all three testing sessions at the same time intervals but received no training or practice.

4.2.9 Data analysis

Steady-state data from the final minute of the 5-minute wheeling block were averaged for each of the metabolic variables of interest [oxygen uptake ($\dot{V}O_2$ (ml/min/kg)), heart rate (bpm), respiratory exchange ratio (RER ($\dot{V}CO_2/\dot{V}O_2$)), pulmonary ventilation ($\dot{V}_E$ (l/min))] and biomechanical (speed and torque) variables of interest. Speed and torque were calculated from the SmartWheel data (Out-Front, Mesa, AZ). Mean PO (Watts) was calculated with the following equation: torque around the wheel axel (Nm) * angular speed (rad/s). The method of calculating the total external power using drag force test procedure (196) was not performed due to equipment error. The metabolic variables $\dot{V}O_2$ and RER were used to calculate energy expenditure using standard thermal equivalents of oxygen for non-protein respiratory quotient, which were used to calculate GME. Energy expenditure (Watts) was calculated with the following equation: ($\dot{V}O_2$ (l/min) * conversion factor (Kcal/l O_2)) * (4184/60). Finally, GME was calculated with the following equation: PO (Watts)/ EE (Watts) * 100. Mean PO was divided by push frequency to calculate average work per push (Joules per push). The maximum PO occurring during each of the two 15 m sprint tests was calculated and averaged together.

4.2.10 Statistical analysis

Details of the statistical analyses can be found in Chapter 3, page 77-79.
To determine if there was a pre-existing relationship between GME and mechanical effectiveness, a Pearson moment correlation (SPSS Version 24.0, IBM Corp. Armonk, NY) was calculated for baseline data (n=31).

4.3 Results

4.3.1 Participants

Thirty-four (16 male, 18 female) able-bodied older adults participated in this study. Details of recruitment and enrolment can be found in the consort diagram (Chapter 3, Figure 3.1). Participants were 62.2 (9.2) years (mean (SD)) of age and had an average BMI of 26.2 (4.5) kg/m^2 (mean (SD)). Most participants (n=22) reported having good to excellent perceived physical fitness.

Participants were randomly allocated to the training (n=10), practice (n=10), and control groups (n=14). Those randomized to the training and practice groups had 100% compliance with the training sessions; however, two participants missed testing sessions due to factors unrelated to the study (e.g., illness, family emergency) and some data were lost due to technical problems with the testing equipment. For example, there were some missing data due to the instrumented wheel not saving data and air leaking from the facemask among individuals that had low nose bridges in a couple of trials. The number of included participants for each variable is outlined in the tables below.

4.3.2 Baseline data

There were no observable differences between groups for age (training: 58.8 (7.7) years, practice: 64.5 (12.2) years, control: 62.9 (7.5) years) ($p=0.37$), BMI (training: 25.8 (6.2) kg/m^2, practice: 25.6 (3.7) kg/m^2, control: 26.8 (3.7) kg/m^2) ($p=0.77$), or sex (training: 6 females and 4 males, practice: 4 females and 6 males, control: 8 females and 6 males) ($p=0.62$). Furthermore, there were no significant differences between groups for outcome variables at baseline (Table 4.1). Interestingly, GME and mechanical effectiveness were not correlated at baseline ($r=0.066$, $n=31$, $p>0.05$), indicating that there is not an inherent relationship between the two variables among able-bodied older adults with no wheeling experience.

Table 4.1. Baseline wheelchair propulsion physiological and biomechanical data categorized by group (mean (SD))

	Training group (*n*=9)	**Practice group (*n*=10)**	**Control group (*n*=13)**	**p-value**
Variables derived from SmartWheel data				
Self-selected speed (m/s)	0.5 (0.1)	0.6 (0.1)	0.5 (0.2)	0.51
Mechanical effectiveness	0.76 (0.08)	0.75 (0.06)	0.79 (0.10)	0.61
Power output (W)	10.8 (3.7)	12.1 (3.0)	11.2 (5.1)	0.80
Relative power output (W/kg)	0.12 (0.02)	0.14 (0.05)	0.12 (0.05)	0.46
Work/push (Joules/push)	10.3 (4.1)	12.7 (4.4)	12.6 (6.8)	0.48
Sprint power output (W)	121.3 (67.4)	134.7 (76.3)	113.4 (53.2)	0.74
Variables derived from metabolic data				
$\dot{V}O_2$ (ml/min/kg)	5.9 (1.4)	7.6 (1.7)	7.6 (2.3)	0.11
Respiratory exchange ratio	0.92 (0.07)	0.98 (0.11)	0.96 (0.09)	0.44
$\dot{V}_E$ (l/min)	13.9 (2.3)	20.1 (6.9)	19.5 (6.9)	0.06
Heart rate (bpm)	86.4 (11.1)	89.9 (6.8)	82.0 (13.3)	0.32
Energy expenditure (W)	146.9 (31.5)	195.6 (55.5)	201.2 (72.7)	0.09
Variable derived from both SmartWheel and metabolic data				
Gross mechanical efficiency (%)	7.5 (2.3)	6.4 (1.9)	6.0 (2.0)	0.25
Self-reported perceived exertion				
Borg scale (rating of perceived exertion, range: 6-20)	10.9 (1.9)	11.6 (1.7)	10.9 (1.0)	0.50

Abbreviations: bpm: beats per minute; kg: kilogram; l: liter; m/s: meters per second; min: minute; ml: milliliters; $\dot{V}_E$: minute ventilation; $\dot{V}O_2$: volume of oxygen consumption; W: Watts

4.3.3 Comparison of groups over time

Generalized linear mixed effects models (GLMMs) were used to analyze the outcomes of interest. Models included a random-effect for participants while adjusting for the age, sex, and BMI. Group and time point were included as ordinal between-subject factors. No outliers were identified and no violations of the homoscedasticity or normality assumptions (174) were observed. Centering was not done on age or BMI as they were confounders and not the explanatory variables of interest. Group means and standard deviations of all variables at all time points for the treadmill testing are presented in Table 4.2. See Appendix Q for detailed GLMM outputs with adjusted p-values for the false discovery rate.

Table 4.2. Effect of motor skill-based wheelchair propulsion training on physiological and biomechanical variables categorized by group and time point (mean (SD))

	Training group			**Practice group**			**Control group**		
Variable	**T1** *n*=9	**T2** *n*=8	**T3** *n*=8	**T1** *n*=10	**T2** *n*=8	**T3** *n*=10	**T1** *n*=13	**T2** *n*=14	**T3** *n*=13
Variables derived from SmartWheel									
Mechanical effectiveness	0.76 (0.08)	0.71 (0.14)	0.71 (0.12)	0.75 (0.06)	0.76 (0.07)	0.75 (0.06)	0.79 (0.10)	0.74 (0.10)	0.75 (0.09)
Power output (W)	10.8 (3.7)	11.1 (4.4)	10.7 (4.2)	12.1 (3.0)	11.8 (4.6)	12.9 (4.2)	11.2 (5.1)	10.9 (6.1)	10.5 (5.9)
Relative power output (W/kg)	0.12 (0.02)	0.11 (0.04)	0.12 (0.04)	0.14 (0.05)	0.14 (0.06)	0.15 (0.06)	0.12 (0.05)	0.12 (0.06)	0.11 (0.05)
Work/ push (Joules/ push)	10.3 (4.1)	25.7 (14.5)	26.1 (16.5)	12.7 (4.4)	13.4 (7.2)	14.9 (7.7)	12.6 (6.8)	11.1 (5.1)	11.5 (6.2)
Sprint power output (W)	121.3 (67.4)	131.0 (61.4)	123.3 (79.5)	134.7 (76.3)	144.6 (73.1)	154.7 (72.5)	113.4 (53.2)	112.8 (53.5)	119.5 (39.2)
	T1 *n*=9	**T2** *n*=8	**T3** *n*=8	**T1** *n*=10	**T2** *n*=8	**T3** *n*=10	**T1** *n*=13	**T2** *n*=14	**T3** *n*=13
Variables derived from metabolic cart									
$\dot{V}O_2$ (ml/min/kg)	5.9 (1.4)	6.3 (0.8)	6.3 (0.8)	7.6 (1.7)	7.0 (1.8)	6.7 (1.8)	7.6 (2.3)	7.0 (2.3)	6.5 (1.9)
RER	0.92 (0.07)	0.86 (0.06)	0.88 (0.07)	0.98 (0.11)	1.02 (0.10)	0.96 (0.12)	0.96 (0.09)	0.98 (0.07)	0.98 (0.12)

$\dot{V}_E$ (l/min)	13.9 (2.3)	14.8 (3.1)	14.2 (3.2)	20.1 (6.9)	17.9 (3.0)	17.3 (5.8)	19.5 (6.9)	17.5 (7.2)	17.4 (7.0)
Heart rate (bpm)	86.4 (11.1)	86.5 (1.5)	84.4 (8.6)	89.9 (6.8)	87.4 (8.7)	84.3 (6.4)	82.0 (13.3)	83.8 (12.4)	83.8 (13.1)
Energy expenditure (W)	146.9 (31.5)	165.8 (42.2)	159.0 (39.5)	195.6 (55.5)	176.6 (33.8)	167.7 (37.4)	202.2 (72.7)	182.8 (76.4)	173.3 (65.4)
	T1 *n*=9	**T2** *n*=8	**T3** *n*=8	**T1** *n*=10	**T2** *n*=8	**T3** *n*=9	**T1** *n*=12	**T2** *n*=12	**T3** *n*=12
Variable derived from both SmartWheel and metabolic data									
GME (%)	7.5 (2.3)	7.1 (2.4)	7.5 (2.5)	6.2 (1.8)	5.3 (1.5)	7.1 (1.9)	6.0 (2.0)	6.2 (1.9)	5.9 (1.7)
Self-reported perceived exertion (used for descriptive purposes)									
Borg scale (rating of perceived exertion, range: 6-20)	10.9 (1.9)	10.6 (1.9)	10.9 (1.7)	11.6 (1.7)	10.0 (1.8)	9.3 (1.9)	10.9 (1.0)	11.2 (1.7)	10.7 (1.9)

Abbreviations: bpm: beats per minute; GME: gross mechanical efficiency; kg: kilogram; l: liter; ml: milliliters; min: minute; T1: time point 1; T2: time point 2; T3: time point 3; $\dot{V}_E$: minute ventilation; $\dot{V}O_2$: Volume of oxygen consumption; W: Watts

There were no observed effects of group or time for mechanical effectiveness, PO, Relative PO, sprint PO, $\dot{V}O_2$, RER, $\dot{V}_E$, heart rate, energy expenditure, or GME. Participant data for GME and mechanical effectiveness are displayed in Figure 4.1. Only work demonstrated a significant difference between groups, with the training group using more work per push compared to the control group ($p=0.05$). There was a trend towards increased work over time between T1 and T2 ($p=0.12$) and between T1 and T3 ($p=0.12$).

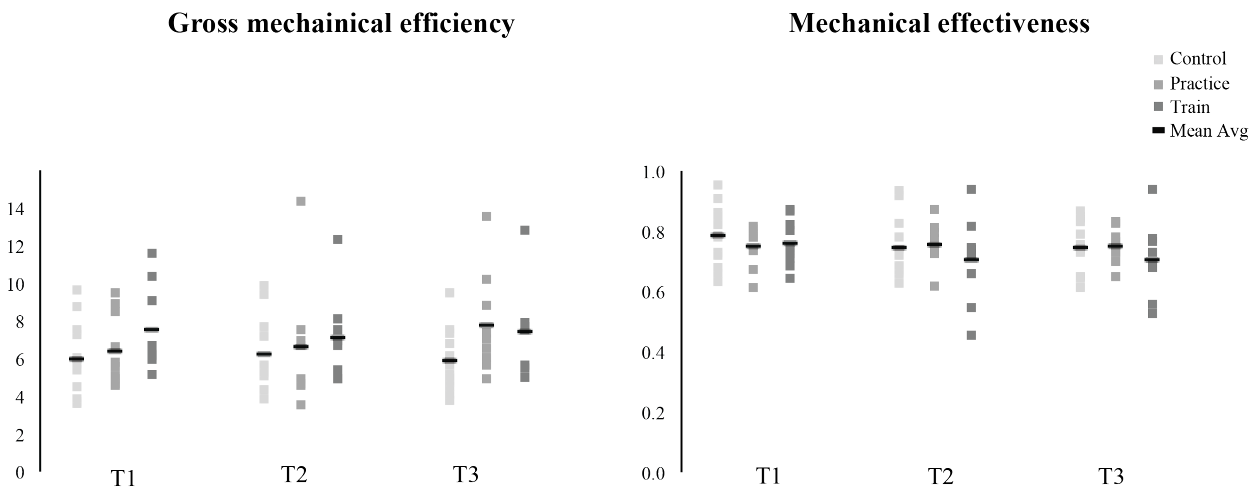


Figure 4.1. Treadmill testing and transfer results for gross mechanical efficiency and mechanical effectiveness for the training, practice, and control groups

Figure legend: Gross mechanical efficiency and mechanical effectiveness of each group (light grey: control, medium grey: practice, dark grey: training) over the three time points (T1: baseline, T2: post training, T3: 2-week retention). The black bars represent the mean value for each group for each time point.

4.3.1 Effect size estimations

The GLMMs produced regression coefficients for each model's main effects (see Appendix Q); in addition to the model results, estimates for Cohen's *d* were also approximated (see Appendix R).

4.4 Discussion

Wheeling efficiency (i.e., GME) and mechanical effectiveness did not improve following wheelchair propulsion training in our cohort of novice older able-bodied adults. We had expected that experience (practice) and motor skill-based training would lead to less 'wasted' energy and therefore a higher GME (90, 91, 101). Both GME and mechanical effectiveness have been used to evaluate the effect of training or learning in past studies; however, they refer to different constructs. Gross mechanical efficiency refers to the ratio of mean PO to the total energy expended, whereas mechanical effectiveness refers to the degree to which force applied to the handrim is effective in producing forward movement.

The effects of GME and mechanical effectiveness or fraction of effective force (FEF) (square root of mechanical effectiveness) following wheelchair propulsion practice and training have been inconsistent. In one study, following three weeks of practice, significant improvements in GME were observed; however, there were no increases in FEF compared to an inactive control group (20). Similarly, another study observed significant improvements in GME in a low tempo practice group and no increases in FEF compared to the inactive control group (156). In contrast, FEF improved following training that incorporated feedback aimed at improving FEF, while GME significantly decreased compared to an active control group (21). The relationship between GME and mechanical effectiveness is clearly inconsistent and appears to differ based on the type of practice or training protocol. Leving et al. found that both GME and FEF significantly improved in the active control group compared to the training group based on feedback aimed at increasing variability (137). Based on our meta-analysis of pre-post studies from Chapter 2, all three studies found positive effects of practice on GME. When the goal of training was to improve mechanical effectiveness or FEF, there appeared to be a detrimental effect on GME (21). We did not observe a significant relationship between GME and mechanical effectiveness among our novice older able-bodied participants at baseline.

There is evidence that increasing forward producing force is associated with increased localized demands on the musculature. Bregman et at. identified through model simulations that increasing tangential force to 75% of total force resulted in increased co-activation around the elbow and higher power production of the shoulder joint. Furthermore, increasing tangential forces came at a 30% higher physiological cost (118).

Although we had anticipated that GME would increase, mechanical efficiency would decrease, and the corresponding variables (e.g., PO) would be modified accordingly, only work per push differed between groups. There was a trend towards increased work per push following training, which was retained two weeks post-training. The training did not aim to increase work per push; however, this trend may be a by-product of increasing the push angle and decreasing the push frequency (Chapter 3).

Our study is one of few that focused on able-bodied older adults with no prior wheeling experience (29, 32). Our GME values at baseline (range: 6.0-7.5%) were lower than a recent study that compared able-bodied older adult males (mean age: 70.9 years, mean GME: 10.6%) to able-bodied younger adult males (mean age: 24.8 years, mean GME: 9.7%) (32). Although the energy expenditure values were similar between the two studies, the PO values were smaller in our study due to the slower self-selected speeds. It is important to consider that GME has been observed to increase at higher POs (20, 21). Therefore, it is possible that we would have observed a higher GME if the self-selected speeds, and subsequent POs, were higher. However, we allowed participants to choose a self-selected speed to make the training as accessible and inclusive as possible.

The slower self-selected speeds (and corresponding lower POs) used for training and testing in this study may be less efficient compared to higher, more functional speeds (e.g., 1.1 m/s at 0.15-0.25 W/kg) examined in other studies (20, 21). Wheelchair propulsion studies have found that GME increases at higher external power outputs (20, 21), and therefore, potential benefits of training may not be detectable at lower power outputs with corresponding lower GME. Many cyclical gross motor skills have an optimal speed associated with decreased energy expenditure. For example, people have optimal walking speeds where speeds that are slower or faster require more energy (197). Perhaps the slower wheeling speeds are not optimal and result in more jerk (changes in accelerations and decelerations).

Both GME and performance can be improved through the selection of a freely chosen rate, which has been reviewed by Sparrow and colleagues (92). Evidence of self-optimization has been observed through the self-selection of movement cycle frequencies for tasks including bicycle ergometry (198) and wheelchair propulsion (152). Although participants in our study self-selected their wheeling speed, the constant speed might have imposed constraints in using their preferred freely chosen frequency. For example, if the demands of the task were too minimal to use a certain force-frequency combination, they may have resorted to using a different frequency. Furthermore, the training recommended using a frequency no higher than 1 Hz, which may not have resulted in the selection of the most efficient frequency. Considering that the practice group did not change their push frequency, it may be speculated that they did not self-optimize or that a constraint prevented optimization (e.g., their self-selected speed).

Efficiency is thought to accompany skilled performance following improvements in motor coordination and control (90). Based on the clinical practice guidelines (3), skilled performance of manual wheelchair propulsion involves a large push angle (i.e., 100°) and a low frequency (maximum of one push per second). Although the training recommended that the push frequency not exceed one push/second (3), we did not instruct participants to use a specific frequency because past research has identified that the preferred work rate is usually the most economical (152). The arc wheeling pattern, which generally exhibits a small push angle and high frequency (81), has been shown to be the most efficient pattern among able-bodied adults with no prior wheeling experience (24). Conversely, the circular wheeling pattern was found to be the least efficient at both 1.11 m/s or 1.39 m/s (24). Reaching further back on the handrim to achieve a longer push angle requires a pulling motion, which may not lend to the application of forward-acting forces, whereas shorter pushes applied further ahead on the handrim may be more mechanically advantageous. Moreover, using a larger push angle may result in more work per push, which could have implications for energy expenditure. The current study observed increased work per push following training but not an overall increase in GME or mechanical effectiveness.

Longer durations of practice or motor skill training or higher power outputs may be needed to improve GME. We had selected six practice and training sessions because previous studies suggest this is sufficient to decrease heart rate and perceived exertion among other cyclical tasks (e.g., rowing) (92); however, the speed and power output of our practice and training may have been too low to elicit improvements in GME. Wheelchair propulsion studies have observed improvements in GME in as few as three practice blocks lasting 4-minutes each (power output: 0.20 W/kg) (155) and as many as 21 wheeling practice sessions lasting 70 minutes each at 30% of participant's heart rate reserve (19).

4.4.1 Limitations

Although testing did not begin until resting RER levels were below 0.9, in some cases the final minute used for data collection demonstrated values higher than 1.0. These high RER values indicate that 100% carbohydrates were used for energy, which is often observed at higher exercise intensities. Higher RER values at steady state exercise are observed among untrained compared to trained individuals (199). The high RER values observed for some trials may have introduced some bias into the findings, as the corresponding thermal equivalent values of the RER values could be inflated. These values could increase EE, and thus decrease GME; however, our GME values were within the range observed in past studies. If we adjusted the thermal equivalent corresponding with an RER of 1.0 to 0.85, GME only decreases by approximately 0.4%; therefore, we believe that the effect of some participants having high RER values would be negligible.

The participants in this study were able-bodied and did not have any physical limitations that would make wheeling less efficient (e.g., discrepancies in strength or range of motion). However, our participants may not have had the same motivation to improve their wheelchair propulsion, and therefore, the findings may not be generalizable to older adults who are prescribed a wheelchair. Furthermore, the slow self-selected speeds (i.e., mean 0.56 m/s) resulted in lower POs; however, PO did not differ across groups or over time. The most commonly reported speed in the literature is 1.1 m/s (Chapter 2); however, this speed was not functional for our sample of older adults. The mean relative POs in the current study ranged from 0.11- 0.15 W/kg, which is lower than the 0.15-0.25 W/kg generally observed in the literature for young adults (Chapter 2).

The sample size used in this study was based on a biomechanical variable not evaluated in this paper (i.e., push angle from Chapter 3); therefore, this study may have been under-powered to detect changes in GME; however, other studies that have identified improvements did so using as few as 20 participants (10 in each of two groups) (20). Due to the inconsistent results in GME and different motor skill practice and training protocols, there is insufficient data to calculate an appropriate sample size. An estimation of effect size was calculated for all dependent variables to compare within this study (Appendix R); however, work per push was the only physiological variable that had a medium-high effect size.

4.5 Conclusion

Although we postulated that there would be less unnecessary movement (i.e., noise) in the system, resulting in improved efficiency, no changes were observed in GME or mechanical effectiveness. Training duration and frequency may have been insufficient to elicit changes among older adults with no wheeling experience. Furthermore, training focused on increasing push angle and reducing frequency, which may have resulted in greater energy expenditure through increasing work per push. Importantly, the modifications in wheeling biomechanics described in Chapter 3 (i.e., increased push angle and decreased push frequency), did not decrease the efficiency of the system. More research is needed to understand whether wheelchair propulsion recommendations (3) result in improved GME and mechanical effectiveness.

The findings from the current study are consistent with the results of our meta-analyses (Chapter 2). A medium effect of practice and training protocols on GME was observed for pre-post design studies; however, there was no significant effect for studies that incorporated independent groups, similar to ours. Why there appears to be a discrepancy in the effect of training and practice protocols based on study design is not well understood. Potential changes in GME may not be detectable over multiple sessions potentially from high inter-session variability when learning a novel task.

Increased GME was hypothesized to support the presence of motor skill learning, with a reduction in metabolic cost attributed to a reduction in unnecessary movement (i.e., noise which will be evaluated in Chapter 5) (90, 91, 101). Furthermore, we had expected that the training would result in a reduction in peak negative force, which was not observed (Chapter 3). The main foci of the motor skill training aimed to reduce push frequency, increase push angle, and reduce peak negative forces in older able-bodied adults; however, the energy cost-effectiveness of making larger and slower movements is unclear based on the literature. Importantly, improvements in biomechanics described in Chapter 3 were not accompanied by decreases in GME (i.e., improvements in wheeling biomechanics did not come at an additional cost compared to baseline), which is especially important for older adult MWUs who are at risk for reduced physical and leisure activity (49). Work per push increased following wheelchair propulsion motor skill training; however, the corresponding energy cost did not increase likely because of the reduction in push frequency.

5 Does intercycle variability change with motor skill-based wheelchair propulsion training in older adults?

5.1 Introduction

Variability in human movement is the normal variations across multiple repetitions of a specific task, which has been extensively reviewed by Stergiou and Decker (200). Historically, variability was thought to be random and independent; however, it is now believed to follow a temporal non-linear relationship (201). Decreased movement variability has long been considered an indicator of motor skill learning, and therefore, when improving a motor skill, a primary goal is to reduce variability in the system (102). Importantly, reducing variability in the system has been shown to improve the gross mechanical efficiency of some motor tasks (202) by refining coordination and eliminating wasteful noise. Motor skill learning may be indicated by a reduction in variability; however, no differences in the coefficient of variation (COV) (SD/Mean*100) were observed between experienced and inexperienced wheelchair users in a recent study (2).

Variability is thought to play an important role in motor skill learning, whereby sensorimotor circuits learn and high variability early on can enhance the learning process (86). The task relevant 'noise' observed in movement variability may allow for movement exploration, which is theorized to predict the rate at which someone learns a motor skill (86). This concept may be particularly important when learning the skill of manual wheelchair propulsion because the hands generally fall outside of the field of vision; therefore, the user cannot depend on vision to cue contact and release of the handrim. One study observed that participants who improved during natural wheeling practice also exhibited more variability (128). In contrast, a recent study that examined training that incorporated feedback to produce higher intra-individual variability did not improve propulsion technique more than the natural learning control group (137). Furthermore, the feedback training group did not improve gross mechanical efficiency (GME) in contrast to the natural learning control group that significantly improved GME (137).

Importantly, factors such as older age may increase the amount of variability when performing various types of motor skills (203). Older age is associated with greater gait variability (204) and increased variability is related to slower walking speeds (205, 206), which are often demonstrated by older adults (207). Compared to younger adults, older adults demonstrated greater variability when releasing their grip force during a grip force modulation task (208). Differences in the grip force task could have implications for wheelchair propulsion (e.g., releasing hand from handrim).

Movement variability is thought to have a protective effect on the body by distributing forces through different tissues; however, too much or too little movement variability may be indicative of pathology for gait and other motor tasks (reviewed in (209)). Decreased variability has been theorized to be associated with over-use injuries related to running; however, the causal direction is unknown (i.e., whether the injury results from decreased variability or the injury results in decreased variability) (209). Although there has been minimal wheelchair propulsion research on the implications of wheelchair propulsion variability, studies have found that both larger kinematic variability during the recovery phase and smaller shoulder joint force variability are associated with shoulder pain in manual wheelchairs users (MWUs) (83-85).

Kinematic studies have identified changes in wheeling technique and pattern over a 10-minute wheeling trial in both able-bodied participants and MWUs with spinal cord injury (2, 210). The wheeling pattern (i.e., trajectory of the hands throughout the wheeling cycle reviewed in Appendix C) has been theorized to adapt to a less injurious pattern using more optimal biomechanics over time. Changes in wheeling pattern across a longer bout of wheeling may be associated with changes in variability. For example, changes in variability could be a mechanism to avoid injury or could be indicative of fatigue. The changes observed in wheelchair propulsion biomechanics (Chapter 3), may correspond with changes in wheeling pattern. If there is a relationship between motor skill learning and decreased variability, the COV should decrease with improvements in wheeling pattern towards a recommended semi-circular pattern (3).

Whether older adults decrease biomechanical variability and modify their hand trajectory (i.e., wheeling pattern) following training is unknown. Therefore, the purpose of this study was to determine whether motor skill-based wheelchair propulsion training effects motor variability (as evaluated by the COV) and whether changes in wheeling trajectory towards the recommended semi-circular wheeling pattern correspond to decreased variability. We hypothesized that variability in biomechanical variables decreases following wheelchair propulsion training compared to practice (active control) and control (inactive control) groups and that training modifies wheeling pattern.

5.2 Method

This chapter is part of the larger randomized controlled trial (RCT) and therefore, we will highlight the differences from Chapter 3. Detailed methods following the Consolidated Standards for Reporting Trials (CONSORT) can be found in Chapter 3, pages 71-79). Ethical approval was obtained from the University of British Columbia's Clinical Research Ethics Board and the participating hospital ethics board. All participants provided informed consent.

5.2.1 Trial design

This chapter is part of the larger three-arm RCT described in Chapter 3, page 71.

5.2.2 Participants

The same cohort of able-bodied older adults described in Chapter 3, page 71-72 was recruited to participate in this study.

5.2.3 Intervention

The intervention is described in Chapter 3, page 72. Details of the training procedures appear in Appendix K.

5.2.4 Control groups

The control groups are described in Chapter 3, page 73. Details of the uninstructed practice (i.e., active control group) appear in Appendix L.

5.2.5 Outcomes

The COV (SD/ mean * 100) was calculated over the last minute of the 5-minute wheeling block to represent intercycle variability for several biomechanical variables, evaluated in Chapter 3, for each participant. These variables included push angle, push frequency, average and peak forces, and peak negative force. Furthermore, sagittal plane two-dimensional kinematic data were collected to identify propulsion pattern changes based on the trajectory of the 3rd metacarpophalangeal joint (81).

5.2.6 Randomization

The randomization procedures can be found in Chapter 3, page 75.

5.2.7 Blinding

The blinding procedures can be found in Chapter 3, page 74-75.

5.2.8 Study protocol

After providing informed consent, participants completed a demographics questionnaire that included age, sex, BMI and perceived level of physical fitness. Participants were then fitted to either a 16- or 17-inch-wide lightweight laboratory wheelchair (Elevation™, PDG Mobility, Vancouver, BC). Seat height and backrest position were adjusted to create a comfortable fit with the elbow creating an optimal angle (degree range: 90-110°) when their hands were centered at the top of the handrim. Participants spent two to three minutes becoming familiar with the wheelchair and set-up and were not provided any instruction except to propel the wheelchair by pushing the handrim (i.e., not pushing the tire) with their hands. The adjusted wheelchair configurations were maintained for each participant and tire pressure was inflated to 100 psi (i.e., 689.5kPa) for all testing and training/practice sessions. An instrumented wheel (SmartWheel - Out-Front, Mesa, AZ) was placed on the dominant side and an inertia-matched dummy wheel was placed on the opposite side.

During the 5-minute wheeling trial, kinetic and spatial-temporal data were collected with the instrumented wheel (see Chapter 3).

Once participants were comfortably fit, the wheelchair was fastened to safety straps on the wide-belt treadmill (Max Mobility, Nashville, Tennessee). Participants selected a comfortable speed that could be maintained for the 5-minute wheeling trial, and then spent two minutes becoming familiar with the treadmill (e.g., stopping and starting). Infrared emitting diodes were placed on participants' dominant hand on the third metacarpophalangeal joint. Kinematic data were collected with two Optotrak 3020 position sensors (NDI, Waterloo, ON). If participants indicated they wanted to continue the study following the first testing session, an opaque envelope with the randomized group allocation (e.g., training, practice, control) was opened. Participants' awareness was not drawn to the differences between the training and practice groups; they were only informed that they were in 'one of the training groups', so that those assigned to the practice group would not anticipate that they would not improve.

If randomized to the practice or training groups, participants scheduled six sessions (2-3 /week). The second testing session was scheduled two to seven days following the last training session and the third testing session was scheduled two weeks later. The three data collection time points illustrated in Figure 1 were scheduled over six weeks (T1: baseline, T2: within one week post-training or practice, and T3: within two weeks post-training or practice). Participants randomized to the control group completed all three testing sessions at the same time intervals but received no training or practice.

This RCT was registered with the NIH clinical trials database (identifier NCT02123043). A full copy of the study protocol is available at: https://clinicaltrials.gov/ct2/show/NCT02123043 There was no financial support for this trial.

5.2.9 Data analysis

Kinetic data analyses are described in Chapter 3, page 77. Two-dimensional kinematic data from the sagittal plane were analyzed using a custom MATLAB program (MathWorks, Natick, MA). Kinematic data were collected at 200 Hz and filtered at 7 Hz using a fourth-order low-pass Butterworth filter. The trajectory of the third metacarpophalangeal joint was plotted for all cycles in the final minute of testing to identify the propulsion pattern used by each participant at each testing session. Two authors independently categorized wheeling patterns based on visual inspection of plotted trajectories over the final minute of the testing sessions and discrepancies were discussed until a conclusion was reached. Authors were blinded to the participant and group allocation.

5.2.10 Statistical analysis

Details of the statistical analyses can be found in Chapter 3, page 77-79.

5.3 Results

5.3.1 Participants

Thirty-four (16 male, 18 female) able-bodied older adults (i.e., 50 years of age and older) participated in this study. Details of recruitment and enrolment can be found in the consort diagram. (Chapter 3, Figure 3.1) Participants were 62.2 (9.2) years (mean (SD)) of age and their BMI was 26.2 (4.5) (mean (SD)).

Participants were randomly allocated to the training (*n*=10), practice (*n*=10), and control groups (*n*=14). Those randomized to the training and practice groups had 100% compliance with the training sessions; however, two participants missed testing sessions due to factors unrelated to the study (e.g., illness, family emergency) and some data were lost due to technical problems with the testing equipment. For example, there were some missing data due to the instrumented wheel not saving data. The number of included participants for each variable is outlined in the tables below.

5.3.2 Baseline data

There were no observable differences between groups for age (training: 58.8 (7.7) years, practice: 64.5 (12.2) years, control: 62.9 (7.5 years)) (p=0.37), BMI (training: 25.8 (6.2) kg/m^2, practice: 25.6 (3.7) kg/m^2, control: 26.8 (3.7) kg/m^2) (p=0.77), or sex (training: 6 females and 4 males, practice: 4 females and 6 males, control: 8 females and 6 males) (p=0.62). Differences were observed between groups for push angle COV and peak total force COV at baseline (Table 5.1).

Table 5.1. Baseline intercycle variability (coefficient of variation (COV)) of wheelchair propulsion biomechanical variables categorized by group (mean (SD))

COV	**Training group (*n*=10)**	**Practice group (*n*=10)**	**Control group (*n*=13)**	**p-value**
Push angle (°)	9.1 (1.9)	9.3 (2.2)	11.9 (3.7)	0.04
Push frequency (Hz)	5.1 (1.8)	5.8 (2.0)	7.6 (3.5)	0.08
Mean tangential force (N)	11.2 (3.6)	12.1 (4.4)	12.7 (3.4)	0.65
Mean total force (N)	12.7 (3.2)	13.1 (4.4)	15.0 (4.4)	0.35
Peak tangential force (N)	13.6 (4.2)	14.8 (5.5)	15.5 (3.9)	0.62
Peak total force (N)	14.9 (3.5)	12.1 (4.4)	17.4 (4.4)	0.02
Peak negative force (N)*	26.8 (7.2)	27.7 (7.5)	30.4 (7.6)	0.492
Mechanical effectiveness	6.4 (2.2)	7.2 (2.6)	6.9 (2.3)	0.71

Abbreviations: COV: coefficient of variation; Hz: Hertz; N: Newtons

5.3.3 Comparison of groups over time

Generalized linear mixed effects models were used to analyze the outcomes of interest. Models included a random-effect for participants while adjusting for the age, sex, and BMI. Group and time point were included as ordinal between-subject factors. No outliers were identified and no violations of the homoscedasticity or normality assumptions (174) were observed. Centering was not done on age or BMI as they were confounders and not the explanatory variables of interest. Group means and standard deviations of all variables at all time points for the treadmill testing are presented in Table 5.2. See Appendix Q for detailed GLMM outputs with adjusted p-values for the false discovery rate.

Push angle COV: Both the practice ($p=0.02$) and training ($p=0.02$) groups demonstrated a smaller variability in push angle compared to the control group; however, no temporal effects (i.e., no differences between T1 and T2 or T2 and T3 ($p>0.05$)) were observed.

Push frequency COV: There were no effects of group or time on push frequency COV ($p>0.05$).

Mean force (tangential and total) COV: The practice group demonstrated a smaller variability in mean tangential force compared to the control group ($p=0.03$); however, no temporal effects (i.e., no differences between T1 and T2 or T2 and T3 ($p>0.05$)) were observed. Similarly, the practice group demonstrated a smaller variability in mean total force compared to the control group ($p=0.03$) and no temporal effects (i.e., no differences between T1 and T2 or T2 and T3 ($p>0.05$)) were observed.

Peak force (tangential and total) COV: The practice group demonstrated smaller variability compared to the control group in peak tangential force ($p=0.03$); however, no temporal effects for peak tangential force (i.e., no differences between T1 and T2 or T2 and T3 ($p>0.05$)) or peak total force (i.e., no differences between T1 and T2 or T2 and T3 ($p>0.05$)) were observed.

Peak negative force COV: There were no effects of group or time on peak negative force COV (p>0.05).

Mechanical effectiveness: There were no effects of group or time on mechanical effectiveness COV (p>0.05).

Table 5.2. Effect of motor skill training on intercycle variability (COV) of wheelchair propulsion biomechanical variables categorized by group and time point (mean±SD and [range])

	Training group			**Practice group**			**Control group**		
	T1 *n*=10	**T2** *n*=9	**T3** *n*=9	**T1** *n*=10	**T2** *n*=9	**T3** *n*=9	**T1** *n*=13	**T2** *n*=12	**T3** *n*=13
Push angle (°)	9±2 [7-13]	8 ±3 [4-13]	10±5 [5-15]	9±2 [6-14]	8±3 [6-13]	8±2 [4-12]	12±4 [6-18]	12±5 [6-20]	13±5 [8-26]
Push frequency (Hz)	5 (2) [3-8]	7 (4) [3-14]	10 (10) [2-34]	6 (2) [3-9]	5 (1) [4-6]	5 (1) [4-8]	8 (4) [3-14]	9 (3) [5-15]	8 (2) [5-12]
Mean tangential force (N)	11 (3) [6-14]	10 (2) [8-13]	12 (3) [8-15]	12 (4) [6-19]	9 (2) [7-12]	10 (3) [7-17]	13 (4) [8-20]	15 (5) [10-27]	13 (2) [9-17]
Mean total force (N)	13 (3) [7-17]	13 (3) [9-18]	14 (3) [10-18]	13 (4) [7-19]	12 (5) [7-22]	12 (3) [9-19]	15 (4) [12-29]	18 (5) [12-27]	15 (3) [8-19]
Peak tangential force (N)	13 (4) [7-22]	14 (2) [10-18]	14 (2) [11-17]	15 (5) [8-24]	11 (2) [9-14]	13 (4) [9-23]	16 (4) [11-25]	18 (6) [12-28]	16 (3) [12-21]
Peak total Force (N)	15 (4) [8-19]	16 (4) [11-23]	17 (6) [12-29]	16 (5) [7-24]	13 (5) [9-24]	14 (5) [9-25]	17 (4) [12-23]	19 (5) [14-29]	17 (3) [11-21]
Peak negative force (N)	27 (7) [18-37]	30 (5) [22-35]	27 (8) [18-40]	28 (8) [17-42]	28 (10) [18-44]	29 (7) [22-40]	30 (8) [21-44]	38 (10) [23-54]	38 (8) [19-48]
Mechanical effectiveness	7 (2) [4-10]	7 (2) [3-10]	8 (3) [4-15]	7 (2) [4-11]	7 (3) [4-12]	7 (2) [5-10]	7 (2) [3-11]	9 (3) [4-13]	8 (3) [4-11]

Abbreviations- Hz: Hertz; N: Newtons; T1: time point 1; T2: time point 2; T3: time point 3

5.3.1 Effect size estimations

The GLMMs produced regression coefficients for each model's main effects (see Appendix Q); in addition to the model results, estimates for Cohen's *d* were also approximated (see Appendix R).

5.3.2 Wheelchair propulsion pattern

At baseline, all participants used either the arc or single-looping over propulsion wheeling patterns. Participants in the control and practice groups did not modify their propulsion pattern between baseline and post-testing and retention time points; however, nearly all participants in the training group transitioned to the semi-circular pattern (Table 5.3). Only two participants from the training group continued to use the arc pattern, in addition to the semi-circular pattern, at T2. At T3, the same two participants continued to use the arc pattern, one exclusively used arc and one used both arc and semi-circular patterns.

Table 5.3. Frequencies of dominant wheelchair propulsion patterns categorized by group and time point

	Training group			Practice group			Control group		
	T1 n=10	**T2** n=9	**T3** n=9	**T1** n=10	**T2** n=9	**T3** n=10	**T1** n=13	**T2** n=13	**T3** n=13
Arc	10	2	2	9	8	9	9	10	10
Single-looping over propulsion	0	0	0	2	2	1	4	4	5
Double-looping over propulsion	0	0	0	0	0	0	0	0	0
Semi-circular	0	9	8	0	0	0	0	1	0

Abbreviations: Arc: arcing; T1: time point 1; T2: time point 2; T3: time point 3

Note: Some participants consistently used more than one wheeling pattern. If at least 10 cycles consisted of the secondary category, the pattern was classified as both.

5.4 Discussion

There were no observable differences in the intercycle variability of biomechanical variables following wheelchair propulsion training. We had anticipated that there would be less unwanted movement (i.e., noise) in the system following motor skill learning, which would be evident by decreased COV. In turn, we had also expected that decreased variability would be associated with increased GME. Similarly, there were also no observable changes in GME following wheelchair propulsion training (Chapter 4). However, we did observe evidence of motor skill learning based on the retention and transfer of changes in wheeling biomechanics following wheelchair propulsion training (Chapter 3).

Variability is inherent within human movement and can be important for preventing overuse injuries. Increased variability has been associated with slower walking speeds, with older adults demonstrating greater variability in step length and stride time due to low leg strength and smaller passive range of motion (205). Examining changes in COV within an individual can serve as an important tool to identify pathologies or impacts of pathology (200), which has only recently been applied to wheelchair propulsion. Importantly, a recent review identified that variability in wheelchair propulsion is impacted by shoulder pain (211). Specifically, larger kinematic spatial variability during the start of the recovery phase was related to shoulder pain (83). Furthermore, MWUs that experience shoulder pain had smaller variability in peak shoulder resultant force (84) and a lower COV in push time and peak resultant force at the level of the handrim (85). Variability may be indicative of injury but may also have a role in injury prevention.

Higher intra-individual variability in pre- and post- testing was observed among individuals who improved their GME more than 10% over the course of a 12-minute bout of wheeling (128). In a recent study, able-bodied adults were expected to demonstrate more intercycle variability than experienced MWUs because they were performing an unfamiliar task; however, no differences were observed in minute-by-minute COV over a 10-minute bout of wheeling between able-bodied adults and MWUs (2). The COVs reported in the article were comparable to the current study. Furthermore, a study that explored the relationship between COV and the number of included pushes analyzed in an experienced wheelchair user observed COVs of 8.1%, 2.7% and 7.4% for push frequency, push angle, and peak force, respectively when examining 30 pushes (212), which were comparable to our study with respect to number of pushes and observed COVs.

Although there were no changes in COV over time as a result of practice or training, the control group demonstrated greater variability compared to the practice groups for all variables except for mechanical effectiveness and push frequency; however, there were no differences in demographic characteristics that explain why the control group generally had greater intercycle variability across biomechanical variables. There were significant differences between groups for push angle and peak total force at baseline (Chapter 3); however, this does not explain the observed differences in intercycle variability.

We did not collect data during the practice or training sessions to reduce participant burden; therefore, we do not know whether variability fluctuated throughout the practice or training sessions. Although the six training sessions were successful in modifying certain biomechanical variables (Chapter 3), more sessions may have been needed to modify the intercycle variability of biomechanical variables. Future research is needed to explore the amount of training required to elicit changes in wheelchair propulsion biomechanics and to understand the role of variability within motor skill-based training among older adults. Increased variability during practice (i.e., initial skill acquisition) is associated with greater improvements in wheeling (128). However, one study that aimed to increase variability with training involving feedback found similar improvements in propulsion technique compared to the active control group; however, they identified improvements in GME in the active control group but not in the training group (137). Therefore, artificially enhancing the amount of variability may not be an effective training strategy.

5.4.1 Changes in wheelchair propulsion pattern following training

There were clear visual differences in the two-dimensional kinematics of the third metacarpophalangeal joint following training compared to the practice and control groups. At baseline, all participants exclusively used the arc pattern or the single looping over propulsion pattern, or used both the arc and single looping over propulsion patterns; however, everyone in the training group used the semi-circular pattern at the post-test and 89% of participants used the semi-circular pattern at the retention time point two weeks later. No individuals from the practice group, and only one individual from the control group partially used the semi-circular wheeling strategy at the post-test. The changes in propulsion pattern in the training group are supported by their corresponding changes in push length and push frequency (Chapter 3). Based on the changes in propulsion pattern and biomechanical variables, there were large variations in motor performance throughout the training sessions (e.g., the training group's mean push length was 40.8° at T1 and 79.1° at T2 (Chapter 3)). The intercycle variability was high for some variables with values upwards of 54% for mechanical effectiveness for some participants (Table 5.2). Perhaps, the novice older adults' inter-session variability was too high to detect changes in intercycle variability as a result of practice or training.

During baseline testing, participants may not have been willing to explore their spatial environment, potentially due to low confidence with wheelchair propulsion on a treadmill (163), which resulted in the use of the arc wheeling strategy. The arc strategy, which is most commonly used among able-bodied individuals, has been found to be the most energy efficient in this population (24), potentially because of the comfort of keeping the hands closer to the handrim. A previous study found that three out of eleven able-bodied participants modified their propulsion pattern over a 10-minute bout of wheeling (2); therefore, we had anticipated that the practice group (i.e., active control), in addition to the training group, would modify their propulsion pattern following 60-minutes of manual wheeling experience.

5.4.2 Limitations

The self-selected speeds by our participants are lower than what has been used in previous studies (20-23, 137, 138, 155). Our slower wheeling speeds may have resulted in greater variability similar to observations of gait at slow speeds (205). Gait studies have identified a negative linear relationship between the amount of gait variability and speed (ranging from 80% to 120% of their preferred walking speed) among older adults (213). In the current study, participants may have selected lower than 'preferred' speeds because of the novelty of the task. Furthermore, the testing environment of the treadmill may have had less variability than over-ground wheeling because the safety straps may have restricted medial lateral movement. Treadmill wheeling biomechanics were observed to highly correlate with over-ground wheeling biomechanics in a study that used a similar strapping system to our treadmill (214); however, no studies to date have compared variability between treadmill and over-ground wheeling.

The sample size used in this study was based on the biomechanical variable, push angle (i.e., the primary biomechanical outcome variable from Chapter 3); therefore, this study may have been under-powered to detect changes in COV. An estimation of effect size was calculated for all dependent variables to compare within this study (Appendix R); however, push angle COV was the only variable that had a medium-high effect size.

5.5 Conclusion

There were no observable differences in intercycle variability of biomechanical variables following wheelchair propulsion training. Although we expected that variability would decrease following training, recent literature suggests that variability may be dynamic and non-linear (201). Moreover, the role of variability within wheeling is not well understood and has not been fully investigated. The literature suggests that larger variability may aid in the exploration of the spatial environment, which may lead to higher GME, but only when the variability occurs naturally. Therefore, future research is warranted to examine how variability may be used to enhance training and motor skill acquisition, especially in the context of manual wheelchair propulsion.

Based on traditional views of the role of variability in motor learning, this study did not provide evidence to support the presence of motor learning; however, the results align better with more current literature that suggests that variability is dynamic and non-linear (201) and does not necessary decrease with skill acquisition (86). Similarly, another study observed no differences in COV between experienced mixed age adult MWUs and able-bodied participants over the course of 10 minutes of wheeling (2). Wheelchair propulsion variability has only recently emerged as a topic of interest resulting from observations linking variability and pathology (211).

Although we initially expected that variability would decrease following wheelchair propulsion training according to Schmidt's Schema Theory (102), the scientific bases for this hypothesis has been controversial and disputed over the past few decades. This expectation was based on the assumption that variability is the result of error due to an inability to predict the motor program parameters and thus would occur if the motor task had not been learned.

There is some evidence that variability increases while learning a motor task; however, we did not evaluate variability throughout the practice and training sessions. We had expected that GME would increase, in part, due to a decrease in noise in the form of unwanted movement; our findings do not support an increase in GME (Chapter 4) or a decrease in variability following practice or training. If variability is dynamic and non-linear, how one's variability should change following training is unclear. Furthermore, a certain amount of variability may be protective and help to prevent overuse injuries. Future research should focus on understanding the role of wheelchair propulsion variability rather than aiming to minimize it. Moreover, an understanding of the trajectory of variability throughout a wheelchair propulsion training program may aid in future designs. Chapter 6 will evaluate intercycle variability, in addition to other variables that may indicate the presence of motor learning, among older adults with physical disabilities. The single subject research design will allow us to examine the trajectories of the COV over the course of each practice and training session.

6 Motor skill-based wheelchair propulsion training for older adults with mobility-related disabilities: a single subject research design

6.1 Introduction

Motor skill-based wheelchair propulsion training has shown promising results in an able-bodied cohort of older adults (Chapter 3); however, the potential benefit for older adults with physical disabilities is unknown. Training effects, including an increased push angle and decreased push frequency, were observed following six motor skill-based wheelchair propulsion training sessions (Chapter 3). The improvements in wheelchair propulsion biomechanics were retained over a two-week period and transferred to over-ground wheeling. Moreover, uninstructed practice did not elicit improvements among older able-bodied adults (Chapter 3).

Motor learning refers to “a set of internal processes associated with practice or experience leading to relatively permanent changes in the capability for motor skill” (100) (p. 466). If motor learning has occurred, a motor skill should be transferable (adaptable) and retained over time (persistent). Further evidence of motor learning (and improved performance) may include decreased variability (i.e., less unwanted noise) (102), which could have implications for decreased energy expenditure (90, 91, 101). Despite the historical popularity of Schmidt’s Schema theory, which states that variability should decrease with motor learning, no differences in intercycle variability were observed following six training sessions compared to the practice group or the control group (Chapter 5). Variability is speculated to be a key feature in learning through the purposeful exploration of motor space, which follows the more recent dynamic systems theory (215).

Given that older adults do not appear to improve their wheeling biomechanics with uninstructed practice (Chapter 3), they may be at greater need for wheelchair propulsion training compared to their younger counterparts who have shown improvement following uninstructed practice (22, 23, 128, 137, 155). Older adults may exhibit age-related physical decline, including decreased strength, flexibility, and endurance (42), which may be augmented by a physical disability. Furthermore, older adults may learn gross motor skills at a slower rate compared to younger individuals (165). Therefore, the training needs of older adults and the course of training may differ from those of younger adults.

Older adults are at risk for abandonment of indoor mobility equipment including manual wheelchairs (131), and wheelchair use is a risk factor for decreased participation in physical and leisure activities (49); however, few studies have included older adults in wheelchair propulsion practice or training studies. One study reported that a 69-year-old female with a spinal cord injury (SCI), improved and maintained her push frequency and push angle by 70-90% (e.g., 70-90% of intervention data points exceeded the highest baseline point) after 1500 wheeling cycles following wheelchair propulsion practice with feedback (135). Conversely, sedentary individuals with chronic SCIs (over 10 years since injury and many of whom were 50 years of age or older), did not improve their propulsion techniques, except for peak force, following 16 weeks of low intensity uninstructed practice (150).

Preliminary knowledge can be garnered from applying interventions designed for people with physical disabilities to able-bodied populations; however, the intervention must also be tested among end-users (i.e., consumers of the intervention). Although able-bodied individuals are often used to represent new or inexperienced wheelchair users, their interest and motivation to learn may differ from MWUs. Although not an ecologically valid substitute for studying MWUs (2), able-bodied participants with no prior wheeling experience may provide insight into the early learning process of manual wheelchair propulsion involving initial skill acquisition.

One of the inherent challenges in studying manual wheelchair propulsion is the diversity of conditions resulting in manual wheelchair use. Older adults use manual wheelchairs for various reasons, including neurological conditions (e.g., cerebral vascular accident, multiple sclerosis), spinal cord conditions (e.g., SCI, spina bifida), and orthopedic conditions (e.g., arthritis-related, amputation) (216). Therefore, MWUs represent a heterogeneous population. As such, examining a group of MWUs, irrespective of their physical and functional capacity, may yield results that are challenging to discern or interpret. Examining individual data is important and can reduce misclassification bias among heterogeneous clinical populations (e.g., those with diverse physical disabilities). The single subject research design (SSRD) enables a systematic and rigorous intra-individual analysis that can provide evidence of the effectiveness of an intervention (217, 218).

The purpose of this study was to examine the effects of motor skill-based wheelchair propulsion training compared to uninstructed practice on wheeling biomechanics and propulsion pattern in two novice older adults with mobility disabilities to evaluate early skill acquisition. We anticipated that six wheelchair propulsion training sessions would improve wheeling biomechanics in people with mobility disabilities that are novice to manual wheelchair propulsion.

6.2 Method

This study has followed the Single-Case Reporting guideline in Behavioural Interventions (SCRIBE) (219). See Appendix S for the SCRIBE checklist. Ethical approval was obtained from the Behavioural Research Ethics Board at the University of British Columbia, and both participants provided informed consent prior to their participation in this study.

6.2.1 Participants

Participants were recruited from the community through poster advertisements and word of mouth. Potential participants were screened to ensure that they met inclusion criteria, including being fluent in English, having a mobility-related disability that could necessitate wheelchair use, having at most one year experience using a manual wheelchair, and being capable of wheeling at a self-selected speed for five consecutive minutes without pain or fatigue. Potential participants that experienced shoulder pain (i.e., a score above 60) as evaluated by the Wheelchair Users Shoulder Pain Index (220) would be excluded (Appendix T).

Both participants were members of a local accessible physical activity centre where they had been cleared for exercise with the Par-MedX (221). Table 6.1 describes participants' physical characteristics.

Table 6.1 Participants' physical characteristics (strength, fitness, flexibility, and self-selected speed)

Participant	Grip strength	Hand dominance	Physical fitness (self-reported)	Shoulder, elbow, wrist flexibility	Self-selected speed
1	Left: 20 kg Right: 19 kg	Right	Average	Symmetrical: Left and right sides within 10°	0.54 m/s
2	Left: 5 kg Right: 32 kg	Right	Average	Asymmetrical: Left shoulder flexion was 30° less and left elbow extension was 15° less (compared to right side)	0.36 m/s

Participant 1 was a 61-year-old female, with a BMI of 24.9 kg/m^2, whose primary mobility device was a 4-wheel walker that she used in the community and at home as needed. She had been using the walker for five years, which was necessitated by lumbar-sacral nerve pain and muscle weakness following corrective surgeries for scoliosis. Participant 1 experiences pain in her right shoulder when lifting overhead and has been advised by her physician not to lift weights over 4.5 kg. At the time of the study, she did not need a manual wheelchair; however, a manual wheelchair could be necessary should her pain and weakness progress.

Participant 2 was a 59-year-old male, with a BMI of 27.8 kg/m^2, whose primary mobility device was a cane used in the home and community. On long walks, he would also wear an ankle foot orthosis on his left ankle. He had been using a cane for less than four years, which was necessitated by progressive muscle weakness following a C3-C5 incomplete spinal cord injury

(SCI) (ASIA grade D). The initial injury was acquired 40 years ago but was exacerbated by a second car accident 18 years ago. Participant 2's walking was asymmetrical and displayed hip hiking on the left side. His SCI also resulted in flexion contractures of his left fingers and minimal grip strength on his left (more affected) side. Participant 2 had never used a manual wheelchair but acknowledged that a different mobility device may be needed if his walking deteriorates. He noted that he has used a scooter provided by the local grocery store when shopping.

6.2.2 Procedure

This study used an SSRD, which followed an A-B model. The SSRD was selected because variations in treatment effects can be identified that allows for inferences to be made about how many sessions are required for change within an individual. SSRDs are ideal for clinical research because they can provide data to show the effectiveness of new interventions in selected individuals and help validate existing theories (217). In the current study, Phase A consisted of six uninstructed blocked (same duration and speed) wheelchair propulsion practice sessions over two to three weeks. Phase B consisted of six motor skill-based wheelchair propulsion training sessions (Appendix U) that incorporated variable practice and sporadic feedback over two to three weeks. The training was nearly identical to Chapter 3 except that the training sessions were slightly rearranged so that the final minute of each session occurred at the participant's self-selected speed.

On the first day of the study, participants completed a demographics questionnaire and provided a history of their mobility disabilities and their assistive mobility devices (Appendix V).

Following completion of the questionnaire, participants' grip strength and upper limb range of motion (e.g., flexion and extension of the wrist, elbow, and shoulder) were measured.

Participant 1 was fitted with a 16-inch laboratory wheelchair (Elevation, PDG Mobility, Vancouver, British Columbia). When her hands were centred at the top of the wheels, her elbows formed a 105° angle. Participant 2 was fitted with a 17-inch laboratory wheelchair (Elevation, PDG Mobility, Vancouver, British Columbia). When his hands were centered at the top of the wheels, his elbows formed a 100° angle. A rubber handrim cover was placed over the left handrim to enhance participant 2's grip. The adjusted wheelchair configurations were maintained for each participant and tire pressure was inflated to 100 psi (i.e., 689.5 kPa) for all practice and training sessions. The 24-inch (61 cm) SmartWheel (Out-Front, Mesa, AZ), weighing 4.9 kg, was positioned on the participant's dominant side of the wheelchair. Once fitted to the wheelchair, each participant wheeled around the laboratory space for two minutes to ensure a comfortable fit. Participants wheelchairs were then secured to the wide belt treadmill (Max Mobility, Nashville, Tennessee) with the safety straps loosely buckled above the castor wheels to ensure that the wheelchair did not fall off the back of the treadmill while minimizing restrictions in medial-lateral movement. Participants became familiar with the treadmill and self-selected a speed they could maintain comfortably for five minutes. Rating of perceived exertion was monitored throughout the practice and training sessions based on the Borg scale (195).

An infrared emitting diode was placed on the third metacarpophalangeal joint to determine the 2D trajectory of the dominant hand by two position sensors (Optotrak 3020/ Certus, NDI, Waterloo, ON). Kinetic and temporal spatial data from the participants' dominant side were recorded from the SmartWheel. Data from the final minute of the second wheeling block from each practice and training session were averaged to determine steady-state. All data were recorded from the second 5-minute wheeling block.

On days 1 (baseline), 6 (final day of Phase A), and 12 (final day of Phase B), participants were also fitted with a heart-rate monitor (Polar H7, Kempele, Finland) and face mask for metabolic testing (TrueOne® 2400, Parvo Medics, Sandy Utah). Participants also completed the SmartWheel Clinical Protocol (157) and 15 m Sprint test on days 1, 6, and 12 (194). Metabolic data were not collected at all sessions to reduce measurement burden on the participants. The SmartWheel Clinical Protocol and 15 m sprint test were not conducted at all sessions so that the added wheeling experience from those tests would not interfere with the results related to the practice or training sessions.

6.2.3 Wheelchair propulsion blocked practice (Phase A)

Phase A consisted of six practice sessions each involving two 5-minute wheeling blocks at each participant's self-selected speed. No feedback or guidance was provided to participants except to push the handrim rather than the tire. The study coordinator engaged in conversation with the participants about topics unrelated to wheelchair propulsion during the 5-minute rest period between wheeling blocks.

6.2.4 Wheelchair propulsion training intervention (Phase B)

The intervention (Phase B) consisted of six training sessions. Each session included two 5-minute blocks of active wheeling that were separated by a 5-minute inactive break involving instruction and discussion related to wheelchair propulsion. The primary investigator, who is experienced in the training procedures and has over 10 years of experience teaching wheelchair skills, served as the trainer and assessor, which prevented blinding. Training focused on increasing push length, decreasing push frequency, decreasing negative braking forces, using a circular wheeling strategy, and using smooth pushes (i.e., matching the speed of the hand with the handrim before contact). The speed used during the training varied by ±0.1 m/s of the participant's self-selected speed. Although the amount of variation was small, ±0.1 m/s was selected so that it would be obtainable by a heterogeneous population. Consistent quantities of sporadic feedback on specific variables were provided to maintain consistency across participants. The inactive break between wheeling blocks had different foci each session (e.g., identifying positive and negative features of videos demonstrating poor vs. effective wheeling techniques, using visual imagery to reflect on effective wheeling characteristics, and having participants describe how they would teach someone how to wheel). Details of the training procedures appear in Appendix U. Although wheeling speed was modified (participant 1: 0.45 m/s-0.63 m/s; participant 2: 0.27 m/s-0.45 m/s)) to introduce variability in speed, the final two minutes of each block were at the participant's self-selected speed.

6.2.5 Outcomes

<u>Primary outcomes (Recorded on all days)</u>

Wheeling biomechanics (treadmill): Biomechanical variables of interest were push angle (°), push frequency (Hz), peak negative force (N), peak and mean total force (N), and mechanical effectiveness ($F_{tangential}/F_{total}$).

Variability of wheeling biomechanics (treadmill): Intra- and inter- session variability was calculated for each of the biomechanical variables.

Propulsion pattern: The 2D trajectory of the 3rd metacarpophalangeal joint was categorized into four established representative patterns (i.e., arcing, semi-circular, double-loop over propulsion, single-loop over propulsion) described in Appendix B (81).

<u>Descriptive outcomes (Recorded on days 1, 6, and 12)</u>

Metabolic variables: Heart rate was recorded, and mean PO was calculated using angular speed and torque about the handrim recorded by the instrumented wheel. Power output relative to the participant's weight (kg) was also calculated.

Gross Mechanical Efficiency: GME (mean power output/ energy expenditure * 100).

Over-ground wheeling biomechanics: The SmartWheel Clinical Protocol (157) was used to evaluate over-ground wheeling biomechanics on tile and ramp. Depending on the variable of interest, this test has high-very high and low-very high intersession reliability for able-bodied individuals and manual wheelchair users, respectively (172).

Sprint power output: The 15 m sprint test was used to evaluate maximum power output (Watts). This test is a validated measure of anaerobic work capacity (194).

Exit questionnaire: This questionnaire aimed to identify whether participants believed they benefitted from training (Phase B) and if they would recommend the training to new MWUs.

6.2.6 Data analysis

Five minutes of data, collected at a sampling frequency of 240Hz, were wirelessly transmitted to a data collection laptop. The previously filtered data were analyzed using proprietary software to allow for direct comparison to other published studies. Biomechanical data from the final minute of the second 5-minute wheeling block were averaged and used in the analyses to represent steady-state. Trajectories of the third metacarpophalangeal joint were plotted over the final minute of testing and representative wheeling pattern(s) were identified by two of the investigators independently (81).

The coefficient of variation (COV) (SD/mean*100) was calculated over the last minute of the second 5-minute wheeling block for each biomechanical variable for each participant to provide the intra-session variability. The range of the intrasession COVs was determined for each phase for each participant.

6.2.7 Statistical analysis

The two standard deviation (2SD) band method was used to determine differences between baseline and intervention (222, 223). If at least two consecutive data points fell outside the 2SD band, the intervention was considered to have made a significant effect on the outcome variable of interest (222, 223).

6.3 Results

6.3.1 Participant 1

Participant 1 rated her perceived exertion for all individual wheeling blocks below 'very light' (level 9). She reported slight discomfort when her right shoulder was in extension during session 8, just prior to beginning the propulsion phase of the wheeling cycle; however, she did not describe the sensation as painful.

Participant 1 increased push angle (°), and reduced push frequency (Hz) and peak negative force (N) during the training sessions compared to practice sessions (Figure 6.1). The ranges of intra-session variability were larger in Phase B for all variables except push frequency and peak total force (Table 6.2, Figure 6.2). The COVs only decreased for push angle during training compared to practice (Figure 6.2). Participant 1 exclusively used the arc wheeling pattern throughout Phase A. During the first four sessions of Phase B, the semi-circular wheeling pattern was predominantly used while reverting occasionally to the arc pattern; however, over the last two sessions the semi-circular wheeling pattern was used exclusively. Participant 1 showed trends for improvement in GME and increases in sprint power output (Table 6.3). Furthermore, there were no trends towards improvement for the over-ground transfer test (Table 6.4).

Table 6.2 Participants' ranges of intra-session variability (COVs) of wheelchair propulsion biomechanics for Phases A and B of the SSRD

		Range of COVs across sessions (each COV represents the intra-session variability for a given session)	
Participant 1	**Variable**	**Phase A**	**Phase B**
	Push angle (°)	11 - 16%	8 - 16%
	Push frequency (Hz)	6 - 12%	6 - 12%
	Peak negative force (N)	28 - 41%	21 - 42%
	Mechanical effectiveness	9 - 13%	9 - 15%
	Mean total force (N)	12 - 16%	10 - 16%
	Peak total force (N)	12 - 20%	10 - 17%
Participant 2			
	Push angle (°)	9 - 15%	5 - 15%
	Push frequency (Hz)	4 - 12%	6 - 12%
	Peak negative force (N)	25 - 38%	18 - 43%
	Mechanical effectiveness	4 - 7%	6 - 13%
	Mean total force (N)	10 - 12%	8 - 14%
	Peak total force (N)	13 - 16%	8 - 14%

Abbreviations: COV: coefficient of variation, Hz: hertz; N: Newtons; Phase A: practice sessions; Phase B: training sessions

Table 6.3 Participants' steady-state metabolic data and maximum power output from the 15 m sprint test collected on days 1, 6, and 12

Participant	Day	Power output (W)	Relative power output (W/kg)	GME (%)	Heart rate (bpm)	Sprint power output (W)
1	1	7.5	0.12	6.1	95.7	138.1
	6	6.3	0.10	5.9	92.7	130.8
	12	8.7	0.14	7.8	89.9	146.3
2	1	8.1	0.09	5.8	88.7	84.0
	6	7.6	0.09	4.4	99.6	98.6
	12	7.7	0.09	5.7	84.1	92.3

Abbreviations: bpm: beats per minute; GME: gross mechanical efficiency; kg: kilogram; Max: maximum; W: Watts

Table 6.4 Wheelchair propulsion biomechanics on tile and ramp categorized by time point (steady-state pushes only) assessed on days 1, 6, and 12

Participant	Day	Speed (m/s)	Push angle (°)	Push frequency (Hz)	Mean total force (N)	Peak total force (N)	Peak negative force (N)	ME
Tile								
1	1	1.2	60.1	0.8	27.2	33.3	-3.1	0.65
	6	1.2	64.7	0.9	26.3	34.5	-3.1	0.72
	12	1.2	43.4	0.7	31.3	40.6	-4.6	0.54
2	1	0.64	61.6	0.6	43.6	59.3	-3.5	0.59
	6	0.61	58.9	0.6	41.8	59.5	-2.9	0.60
	12	0.72	64.5	0.6	46.7	69.3	-3.0	0.70
Ramp								
1	1	0.7	77.6	0.9	46.4	63.4	-2.6	0.83
	6	0.7	76.8	0.9	47.1	69.2	-1.6	0.80
	12	0.6	77.9	0.8	55.1	80.7	-1.5	0.72
2	1	-	-	-	-	-	-	-
	6	-	-	-	-	-	-	-
	12	-	-	-	-	-	-	-

Abbreviations: Hz: Hertz; ME: mechanical effectiveness; N: Newtons; -: No data (participant was unable to complete task)

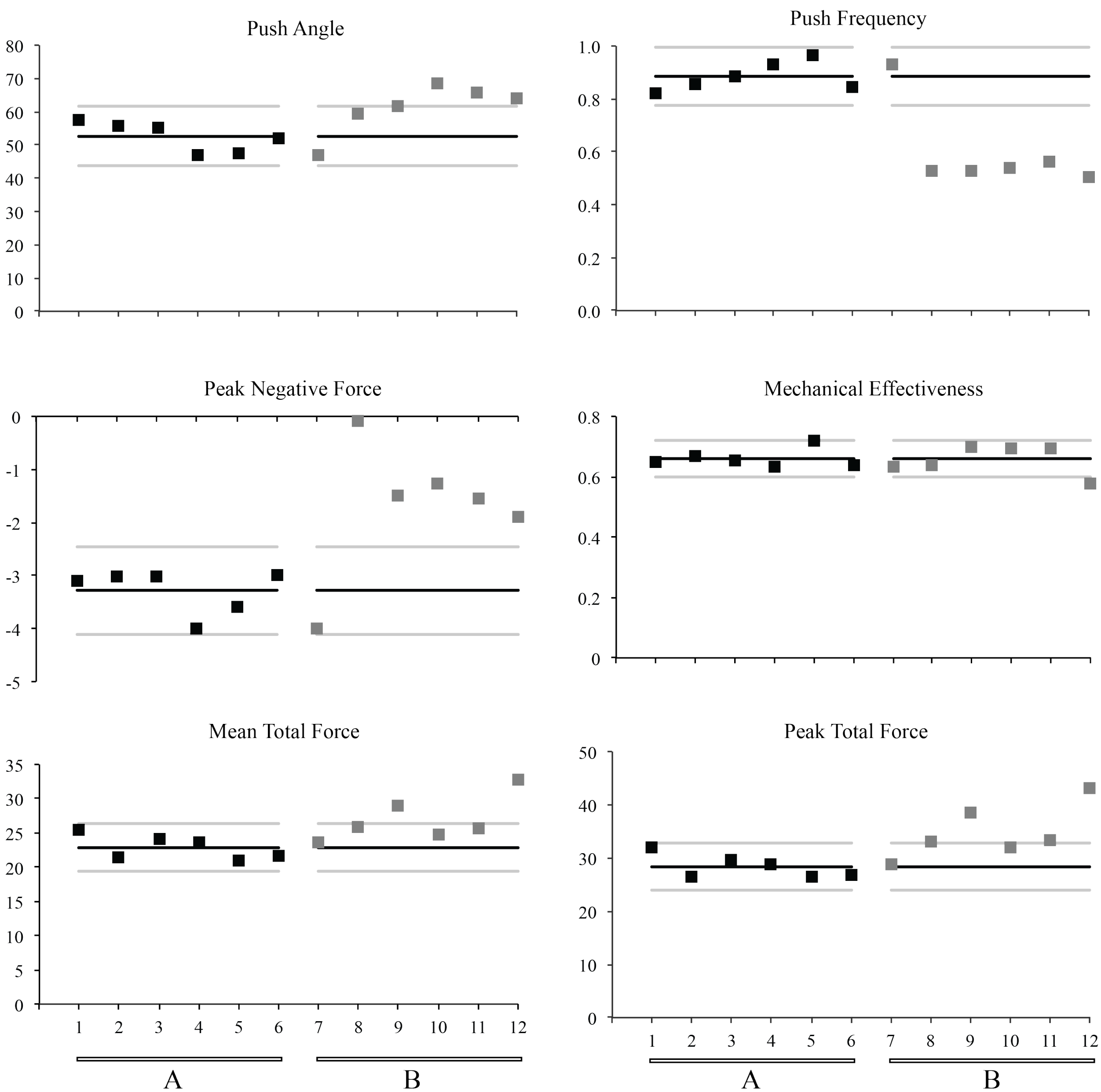


Figure 6.1 Participant 1's SSRD wheelchair propulsion results for biomechanical variables during practice sessions (Phase A) and training sessions (Phase B)

Phase A represents the practice sessions (black boxes) and Phase B represents the wheelchair propulsion training sessions (grey boxes). The black lines represent the mean of the Phase A values and the grey lines represent ± two standard deviations of the mean of the Phase A values.

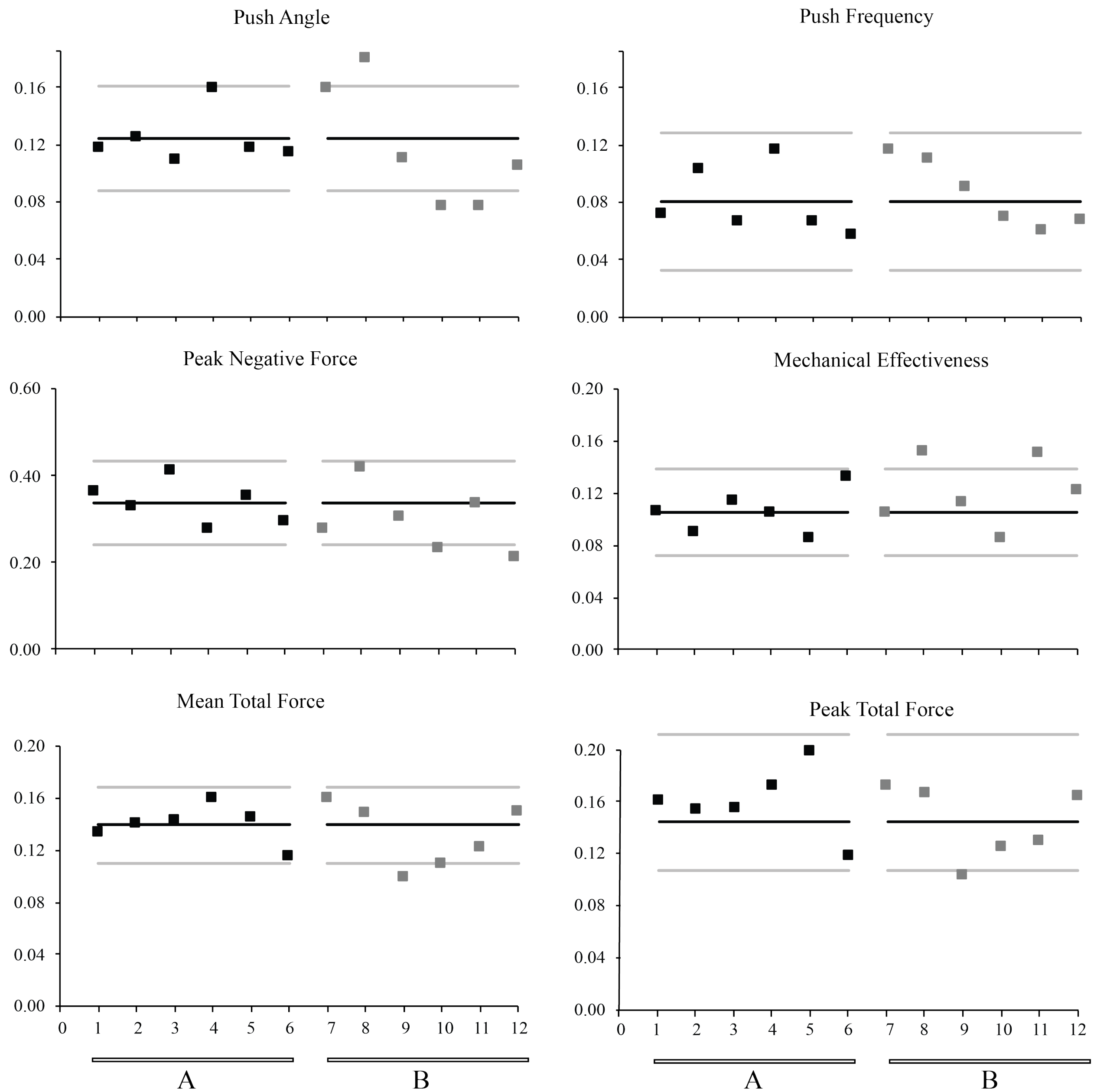


Figure 6.2 Participant 1's SSRD wheelchair propulsion COVs of biomechanical variables during practice sessions (Phase A) and training sessions (Phase B)

Phase A represents the practice sessions (black boxes) and Phase B represents the wheelchair propulsion training sessions (grey boxes). The black lines represent the mean of the Phase A values and the grey lines represent ± two standard deviations of the mean of the Phase A values.

6.3.2 Participant 2

Participant 2 rated his perceived exertion for all individual testing blocks below 'fairly light' (level 11). Participant 2 had a slight discomfort in his right shoulder during session 7, which he speculated was from sleeping; the discomfort did not return during the remaining sessions. Participant 2 could wheel on level surfaces but could not wheel up the inclined surface due the discrepancy in strength of his left arm.

Participant 2 increased push angle (°) and peak total force (N), and reduced push frequency (Hz) and peak negative force (N) during the training sessions compared to practice sessions (Figure 3). The ranges of intra-session variability were larger in Phase B for all variables (except push frequency and mean total force) (Table 6.3). The COVs only decreased for peak total force during training compared to practice (Table 6.2, Figure 6.4). Participant 2 exclusively used the single-looping over propulsion wheeling pattern during Phase A and exclusively used the semi-circular wheeling pattern in Phase B. Participant 2 did not show trends towards improved GME or increases in peak power output (Table 6.3). Furthermore, there were no trends towards improvement for the tile over-ground transfer test (Table 6.4).

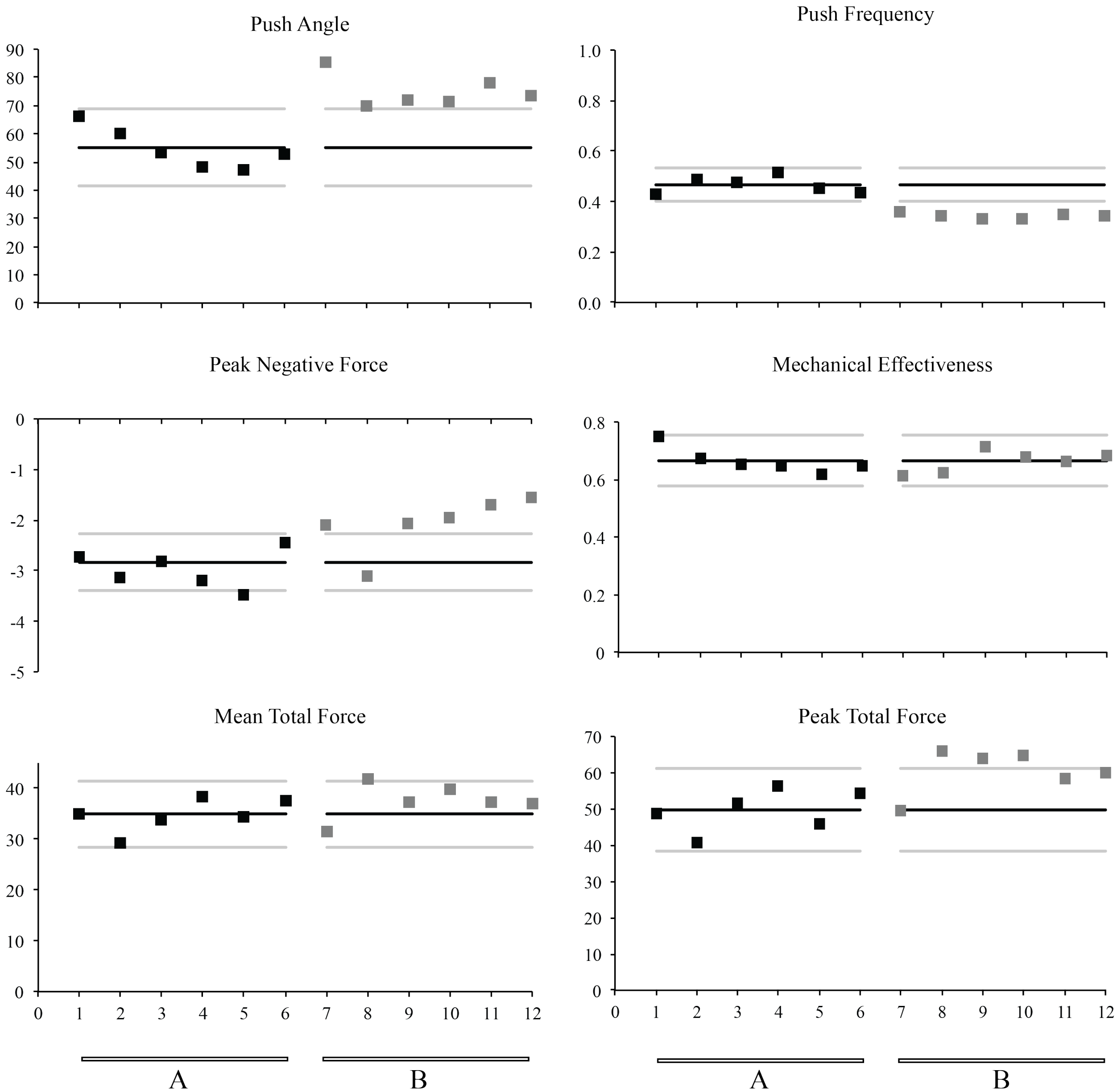


Figure 6.3 Participant 2's SSRD wheelchair propulsion results for biomechanical variables during practice sessions (Phase A) and training sessions (Phase B)

Phase A represents the practice sessions (black boxes) and Phase B represents the wheelchair propulsion training sessions (grey boxes). The black lines represent the mean of the Phase A values and the grey lines represent ± two standard deviations of the mean of the Phase A values.

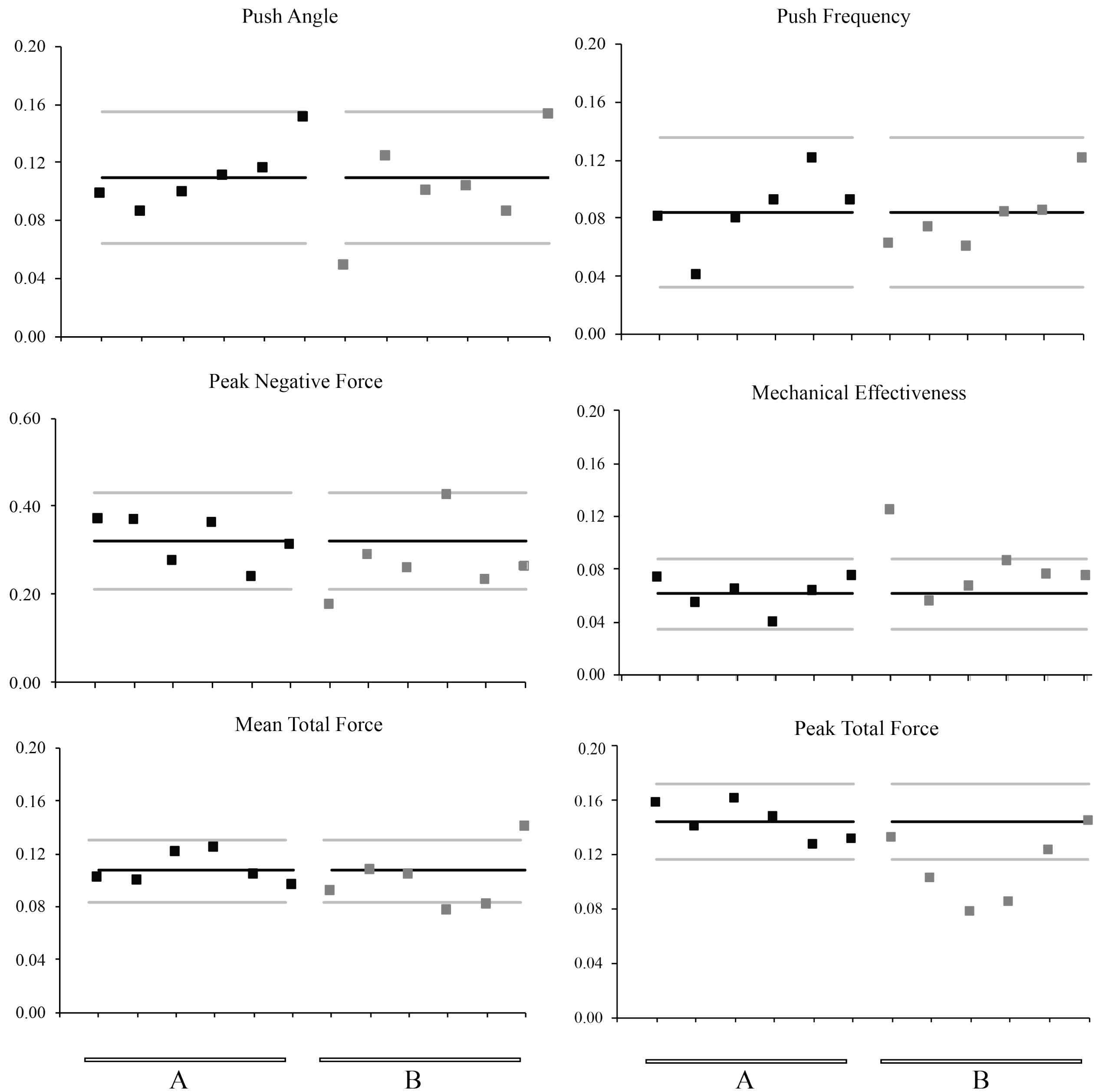


Figure 6.4 Participant 2's SSRD wheelchair propulsion COVs of biomechanical variables during practice sessions (Phase A) and training sessions (Phase B)

Phase A represents the practice sessions (black boxes) and Phase B represents the wheelchair propulsion training sessions (grey boxes). The black lines represent the mean of the Phase A values and the grey lines represent ± two standard deviations of the mean of the Phase A values.

6.3.3 Exit questionnaire

Both participants reported that the training was neither stressful nor uncomfortable and that they believed they improved their abilities to perform wheelchair propulsion over the six training sessions. They also reported that they would recommend these training sessions to a new MWU.

6.4 Discussion

This study is the first to examine wheelchair propulsion training among older adults with mobility-related disabilities. Our SSRD involved six wheelchair propulsion practice sessions followed by six motor skill-based training sessions; however, improvements in biomechanical variables were observed after as few as two to four training sessions (Figures 6.1 and 6.3). Push angle, push frequency, and peak negative force significantly improved for both participants during training compared to uninstructed practice. These findings are consistent with the findings of our randomized controlled trial (RCT), which examined the efficacy of the training among able-bodied older adult participants. Specifically, the training group increased push angle and decreased push frequency and the practice and control groups did not modify their wheeling biomechanics (Chapter 3).

Both participants' improved their wheelchair propulsion pattern based on the recommendations of the clinical practice guidelines towards a semi-circular pattern (3). The initial use of the arc (Participant 1) and single-looping over propulsion (Participant 2) wheeling strategies during the practice sessions coincided with lower push angles, higher frequencies, and higher peak negative forces. Surprisingly, Participant 2 also increased his peak total force, which may have been an unintended consequence of the training. High peak forces applied to the handrim may lead to increased risk of overuse injuries over time (3). The increase in Participant 2's peak total force may relate to his asymmetry, given that his right arm (the evaluated side) was stronger than the left (Table 6.1). Standardized training may have limitations when applied to participants with large discrepancies in strength or range of motion.

Decreased movement variability is postulated to coincide with improved performance of a motor skill (102). Both participants demonstrated a larger range of intra-session (within day) variability across Phase B compared to Phase A, which may have resulted from greater exploration of movement during the training sessions. However, based on our 2SD band analysis, COVs only differed from baseline to training for push angle (Participant 1) and peak total force (Participant 2). Increased variability is thought to facilitate motor skill learning by increasing movement exploration (86, 215). Interestingly, a recent study found that individuals who improved their wheeling GME by 10% or more demonstrated greater variability during the wheeling practice sessions (128).

Participant 1 demonstrated trends towards improved GME, suggesting that she may have improved her wheeling efficiency, whereas Participant 2 did not. These findings are similar to other studies that do not identify consistent improvements in GME across participants (i.e., they identify improvers and non-improvers) (128). The inconsistencies observed in GME may indicate that the training, which focused on increasing the push angle and decreasing the push frequency, may not correlate with decreased energy expenditure, especially for someone with asymmetries in strength and range of motion. The number of training sessions (i.e., six) and the intensity of wheeling used in the current study may have been insufficient to allow for improvements in GME. Other studies have reported improvements in GME with a training power output of approximately 0.15-0.25 W/ kg (20-22, 25, 107, 137, 151), whereas in our study the average power output per session ranged from 0.10-0.15 Watts/kg for participant 1 and was consistent at 0.09 W/kg for Participant 2, corresponding to the speeds that they self-selected.

Only Participant 1 showed trends towards increased sprint power output, evaluated by the 15 m Sprint Test (194), over the course of the study (Table 6.3). Although we did not expect participants to increase their physical capacity, we thought that sprint power output could increase through improved wheeling technique. Similarly, sprint power output did not improve among the training or practice groups in our RCT (Chapter 4). Furthermore, there were no descriptive trends for the over-ground wheeling transfer conditions on tile or ramp. The training may not have transferred to over-ground wheeling because the safety straps may have reduced the amount of medial-lateral rotation, which may have been detrimental especially for someone with asymmetries in strength and range of motion.

We evaluated older adults with mobility disabilities among participants that, at the time of the study, were not prescribed a manual wheelchair by a health professional. Therefore, the generalizability of our data to older adults prescribed their first manual wheelchair is unknown. Both participants acknowledged that a manual wheelchair or other form of assistive mobility device (e.g., scooter or power wheelchair) could be recommended in the future if their walking were to deteriorate.

6.4.1 Methodological consideration

As with any study based on a SSRD, the findings from this study cannot be generalized to a larger population. However, the results do provide an in-depth examination of two individuals with mobility disabilities who had no prior wheeling experience. Although the participants had different disabilities, their training responses were comparable. The changes in biomechanical variables observed for both participants were changes in level rather than trend (217). Although the number of trials for each phase was established *a priori*, to be consistent with the practice and training delivered in our RCT (Chapters 3, 4, 5), we believe that data stability was achieved at baseline (223).

The wheelchair propulsion training was designed to be low intensity, as we were not aiming to elicit physiological changes. Nonetheless, Participant 1 experienced slight discomfort in her right shoulder during the second training session and Participant 2 experienced slight discomfort in his right shoulder during the first training session. The added weight of the instrumented and inertia matched wheels may have increased the difficulty of the wheeling task; however, both participants indicated that the activity was of low intensity based on their ratings of perceived exertion. Participant 2 was unable to wheel up the 8.3% grade (i.e., 5°) incline, which could be partly attributed to the weight of the wheels (29).

An ABA (i.e., practice- training- practice) design may have been beneficial, but because we were examining responses to training, we could not have removed the impact of motor skill learning (i.e., our dependent variables did not necessarily exhibit the property of reversibility considering that motor learning is thought to lead to a ‘relatively permanent change’ (100) (p. 466)). This design could have allowed us to examine short-term retention more closely and determine whether improvements persisted following training. Our findings show evidence of skill acquisition but not long-term retention.

6.4.2 Conclusion

We identified that six motor skill-based wheelchair propulsion training sessions, based on motor learning principles, improved wheeling biomechanics (i.e., increased push angle and decreased push frequency and peak negative force) compared to uninstructed blocked practice in two older adults with mobility disabilities who had no prior wheeling experience. Given the heterogeneity of older adult wheelchair users, SSRD studies provide valuable insight into the efficacy of wheelchair propulsion training. Training should be individualized to accommodate asymmetries and individual needs related to wheelchair propulsion. Although we provided individualized feedback with common training goals, the goals may not be suitable for all MWUs (e.g., aiming for a push length of 100°). Future research should consider wheelchair propulsion recommendations and goals based on each individual's health status and physical ability.

This SSRD study enabled us to examine wheelchair propulsion training compared to uninstructed practice in two older adults with physical disabilities who may be candidates for wheelchair propulsion if their assisted gait deteriorates. Although we had observed that the training was effective in improving biomechanical variables (i.e., push angle, push frequency) among able-bodied older adults in our RCT (Chapter 3), older adults with physical disabilities may experience further challenges related to wheelchair propulsion (e.g., discrepancies in bilateral strength, fatigue, postural concerns). The results of the current study further support the observations from the RCT (Chapter 3) and the meta-analyses (Chapter 2), which identified a medium effect of practice or training on push angle and push frequency among pre-post design studies.

We had hypothesized that GME increases (Chapter 4) and intercycle variability decreases (Chapter 5) following training, which would support of the presence of motor learning; however, we did not observe changes in GME or intercycle variability following training in the RCT. The current study based on a SSRD allowed us to more closely examine changes in variability throughout the practice and training sessions, which was not feasible in the RCT. There were no specific trends or clear trajectories over time in the COVs during practice or training sessions in the two participants. This observation may support the theory that variability is dynamic and non-linear. Furthermore, we aimed to train a different movement pattern which may or may not have been more efficient; therefore, we may not have expected to see a change in GME following six training sessions considering that participants were learning a new motor skill throughout those sessions. Perhaps more training or practice using the new motor pattern is needed to improve GME. Moreover, our training program may not have been long enough to elicit such changes (e.g., participants underwent 60 minutes of practice or training). Our initial hypotheses related to GME and intercycle variability may not have been valid.

In summary, we developed a motor skill-based wheelchair propulsion training program based on past wheelchair propulsion literature and generalized motor learning principles. We incorporated select foundational principles of motor learning but did not aim to individually examine the components of the training program; therefore, we cannot be certain if changes are a result of specific elements of the training. We aimed to create a reproducible training program that had a theoretical foundation, unlike some of the existing wheelchair propulsion literature.

Most importantly, we observed from studies based on a RCT and a SSRD that wheeling biomechanics do not change with uninstructed practice. This unexpected finding contradicts much of the wheelchair propulsion literature that has focused on younger adults. Although we cannot be certain why there appears to be a discrepancy in the ability to modify wheeling biomechanics with uninstructed practice based on age, older adults may not explore their spatial environment to the same extent or may be more hesitant to explore the movement pattern. A detailed kinematic analysis of movement during wheelchair propulsion practice may provide insight into this speculation. We aimed to create an ecologically valid program of research by incorporating older adults into our research aims. Furthermore, we applied our training program to older adults with physical disabilities to further examine the ecological validity. Although we observed improvements following training in our two participants with physical disabilities, we may have observed even greater improvements had we customized the training to the participants' unique physical challenges. Finally, motor skill training in addition to strength training and an appropriate lightweight and well-fitted wheelchair would likely produce optimal results.

7 Conclusion

7.1 Summary of results

Older adults comprise the largest and fastest growing cohort of manual wheelchair users (MWUs) in Canada and the United States; however, they are often excluded from or under-represented in research studies. To date, wheelchair propulsion training has not been examined in older populations. Manual wheelchair use is a risk factor for reduced participation in physical and leisure activity (49), and can be perceived as a barrier to participation among older adults (224). Interventions that aim to improve wheelchair propulsion among older adults are needed as they could enhance independent mobility.

Motor learning has many applications to rehabilitation (105, 132, 133, 225); however, much of the existing wheelchair propulsion literature provides minimal detail regarding the training or practice (i.e., discovery learning) protocols and supporting theoretical backgrounds (Chapter 2). We developed a wheelchair propulsion training program based on several motor learning principles (e.g., variable practice, sporadic feedback, mental imagery) that have been consistently applied to complex motor tasks with success (100, 102, 132, 136). The use of generalized motor learning principles in training older adults wheelchair propulsion has been under-used yet offers potential to improve wheeling biomechanics and, in turn, reduce overuse injuries, which could have implications for enhanced participation.

Several studies have aimed to improve wheelchair propulsion biomechanics and efficiency through practice or training protocols but have had mixed results. Based on our systematic review and meta-analyses, we observed that wheelchair propulsion practice and training protocols are effective for improving push angle, push frequency, and gross mechanical efficiency (GME) when evaluated within a pre-post design study (Chapter 2). However, when studies included more than one group to compare the effect of the intervention, there were no significant effects of the practice and training protocols. Most studies included able-bodied participants (see Chapter 2, Table 2.1) and only eight studies included some participants over 50 years of age. Furthermore, no studies exclusively explored the effect of wheelchair propulsion training on older adults.

A primary objective of this research program was to examine the effect of wheelchair propulsion training in older adults. To identify whether training was successful, we analyzed changes in wheelchair propulsion biomechanical variables, physiological variables, and intercycle variability. In line with Schmidt's definition of motor learning, "a set of internal processes associated with practice or experience leading to relatively permanent changes in the capability for motor skill" (100) (p. 466), we considered changes in motor performance that were retained over time and transferred to over-ground wheeling (e.g., tile and ramp) to support the presence of motor learning. We performed a 3-arm randomized controlled trial (RCT) that compared the motor skill-based wheelchair propulsion training, which incorporated specific motor learning principles (intervention), to uninstructed practice (active control) and no intervention (inactive control). We hypothesized that such training would be superior to both active and inactive control conditions. Furthermore, we hypothesized that the uninstructed practice would result in improvements relative to the inactive control group based on observations from past studies, which observed improvements following practice protocols (22, 128, 155).

In Chapter 3, we explored the effect of our motor skill-based training on wheelchair propulsion biomechanics. We identified improvements in push angle and push frequency following training, which were retained two weeks later and transferred to over-ground wheeling. Interestingly, the practice group did not improve compared to the inactive control group, which suggests that practice may be insufficient for improving wheelchair propulsion biomechanics among older adults. In Chapter 4, we explored the impact of our training on GME, mechanical effectiveness, and other metabolic variables. Although training did not affect GME or mechanical effectiveness, we observed an increase in work per push following training, which coincided with the reduced number of pushes (i.e., reduced push frequency) observed in Chapter 3. We explored the effect of training on intercycle variability in Chapter 5. Interestingly, no effects of training on the amount of variability, as measured by the coefficient of variation (COV), were observed.

We applied our wheelchair propulsion training to two individuals with mobility-related disabilities in our single subject research design (SSRD) (i.e., A-B) study in Chapter 6. The participants had not been prescribed a manual wheelchair but were motivated to learn in the case their assisted walking deteriorated. Compared to baseline (phase A), Participant 1 increased push angle, and decreased push frequency and peak negative force, whereas Participant 2 increased push angle and peak total force and decreased push frequency and peak negative force within two to four training sessions in phase B. The COVs in the SSRD did not follow any specific trends for either the practice or training sessions.

Overall, the results of our studies provide supporting evidence to the earlier findings of our systematic review. Push angle and push frequency, which are related constructs, appear to be modifiable with training. Contrary to our systematic review, which only identified significant effects of pre-post design studies, our 3-arm RCT identified significant effects of training on push angle and push frequency. Importantly, uninstructed practice did not have an effect on wheelchair propulsion biomechanics among older adults in our RCT or SSRD, indicating that wheelchair propulsion training may be critical for improving wheeling patterns associated with a reduction in push frequency, which could in turn reduce overuse injuries.

7.2 What is the evidence for wheelchair propulsion practice and training?

Based on our systematic review of the literature, motor skill training and practice protocols had a medium effect on push angle, push frequency, and GME among lower evidence pre-post design studies; however, the meta-analyses of studies including independent groups observed no significant effects of training and there is little consensus regarding what practice and training methods are most effective (e.g., the number of sessions, time per session, training protocol). Moreover, the theoretical backgrounds and specific training protocols are often not discernable from the published studies. There may also be additional bias in the included studies based on the participants in the samples.

More than half of the studies included in the systematic review exclusively examined able-bodied participants; therefore, we cannot be certain of the ecological validity and how the findings translate to older adult MWUs. Only 31% of studies in the review included participants over 50 years of age, all of which were MWUs. Moreover, the practice and training protocols used may not have been tailored for MWUs with physical disabilities. Although we aimed to design our training to be inclusive (e.g., using self-selected speeds, 5-minute wheeling blocks), it may not be appropriate for all MWUs. The two participants from our study using a SSRD with physical disabilities did report pain with training, albeit minimal. Asymmetrical strength and range of motion may require further modifications within the practice and training protocols; therefore, the generalizability of these practice and training protocols for MWUs is not well understood.

The quality of several studies included in our systematic review were poor (n=13). All single day pre-post design studies (n=10) had low evidence compared to studies that took place over multiple days, which tended to be higher quality. Among the 13 studies that included more than one group, PEDro scores ranged from 4/10 to 6/10, with a mean (SD) score of 5.0 (0.8). As most of the studies that randomized participant group did not conceal the group allocation or incorporate blinding into their study design, there are obvious risks of bias that may confound the results, and therefore higher quality studies are needed to evaluate wheelchair propulsion training protocols.

Most existing studies examine motor performance; however, short-term change in performance does not indicate whether there has been a lasting effect of training or whether learning has occurred. To identify whether learning has occurred, changes in motor performance must be lasting (retained) and transferable to similar motor tasks. Importantly, many studies do not examine whether improvements transfer to real-world settings outside of the laboratory;

improvements isolated to a laboratory setting will only examine the efficacy of an intervention as opposed to its effectiveness.

IMPLICATIONS: There is conflicting evidence in the literature regarding the efficacy and effectiveness of wheelchair propulsion practice and training protocols. Based on our findings, push angle and push frequency appear to be modifiable among older adults with training. Older adults did not improve with uninstructed practice, indicating that they may need motor skill-based training to improve their wheelchair propulsion biomechanics.

7.3 How is wheelchair propulsion training evaluated?

Wheelchair propulsion practice or training protocols are generally evaluated by measurable change in spatial-temporal wheeling characteristics (e.g., push angle, push frequency), kinetics (e.g., total, tangential, and negative forces applied to the handrim) or kinematics (e.g., movement trajectories, joint angles). Consequently, changes in efficiency are expected to coincide with improved wheeling biomechanics; however, this relationship is not well understood. Traditional views of the role of movement variability, based on Schmidt's Schema theory, suggest that variability will decrease with improved motor performance (102); however, more current literature suggests that variability may play a greater role when learning a motor skill and that variability does not necessary decrease with skill acquisition (86). Moreover, variability is thought to follow a dynamic non-linear relationship when learning a motor task (201).

Biomechanical change can be an indicator of improved motor performance. Researchers tend to focus on the biomechanics of the wheelchair-user interface because this is often the focus of training. For example, we tend to evaluate push angle, or forces applied to the handrim; however, it may also be important to consider how changes at the level of the wheelchair-user interface effect the biomechanics of the wheelchair user. Although we observed improvements in wheeling biomechanics, it is possible that biomechanics of the wheelchair user could have been compromised. Our training involved adjusting participant form, (e.g., asking participants to relax their shoulders and not to extend their shoulders too far to avoid strain when initially contacting the handrims). Furthermore, the training aimed to reduce negative and peak forces by increasing the smoothness of the push (i.e., matching the speed of the hands with the handrims upon contact).

Many researchers have hypothesized that GME improves following wheelchair propulsion practice or training as a result of improved motor performance and a reduction in movement variability (i.e., noise); however, the literature shows limited support for this relationship. A study that compared trained and untrained cyclists observed that those who were trained had a higher GME (226) as would be expected. However, several experimental design studies did not observed significant improvements in GME following wheelchair propulsion training (21, 137, 150) or training of other complex cyclical tasks such as crawling (90). Nonetheless, other wheelchair propulsion studies have identified improvements in GME following training, which included wheelchair skills and wheelchair basketball (151). How we define a person who is trained in a motor skill is important. Our wheelchair propulsion training, which consisted of six 10-minute sessions, is not equivalent to years of experience. Thus, improvements in wheelchair propulsion biomechanics may occur following extended practice in older adults; however, it may be pertinent for older adults to improve their wheeling biomechanics soon after getting their wheelchair to reduce negative associations that could result in decreased activity or abandonment of their wheelchair.

Traditional theories of motor learning propose that variability should decrease as motor performance improves (102); therefore, we had anticipated that the amount of variability, evaluated by the COV, would decrease following training. Recent literature in the field of motor learning has expressed that variability may present differently than previously thought and is theorized to follow a non-linear and dynamic process (201). As we were evaluating pre- and post-performance, rather than the learning process, we used a generalized linear mixed effects model for our RCT, which allowed us to model the correlated structure associated with repeated measures in pre- and post- measurements, thus reducing the intra-individual variability. We observed no clear violations of the linearity assumption in our models, which we did not expect due to the number of time points. Our SSRD showed limited evidence relating to the learning process; however, nonlinear variability could explain why we did not observe many differences in intercycle variability based on the two standard deviation band method of analysis that requires two consecutive data points fall outside of the two standard deviation lines.

The use of a standardized wheelchair skills test (e.g., Wheelchair Skills Test (178)) could have provided more information about transfer of the treadmill training to other wheelchair propulsion-related skills; however, we wanted to be sure that all participants received the same amount of wheeling experience, which may not have been possible with a wheelchair skills test. Furthermore, had the participants performed the Wheelchair Skills Test at each testing time point, we would not be able to discern whether improvements were influenced by the added experience. Some participants may have wanted to attempt more skills than others which could have influenced their wheeling experience and skill level, especially among those in the inactive control group.

IMPLICATIONS- There are multiple ways to evaluate improvements in motor performance. Specific indicators can support the presence of motor learning (e.g., whether changes were retained and are transferable); however, improvements in performance do not guarantee the occurrence of motor learning. Multiple perspectives (e.g., kinetic, kinematic, temporal-spatial, physiological) should be evaluated when examining the effect of training or practice protocols to provide a greater understanding of the impact beyond what can be visually observed.

7.4 Is practice sufficient for older adults to improve wheeling?

Several studies have identified changes in wheeling biomechanics following blocked practice (i.e., natural learning protocols) in young able-bodied adults (20, 22, 128, 151, 155). Vegter et al. had observed that able-bodied men (mean age: 22.9 years) who improved GME to a greater extent (i.e., more than 10%) demonstrated increased variability during practice (138). In our RCT, which involved older adults, we did not observe any improvement with practice, which suggests that older adults may not explore their spatial environment to the same extent as their younger counterparts or they may need specific guidance associated with practice.

Age-related differences in variability may be due to older adults learning some motor skills, specifically complex tasks, differently than younger adults (reviewed in (44)). Wheelchair propulsion, a *locomotion on object task*, lies towards the ‘complex’ end of the simple-complex spectrum because it has multiple degrees of freedom and is not an 'artificial' task (134, 227). However, the motor skill of wheelchair propulsion can arguably be acquired within a single session based on the positive findings of within-day studies from our systematic review, which is often the case of simple tasks such as reaching.

There are several reasons why age-related physical decline may impact motor performance of wheelchair propulsion. Decreased flexibility may limit the size of the push angle and decreased strength could affect forces applied to the handrim with lower applied forces requiring a higher push frequency to maintain a specific speed. Furthermore, impairments in sensorimotor functioning (228, 229) and perceptual functioning (e.g., vision) (230) could affect wheelchair-related confidence and fear of falling, which may explain the abundant use of the arc propulsion pattern. When using the arc pattern, people often keep their hands in contact with or very near the handrim, which could be a response to a fear of letting go of the handrim. The arc pattern was predominantly used during pre-testing of our RCT by 85% of our participants, which largely changed to a semi-circular pattern following training during the post-testing and retention testing; only one participant from the training group exclusively used the arc pattern during retention testing.

Variable practice was incorporated into the training because it is hypothesized to enhance learning through increasing exploration of the movement, which is thought to be more effective for schema development, based on Schmidt's Schema theory (102). Whether our 'variable practice' within the intervention actually resulted in increased spatial exploration is not known. Future research should conduct a detailed kinematic analysis to examine spatial exploration throughout practice and training protocols in older adults. The relationship between age and variability has not been well established, particularly among novel skill acquisition (44). One study examined differences in grip precision based on age and although they found similar performance between younger and older participants, older participants were variable when releasing their grip (208). Similarly variability plays an important role in other forms of locomotion, too much or too little step width variability has been indicative of gait pathologies or fall risk (231). Interestingly, larger kinematic spatial variability during the recovery phase of wheeling (83) and smaller force (handrim and shoulder) variability appear to be related to shoulder pain among MWUs (84, 85).

We did not observe improvements in wheeling biomechanics or GME following 60 minutes of uninstructed wheelchair propulsion practice; however, studies have observed improvements among younger participants in as little as 12 minutes (22, 138). Older adults could require a longer period of practice before improvements are observed, as 10 minutes of wheeling per session may not have been long enough; however, we did not want to elicit fatigue because it is known to alter wheeling biomechanics and propulsion pattern (87, 232). Importantly, not all studies that included younger adults identified improvements in wheeling biomechanics following wheeling practice (156), therefore, factors other than age are likely influencing the natural exploration of spatial environments.

IMPLICATIONS- Overall, 60 minutes of uninstructed practice did not lead to improvements in biomechanical or metabolic variables. Based on our findings, older able-bodied adults do not appear to explore their spatial environment, with unguided practice, to an extent which leads to changes in wheeling technique.

7.5 What is the evidence for wheelchair propulsion training in older adults?

Observational studies have compared wheeling biomechanics among older and younger adults (32) and have explored the impact of wheelchair configuration on wheeling biomechanics (29); however, to our knowledge no other studies have applied wheelchair propulsion training to older adults. The limited literature on older adults is likely the consequence of convenience sampling among university students and the challenges in recruiting older MWUs who experience many barriers to participation, including transportation (233). The use of nonprobability sampling may severely bias the generalizability of those results, limiting the scope and their validity to older populations. Our findings and their applicability to MWUs must be interpreted with caution considering that we did not specifically include MWUs in our study designs.

Although there are no other wheelchair propulsion training studies that have focused on older adults, two new wheelchair skills training interventions have shown promising results. A recent peer-led Wheelchair training Self-Efficacy Enhanced for Use (WheelSeeU) and a monitored manual wheelchair skills training home program identified positive feasibility indicators, including reported perceived benefits from the training among the older adult participants (234, 235). Self-efficacy impacts motivation, as well as attainment of knowledge (236), and therefore could have affected how our participants learned the motor skill of wheelchair propulsion. Importantly, wheelchair-related self-efficacy is significantly related to participation among older adults (39, 237).

Our study sought to examine one of the most foundational wheelchair skills from a biomechanical and physiological perspective, and although we focused on training wheelchair propulsion, there are many other factors that are important to consider for a new or experienced MWU, including self-efficacy and other wheelchair skills that are critical for independent mobility in the home and community (e.g., wheeling up an incline, wheeling over a rough surface). Other factors including the time of wheelchair acquisition (e.g., the age when the wheelchair is prescribed and acquired) and the disability necessitating wheelchair use (e.g., whether the condition is stable, progressive, or will improve over time) may affect one's motivation to learn the skill of wheelchair propulsion. Lastly, the attainment of an appropriate ultralight, well-fit manual wheelchair is essential for optimal biomechanics (3, 29, 160).

IMPLICATIONS- Based on the findings of our RCT and SSRD studies, wheelchair propulsion training improved push angle and push frequency among older able-bodied adults. Future wheelchair propulsion research focusing on older adults is needed to corroborate our findings and extend these to people with various disabilities.

7.6 Strengths and limitations

Our older adult population was heterogeneous with respect to age, ability, fitness, strength, and anecdotally varied in confidence, which can be considered as both a strength and weakness. The fact that we observed effects of training in a diverse sample provides more validity to our findings; however, there may have been non-responders who could have been missed. We selected individuals 50 years of age and older to represent older adults, rather than the age of 60 or 65 years, which may have made our population more diverse.

A major strength of this study was its novelty with respect to studying wheelchair propulsion in detail in older adults. Specifically, we examined the impact of our training from multiple perspectives, including wheelchair propulsion biomechanics (e.g., kinetics, kinematics, and spatial-temporal variables), physiology (e.g., energy expenditure, power output, GME, and effectiveness), and intercycle variability (e.g., COV). We aimed to consider the 'big picture'; however, there are several other factors that we were unable to appropriately evaluate, including wheelchair-related confidence and the translation of our training to other wheelchair skills. We had intended to evaluate the impact of our training on wheelchair skills, but inconsistent wheeling exposure may have impacted wheeling performance in such a way that we would not be able to discern the effects of training. For example, if one participant had high confidence and wanted to try completing the majority of skills, they may have improved based on the exposure to the wheelchair skills test rather than our training protocol. Therefore, we aimed to keep our training as standardized as possible.

We observed clear changes in wheeling patterns among participants in the training group of our RCT, but in many cases not in individual biomechanical variables. We have noted in an earlier study that the sum of the parts (i.e., wheeling pattern) may demonstrate observable change; however, the individual biomechanical variables may not (2). Given the complex relationship between variables, the lack of sensitivity in the methods of testing required to detect small degrees of change, and the large amount of variability observed while learning a motor task, our study may simply be underpowered to detect such effects. Recent research has identified that there are often responders and non-responders (i.e., improvers and non-improvers) to a given practice or training protocol (128, 138), identified based on a specific value or a percent change. Past wheelchair propulsion research has identified responders as those that increase their GME by 10% or more (128). Due to our small sample size, we did not do a sub-analysis to examine responders versus non-responders to either the training intervention or practice. Alternatively, our training may not be effective for modulating certain variables.

A limitation of the study, with respect to its applicability of the results, is the cost. The training protocol that we used could be costly if applied in a real-world setting because it requires an expensive wide-belt treadmill and only enables one participant to be trained at a time. Furthermore, the cost benefit of the observed changes in biomechanics is not known. Theoretically, the observed decrease in repetition of wheelchair propulsion pushes following training would help to decrease over-use injuries; however, there have been no longitudinal studies to support this. If fewer sessions are required, the cost-benefit of training could be improved. Additionally, the training could be adapted to an over-ground group setting so that costly equipment is not required. We opted to use the treadmill in the laboratory setting so that we could standardize our training and allow for measurement of biomechanical and metabolic variables. The specific components of our training protocol that resulted in improved push angle and push frequency among older adults is unknown. Therefore, our training protocol may be longer than required to elicit the observed changes in biomechanical variables or may have unnecessary components (e.g., perhaps the mental imagery used during the break did not have an added effect). Based on the trends of the study including the SSRD, only 2-4 training sessions appeared to be needed to elicit changes in biomechanical variables; however, these findings may not be generalizable.

7.7 Future directions

Ideally, researchers should strive to evaluate the effect of wheelchair propulsion training programs on new or experienced older adult MWUs, as opposed to able-bodied participants. Based on our systematic review, very few intervention studies have included older adults, and even fewer have included older adults with physical disabilities. This population is at risk of being inactive in physical and leisure activities (49) and relatedly having low wheelchair-related self-efficacy (39, 237). The applicability of past studies to this population is unknown. We did not observe significant improvements in wheelchair propulsion biomechanics following 60 minutes of uninstructed practice; however, younger able-bodied cohorts have improved in as little as 12 minutes. This finding may indicate that older adults need more practice time or specific instruction to improve. As such, future training programs for older adults may need to be more personalized, especially in the context of adaptations for physical disabilities.

We provided a standardized intervention that personalized speed and feedback; however, we maintained the number and length of sessions. Our heterogeneous participant population may have benefitted from individualized training; for example, some participants visually appeared to improve after two sessions while others may have benefitted from additional sessions. Furthermore, some participants reported very low perceived exertion (e.g., 8- very light) while others reported much higher perceived exertion (e.g., 15- hard) for the testing sessions. This variation in perceived exertion may be a result of differences in self-selected speed as well as differences in fitness level and comfort with the wheeling task. To ensure the training was as accessible as possible, we opted to use self-selected speeds; however, the selected speeds were much lower than what is typically observed in the literature. The speeds used in the RCT and SSRD would not be considered functional speeds. Consequently, the low self-selected speeds resulted in low mean power outputs and thus low GME. Therefore, the intensity of training, may have been too low to allow for detectable change relative to variability.

Many studies that have focused on younger able-bodied adults have standardized speed and PO because biomechanical and physiological variables are dependent on these factors; however, our sample was too heterogeneous to have standardized these variables. There were no differences in self-selected speed or mean or relative PO across groups; therefore, not standardizing PO and speed is unlikely to have had an effect. Although all participants in the training group showed a similar response to training, future work should look more closely to determine if there are older adults who modify their wheeling technique with unguided practice through discovery learning similar to the findings of Vegter et al. (138).

Although the wheelchair propulsion training positively affected wheeling biomechanics of naïve wheelchair users, the impact of this training on experienced MWUs is unknown. Future research should examine the impact of the training on those with existing wheelchair propulsion habits so that re-learning can be established through changes in technique. Experienced MWUs with existing habits may require more or different training to modify their propulsion technique.

The training may not be suitable for all clinical populations of older adult wheelchair users. For example, individuals with Alzheimer's disease have been shown to benefit more from constant practice (238) rather than variable practice, and explicit information may interfere with motor learning following stroke (239). Specific training considerations should be taken for various clinical populations. Therefore, the importance of individualized training, especially among populations with conditions that impact attentional networks, is evident. To better inform future training protocols, qualitative methods should be applied to provide greater understanding of MWUs' experiences and perspectives of training.

The cost effectiveness of a wheelchair propulsion training program for older adults is not known. Although the clinical practice guidelines advocate for specific biomechanical patterns to help reduce repetition (e.g., longer, less frequent, smoother pushes) (3), the long-term benefits have not been thoroughly studied. Improvements in biomechanical variables may come at the expense of increased work per push; however, considering that we did not observe a corresponding increase in energy expenditure, the overall net energy requirements did not appear to change. As such, if the training helps to reduce overuse injuries, it could have long-term implications on healthcare utilization.

Lastly, our training incorporated many different principles of motor learning; therefore, the select components or the interaction of select components that resulted in change is unknown. The training was developed such that it would be effective on a heterogenous population; however, understanding the 'active ingredient(s)' is essential for demising a more cost-effective approach. Future research should systematically examine how older adults respond to training involving different motor learning principles. Furthermore, Dynamic Systems Theory may provide a useful framework when considering the process of self-organization as it applies to learning wheelchair propulsion. The framework may help to understand the role of variability, across the time course of initial skill acquisition through long-term experience, within learning and adapting the motor skill.

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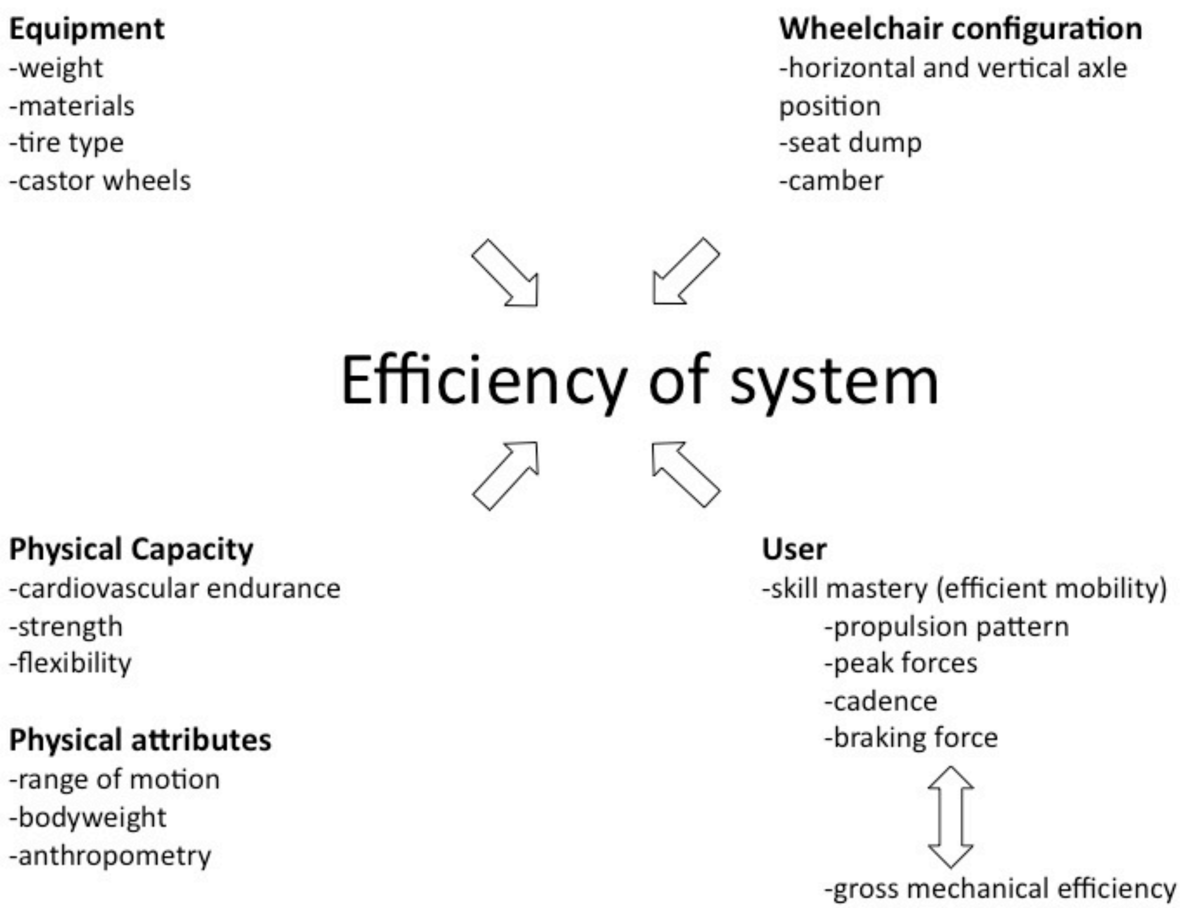
Appendices

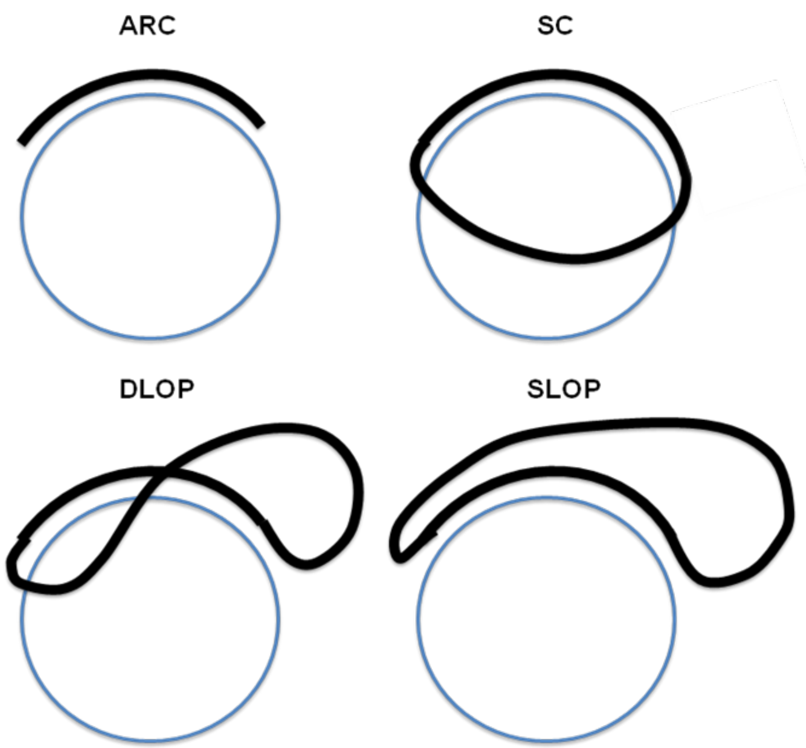
Appendix A: Factors that influence wheelchair propulsion



Appendix B: Classification of wheelchair propulsion patterns

There are four commonly defined wheeling patterns:

1. *Arcing* (ARC): The ARC pattern is defined by the hands following the path of the handrim (81).
2. *Semi-circular* (SC): The SC pattern is defined by the hands falling below the path of the handrim (81).
3. *Double looping over propulsion* (DLOP): The DLOP pattern is defined by the hands initially rising above the handrim and then dropping below the handrim (17).
4. *Single looping over propulsion* (SLOP): The SLOP pattern is defined by the hands rising above the path of the handrim (82).



Appendix C: Important calculations

Total force = $(\sqrt{(Fx^2+Fy^2+Fz^2)}$

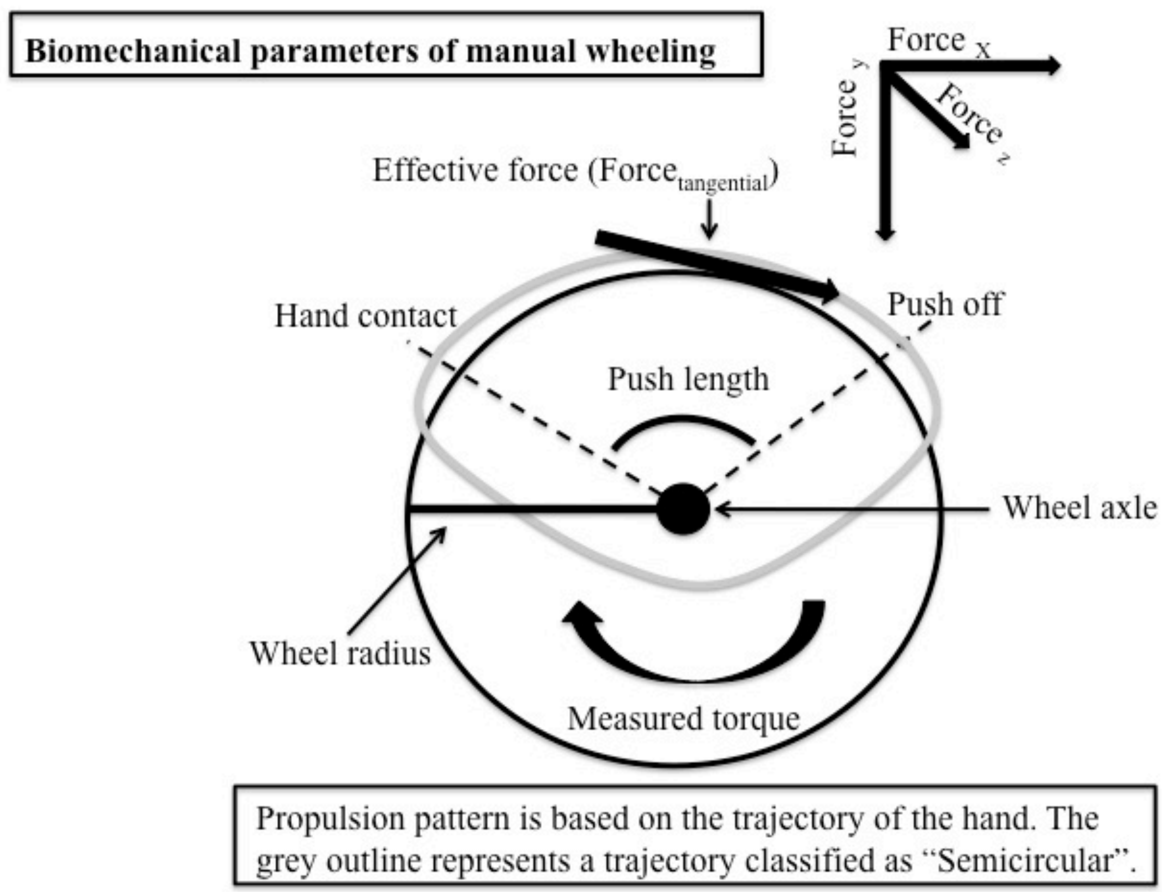
Mechanical Efficiency = $Force_{tangential}^2/Force_{total}^2$

Power output (calculated with SmartWheel data) = Measured torque* wheel velocity/ wheel radius

Work per cycle = Mean power output/ frequency

Gross mechanical efficiency = (Mean power output/ Energy Expenditure)*100

Intercycle variability = (coefficient of variation) =|SD/mean|*100



Appendix D: PRISMA checklist for systematic review

Section/topic	#	Checklist item	Reported on page #
TITLE			
Title	1	Identify the report as a systematic review, meta-analysis, or both.	27
ABSTRACT			
Structured summary	2	Provide a structured summary including, as applicable: background; objectives; data sources; study eligibility criteria, participants, and interventions; study appraisal and synthesis methods; results; limitations; conclusions and implications of key findings; systematic review registration number.	
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of what is already known.	27-30
Objectives	4	Provide an explicit statement of questions being addressed with reference to participants, interventions, comparisons, outcomes, and study design (PICOS).	30
METHODS			
Protocol and registration	5	Indicate if a review protocol exists, if and where it can be accessed (e.g., Web address), and, if available, provide registration information including registration number.	30
Eligibility criteria	6	Specify study characteristics (e.g., PICOS, length of follow-up) and report characteristics (e.g., years considered, language, publication status) used as criteria for eligibility, giving rationale.	31
Information sources	7	Describe all information sources (e.g., databases with dates of coverage, contact with study authors to identify additional studies) in the search and date last searched.	31-32
Search	8	Present full electronic search strategy for at least one database, including any limits used, such that it could be repeated.	30-31
Study selection	9	State the process for selecting studies (i.e., screening, eligibility, included in systematic review, and, if applicable, included in the meta-analysis).	31
Data collection process	10	Describe method of data extraction from reports (e.g., piloted forms, independently, in duplicate) and any processes for obtaining and confirming data from investigators.	32
Data items	11	List and define all variables for which data were sought (e.g., PICOS, funding sources) and any assumptions and simplifications made.	30-31

Risk of bias in individual studies	12	Describe methods used for assessing risk of bias of individual studies (including specification of whether this was done at the study or outcome level), and how this information is to be used in any data synthesis.	33
Summary measures	13	State the principal summary measures (e.g., risk ratio, difference in means).	33
Synthesis of results	14	Describe the methods of handling data and combining results of studies, if done, including measures of consistency (e.g., I^2) for each meta-analysis.	33

Section/topic	#	Checklist item	Reported on page #
Risk of bias across studies	15	Specify any assessment of risk of bias that may affect the cumulative evidence (e.g., publication bias, selective reporting within studies).	33
Additional analyses	16	Describe methods of additional analyses (e.g., sensitivity or subgroup analyses, meta-regression), if done, indicating which were pre-specified.	31-34
RESULTS			
Study selection	17	Give numbers of studies screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally with a flow diagram.	Fig 2.1, p 35
Study characteristics	18	For each study, present characteristics for which data were extracted (e.g., study size, PICOS, follow-up period) and provide the citations.	Table 2.1
Risk of bias within studies	19	Present data on risk of bias of each study and, if available, any outcome level assessment (see item 12). *PEDro*	Table 2.1
Results of individual studies	20	For all outcomes considered (benefits or harms), present, for each study: (a) simple summary data for each intervention group (b) effect estimates and confidence intervals, ideally with a forest plot.	Figs 2.2,2.3,2.4
Synthesis of results	21	Present results of each meta-analysis done, including confidence intervals and measures of consistency.	53-56
Risk of bias across studies	22	Present results of any assessment of risk of bias across studies (see Item 15).	53-56
Additional analysis	23	Give results of additional analyses, if done (e.g., sensitivity or subgroup analyses, meta-regression [see Item 16]).	NA
DISCUSSION			

Summary of evidence	24	Summarize the main findings including the strength of evidence for each main outcome; consider their relevance to key groups (e.g., healthcare providers, users, and policy makers).	60-64
Limitations	25	Discuss limitations at study and outcome level (e.g., risk of bias), and at review-level (e.g., incomplete retrieval of identified research, reporting bias).	64
Conclusions	26	Provide a general interpretation of the results in the context of other evidence, and implications for future research.	66-67
FUNDING			
Funding	27	Describe sources of funding for the systematic review and other support (e.g., supply of data); role of funders for the systematic review. *There is no funding for this systematic review*	

From: Moher D, Liberati A, Tetzlaff J, Altman DG, The PRISMA Group (2009). Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. PLoS Med 6(6): e1000097. doi:10.1371/journal.pmed1000097

For more information, visit: **www.prisma-statement.org**.

Appendix E: Subject headings used for each database

MEDLINE	EMBASE	PsychINFO	ERIC	SportDiscus	CINAHL
Wheelchairs	Wheelchair	Mobility aids	Assistive technology	Wheelchairs	Wheelchairs
Teaching	Teaching	Teaching	-	Teaching	Teaching
Learning	Learning	Learning	Learning	Psychology of learning	Learning
Retention (Psychology)	Skill retention	Retention	Retention (Psychology)	Memory	Skill retention
Transfer (Psychology)	Transfer (Psychology)	-	Transfer of learning	Transfer of training	Transfer (Psychology)
Motor skills	Motor performance	Motor skills	Psychomotor skills	Motor ability	Motor skills

Appendix F: Example search strategy from EMBASE (Ovid)

1. (wheelchair* adj4 (instruct* or practice* or train* or learn*)).mp. [mp=title, abstract, subject headings, heading word, drug trade name, original title, device manufacturer, drug manufacturer, device trade name, keyword]	Key words
2. Wheelchair/ 3. Teaching/ 4. Learning/ 5. Skill retention/ 6. Transfer (Psychology)/ 7. Motor performance/ 8. or/3-7 9. 8 and 2 [wheelchairs and ML-related words] 10. 9 or 1 Subject headings: 2–7	

Abbreviations: adj4: adjacent within 4 words; mp: multi-purpose; ML: motor learning

Appendix G: PEDro criterion assessment and scores for RCTs and non-RCTs (*n*=13)

PEDro Criterion (criterion met = 1, criterion not met = 0)											
Study	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**TOTAL /10**
de Groot *et al.* 2002[1]	1	0	0	1	1	1	1	0	0	1	6
de Groot *et al.* 2002[2]	1	0	1	0	0	0	1	1	1	1	6
de Groot *et al.* 2005	1	0	0	0	0	0	0	1	1	1	4
de Groot *et al.* 2008	1	0	0	0	0	0	1	1	1	1	5
Goosey-Tolfrey *et al.* 2011	0	0	1	0	0	0	1	1	1	0	4
Lenton *et al.* 2010	0	0	1	0	0	0	1	1	1	1	5
Leving *et al.* 2015	0	0	1	0	0	0	1	1	1	1	5
Leving *et al.* 2016	0	0	1	0	0	0	1	1	1	1	5
Rice *et al.* 2013	1	0	1	0	0	0	0	0	1	1	4
Rice *et al.* 2014	1	0	1	0	0	1	0	0	1	1	5
van der Scheer *et al.* 2015	1	1	1	0	0	0	0	1	1	1	6
Yao *et al.* 2009	1	0	1	0	0	0	0	0	1	1	4
Yao *et al.* 2012	1	0	1	0	0	0	0	0	1	1	4

Abbreviations: PEDro: physiotherapy evidence database; RCT: randomized controlled trial; non-RCT: non-randomized controlled trial

Appendix H: CONSORT checklist

CONSORT 2010 checklist of information to include when reporting a randomised trial*

Section/Topic	Item No	Checklist item	Reported on page No
Title and abstract			
	1a	Identification as a randomised trial in the title	68
	1b	Structured summary of trial design, methods, results, and conclusions (for specific guidance see CONSORT for abstracts)	
Introduction			
Background and objectives	2a	Scientific background and explanation of rationale	68-71
	2b	Specific objectives or hypotheses	70-71
Methods			
Trial design	3a	Description of trial design (such as parallel, factorial) including allocation ratio	71
	3b	Important changes to methods after trial commencement (such as eligibility criteria), with reasons	-
Participants	4a	Eligibility criteria for participants	71
	4b	Settings and locations where the data were collected	61
Interventions	5	The interventions for each group with sufficient details to allow replication, including how and when they were actually administered	72
Outcomes	6a	Completely defined pre-specified primary and secondary outcome measures, including how and when they were assessed	73
	6b	Any changes to trial outcomes after the trial commenced, with reasons	-
Sample size	7a	How sample size was determined	74
	7b	When applicable, explanation of any interim analyses and stopping guidelines	-
Randomisation:			
Sequence generation	8a	Method used to generate the random allocation sequence	74-75
	8b	Type of randomisation; details of any restriction (such as blocking and block size)	74-75
Allocation concealment mechanism	9	Mechanism used to implement the random allocation sequence (such as sequentially numbered containers), describing any steps taken to conceal the sequence until interventions were assigned	74-75
Implementation	10	Who generated the random allocation sequence, who enrolled participants, and who assigned participants to interventions	74-75
Blinding	11a	If done, who was blinded after assignment to interventions (for example, participants, care providers, those assessing outcomes) and how	75

	11b	If relevant, description of the similarity of interventions	71
Statistical methods	12a	Statistical methods used to compare groups for primary and secondary outcomes	77-79
	12b	Methods for additional analyses, such as subgroup analyses and adjusted analyses	77
Results			
Participant flow (a diagram is strongly recommended)	13a	For each group, the numbers of participants who were randomly assigned, received intended treatment, and were analysed for the primary outcome	79-82
	13b	For each group, losses and exclusions after randomisation, together with reasons	81-82
Recruitment	14a	Dates defining the periods of recruitment and follow-up	81-82
	14b	Why the trial ended or was stopped	-
Baseline data	15	A table showing baseline demographic and clinical characteristics for each group	83
Numbers analysed	16	For each group, number of participants (denominator) included in each analysis and whether the analysis was by original assigned groups	83-85
Outcomes and estimation	17a	For each primary and secondary outcome, results for each group, and the estimated effect size and its precision (such as 95% confidence interval)	84-88
	17b	For binary outcomes, presentation of both absolute and relative effect sizes is recommended	-
Ancillary analyses	18	Results of any other analyses performed, including subgroup analyses and adjusted analyses, distinguishing pre-specified from exploratory	-
Harms	19	All important harms or unintended effects in each group (for specific guidance see CONSORT for harms)	-
Discussion			
Limitations	20	Trial limitations, addressing sources of potential bias, imprecision, and, if relevant, multiplicity of analyses	91-92
Generalisability	21	Generalisability (external validity, applicability) of the trial findings	89-91
Interpretation	22	Interpretation consistent with results, balancing benefits and harms, and considering other relevant evidence	89-91
Other information			
Registration	23	Registration number and name of trial registry	
Protocol	24	Where the full trial protocol can be accessed, if available	71
Funding	25	Sources of funding and other support (such as supply of drugs), role of funders	-

*We strongly recommend reading this statement in conjunction with the CONSORT 2010 Explanation and Elaboration for important clarifications on all the items. If relevant, we also recommend reading CONSORT extensions for cluster randomised trials, non-inferiority and equivalence trials, non-pharmacological treatments, herbal interventions, and pragmatic trials. Additional extensions are forthcoming: for those and for up to date references relevant to this checklist, see www.consort-statement.org.

Appendix I: Physical Activity Readiness Questionnaire + (PAR-Q+)

CSEP approved Sept 12 2011 version

PAR-Q+

The Physical Activity Readiness Questionnaire for Everyone

Regular physical activity is fun and healthy, and more people should become more physically active every day of the week. Being more physically active is very safe for MOST people. This questionnaire will tell you whether it is necessary for you to seek further advice from your doctor OR a qualified exercise professional before becoming more physically active.

SECTION 1 - GENERAL HEALTH

	Please read the 7 questions below carefully and answer each one honestly: check YES or NO.	YES	NO
1.	Has your doctor ever said that you have a heart condition OR high blood pressure?	☐	☐
2.	Do you feel pain in your chest at rest, during your daily activities of living, OR when you do physical activity?	☐	☐
3.	Do you lose balance because of dizziness OR have you lost consciousness in the last 12 months? Please answer NO if your dizziness was associated with over-breathing (including during vigorous exercise).	☐	☐
4.	Have you ever been diagnosed with another chronic medical condition (other than heart disease or high blood pressure)?	☐	☐
5.	Are you currently taking prescribed medications for a chronic medical condition?	☐	☐
6.	Do you have a bone or joint problem that could be made worse by becoming more physically active? Please answer NO if you had a joint problem in the past, but it does not limit your current ability to be physically active. For example, knee, ankle, shoulder or other.	☐	☐
7.	Has your doctor ever said that you should only do medically supervised physical activity?	☐	☐

If you answered NO to all of the questions above, you are cleared for physical activity.

Go to Section 3 to sign the form. You do not need to complete Section 2.

- Start becoming much more physically active – start slowly and build up gradually.
- Follow the Canadian Physical Activity Guidelines for your age (www.csep.ca/guidelines).
- You may take part in a health and fitness appraisal.
- If you have any further questions, contact a qualified exercise professional such as a CSEP Certified Exercise Physiologist® (CSEP-CEP) or CSEP Certified Personal Trainer® (CSEP-CPT).
- If you are over the age of 45 yrs. and NOT accustomed to regular vigorous physical activity, please consult a qualified exercise professional (CSEP-CEP) before engaging in maximal effort exercise.

If you answered YES to one or more of the questions above, please GO TO SECTION 2.

Delay becoming more active if:

- You are not feeling well because of a temporary illness such as a cold or fever – wait until you feel better
- You are pregnant – talk to your health care practitioner, your physician, a qualified exercise professional, and/or complete the PARmed-X for Pregnancy before becoming more physically active OR
- Your health changes – please answer the questions on Section 2 of this document and/or talk to your doctor or qualified exercise professional (CSEP-CEP or CSEP-CPT) before continuing with any physical activity programme.

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SECTION 2 - CHRONIC MEDICAL CONDITIONS

No.	Please read the questions below carefully and answer each one honestly: check YES or NO.	YES	NO
1.	Do you have Arthritis, Osteoporosis, or Back Problems?	☐ If yes, answer questions 1a-1c	☐ If no, go to question 2
1a.	Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer NO if you are not currently taking medications or other treatments)	☐	☐
1b.	Do you have joint problems causing pain, a recent fracture or fracture caused by osteoporosis or cancer, displaced vertebra (e.g., spondylolisthesis), and/or spondylolysis/pars defect (a crack in the bony ring on the back of the spinal column)?	☐	☐
1c.	Have you had steroid injections or taken steroid tablets regularly for more than 3 months?	☐	☐
2.	Do you have Cancer of any kind?	☐ If yes, answer questions 2a-2b	☐ If no, go to question 3
2a.	Does your cancer diagnosis include any of the following types: lung/bronchogenic, multiple myeloma (cancer of plasma cells), head, and neck?	☐	☐
2b.	Are you currently receiving cancer therapy (such as chemotherapy or radiotherapy)?	☐	☐
3.	Do you have Heart Disease or Cardiovascular Disease? This includes Coronary Artery Disease, High Blood Pressure, Heart Failure, Diagnosed Abnormality of Heart Rhythm	☐ If yes, answer questions 3a-3e	☐ If no, go to question 4
3a.	Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer NO if you are not currently taking medications or other treatments)	☐	☐
3b.	Do you have an irregular heart beat that requires medical management? (e.g. atrial brillation, premature ventricular contraction)	☐	☐
3c.	Do you have chronic heart failure?	☐	☐
3d.	Do you have a resting blood pressure equal to or greater than 160/90 mmHg with or without medication? (Answer YES if you do not know your resting blood pressure)	☐	☐
3e.	Do you have diagnosed coronary artery (cardiovascular) disease and have not participated in regular physical activity in the last 2 months?	☐	☐
4.	Do you have any Metabolic Conditions? This includes Type 1 Diabetes, Type 2 Diabetes, Pre-Diabetes	☐ If yes, answer questions 4a-4c	☐ If no, go to question 5
4a.	Is your blood sugar often above 13.0 mmol/L? (Answer YES if you are not sure)	☐	☐
4b.	Do you have any signs or symptoms of diabetes complications such as heart or vascular disease and/or complications affecting your eyes, kidneys, and the sensation in your toes and feet?	☐	☐
4c.	Do you have other metabolic conditions (such as thyroid disorders, pregnancy-related diabetes, chronic kidney disease, liver problems)?	☐	☐
5.	Do you have any Mental Health Problems or Learning Difficulties? This includes Alzheimer's, Dementia, Depression, Anxiety Disorder, Eating Disorder, Psychotic Disorder, Intellectual Disability, Down Syndrome)	☐ If yes, answer questions 5a-5b	☐ If no, go to question 6
5a.	Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer NO if you are not currently taking medications or other treatments)	☐	☐
5b.	Do you also have back problems affecting nerves or muscles?	☐	☐

	Please read the questions below carefully and answer each one honestly: check YES or NO.		YES	NO
6.		Do you have a Respiratory Disease? This includes Chronic Obstructive Pulmonary Disease, Asthma, Pulmonary High Blood Pressure	☐ If yes, answer questions 6a-6d	☐ If no, go to question 7
	6a.	Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer NO if you are not currently taking medications or other treatments)	☐	☐
	6b.	Has your doctor ever said your blood oxygen level is low at rest or during exercise and/or that you require supplemental oxygen therapy?	☐	☐
	6c.	If asthmatic, do you currently have symptoms of chest tightness, wheezing, laboured breathing, consistent cough (more than 2 days/week), or have you used your rescue medication more than twice in the last week?	☐	☐
	6d.	Has your doctor ever said you have high blood pressure in the blood vessels of your lungs?	☐	☐
7.		Do you have a Spinal Cord Injury? This includes Tetraplegia and Paraplegia	☐ If yes, answer questions 7a-7c	☐ If no, go to question 8
	7a.	Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer NO if you are not currently taking medications or other treatments)	☐	☐
	7b.	Do you commonly exhibit low resting blood pressure significant enough to cause dizziness, light-headedness, and/or fainting?	☐	☐
	7c.	Has your physician indicated that you exhibit sudden bouts of high blood pressure (known as Autonomic Dysreflexia)?	☐	☐
8.		Have you had a Stroke? This includes Transient Ischemic Attack (TIA) or Cerebrovascular Event	☐ If yes, answer questions 8a-c	☐ If no, go to question 9
	8a.	Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer NO if you are not currently taking medications or other treatments)	☐	☐
	8b.	Do you have any impairment in walking or mobility?	☐	☐
	8c.	Have you experienced a stroke or impairment in nerves or muscles in the past 6 months?	☐	☐
9.		Do you have any other medical condition not listed above or do you live with two chronic conditions?	☐ If yes, answer questions 9a-c	☐ If no, read the advice on page 4
	9a.	Have you experienced a blackout, fainted, or lost consciousness as a result of a head injury within the last 12 months OR have you had a diagnosed concussion within the last 12 months?	☐	☐
	9b.	Do you have a medical condition that is not listed (such as epilepsy, neurological conditions, kidney problems)?	☐	☐
	9c.	Do you currently live with two chronic conditions?	☐	☐

Please proceed to Page 4 for recommendations for your current medical condition and sign this document.

PAR-Q+

If you answered NO to all of the follow-up questions about your medical condition, you are ready to become more physically active:

- It is advised that you consult a qualified exercise professional (e.g., a CSEP-CEP or CSEP-CPT) to help you develop a safe and effective physical activity plan to meet your health needs.
- You are encouraged to start slowly and build up gradually – 20-60 min. of low- to moderate-intensity exercise, 3-5 days per week including aerobic and muscle strengthening exercises.
- As you progress, you should aim to accumulate 150 minutes or more of moderate-intensity physical activity per week.
- If you are over the age of 45 yrs. and NOT accustomed to regular vigorous physical activity, please consult a qualified exercise professional (CSEP-CEP) before engaging in maximal effort exercise.

If you answered YES to one or more of the follow-up questions about your medical condition:

- You should seek further information from a licensed health care professional before becoming more physically active or engaging in a fitness appraisal and/or visit a or qualified exercise professional (CSEP-CEP) for further information.

Delay becoming more active if:

- You are not feeling well because of a temporary illness such as a cold or fever – wait until you feel better
- You are pregnant - talk to your health care practitioner, your physician, a qualified exercise profesional, and/or complete the PARmed-X for Pregnancy before becoming more physically active OR
- Your health changes - please talk to your doctor or qualified exercise professional (CSEP-CEP) before continuing with any physical activity programme.

SECTION 3 - DECLARATION

- You are encouraged to photocopy the PAR-Q+. You must use the entire questionnaire and NO changes are permitted.
- The Canadian Society for Exercise Physiology, the PAR-Q+ Collaboration, and their agents assume no liability for persons who undertake physical activity. If in doubt after completing the questionnaire, consult your doctor prior to physical activity.
- If you are less than the legal age required for consent or require the assent of a care provider, your parent, guardian or care provider must also sign this form.
- Please read and sign the declaration below:

I, the undersigned, have read, understood to my full satisfaction and completed this questionnaire. I acknowledge that this physical activity clearance is valid for a maximum of 12 months from the date it is completed and becomes invalid if my condition changes. I also acknowledge that a Trustee (such as my employer, community/fitness centre, health care provider, or other designate) may retain a copy of this form for their records. In these instances, the Trustee will be required to adhere to local, national, and international guidelines regarding the storage of personal health information ensuring that they maintain the privacy of the information and do not misuse or wrongfully disclose such information.

NAME ______________________________________ DATE ______________________________

SIGNATURE ___________________________WITNESS ____________________________________

SIGNATURE OF PARENT/GUARDIAN/CARE PROVIDER ____

For more information, please contact:
Canadian Society for Exercise Physiology
www.csep.ca

KEY REFERENCES

1. Jamnik VJ, Warburton DER, Makarski J, McKenzie DC, Shephard RJ, Stone J, and Gledhill N. Enhancing the eectiveness of clearance for physical activity participation; background and overall process. APNM 36(S1):S3-S13, 2011.
2. Warburton DER, Gledhill N, Jamnik VK, Bredin SSD, McKenzie DC, Stone J, Charlesworth S, and Shephard RJ. Evidence-based risk assessment and recommendations for physical activity clearance; Consensus Document. APNM 36(S1):S266-s298, 2011.

The PAR-Q+ was created using the evidence-based AGREE process (1) by the PAR-Q+Collaboration chaired by Dr. Darren E. R. Warburton with Dr. Norman Gledhill, Dr. Veronica Jamnik, and Dr. Donald C. McKenzie (2). Production of this document has been made possible through financial contributions from the Public Health Agency of Canada and the BC Ministry of Health Services. The views expressed herein do not necessarily represent the views of the Public Health Agency of Canada or BC Ministry of Health Services.

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THE GOLD STANDARD IN EXERCISE SCIENCE AND PERSONAL TRAINING

Appendix J: Folstein mini mental state exam (MMSE)

Date: ___________________ **Participant No: ___________**

Score 1 for every correct answer: You do not have to answer any question that you do not feel comfortable answering.

1. What year is it? _____

2. What season are we in? _____

3. What month are we in? _____

4. What is today's date? _____

5. What day of the week is it? _____

6. What country are we in? _____

7. What province are we in? _____

8. What city are we in? _____

9. What hospital are we in? _____

10. What floor of the hospital are we on? _____

Name three objects ("Ball," "Car," "Man"). Take a second to pronounce each word. Then ask the patient to repeat all 3 words. Take into account only correct answers given on the first try. Repeat these steps until the subject learns all the words.

11. Ball? _____

12. Car? _____

13. Man? _____

Either "please spell the word WORLD and now spell it backwards" or "Please count from 100 subtracting 7 every time"

14. "D" or 93 _____

15. "L" or 86 _____

16. "R" or 79 _____

17. “O” or 72 ______

18. “W” or 65 ______

What were the 3 words I asked you to remember earlier?

19. Ball? ______

20. Car? ______

21. Man? ______

Show the subject a pen and ask: “Could you name this object?”

22. Pen. ______

Show the subject your watch and ask: “Could you name this object?”

23. Watch ______

Listen and repeat after me:

24. “No ifs, ands, or buts.” ______

Put a sheet of paper on the desk and show it while saying: “Listen carefully and do as I say.”

25. Take the sheet with your left/right (unaffected) hand. ______

26. Fold it in half. ______

27. Put in on the floor. ______

Show the subject the visual instruction page directing him/her to “CLOSE YOUR EYES” and say:

28. Do what is written on this page. ______

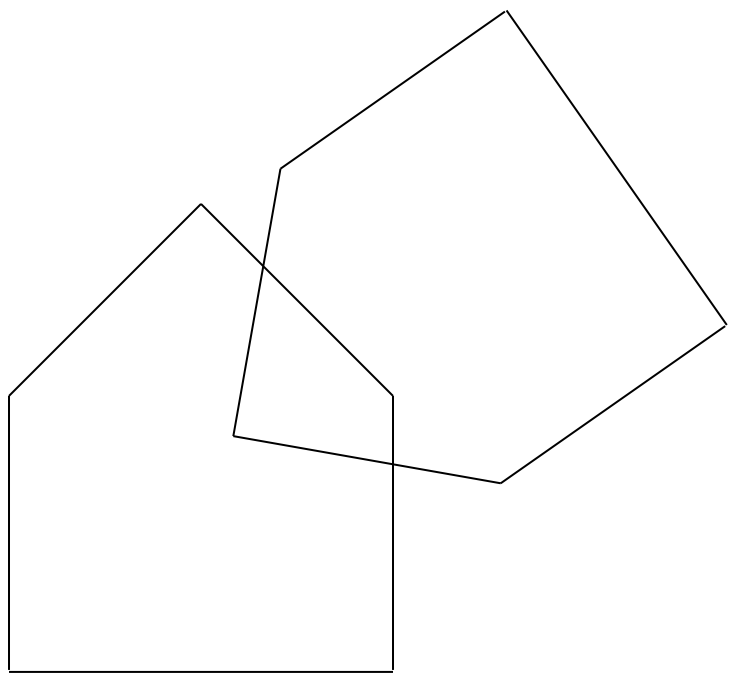
Give the subject a blank sheet and a pen and ask:

29. Write or say a complete sentence of your choice. ______

Give the patient the geometric design page and ask:

30. Could you please copy this drawing? ______

Total Score: (/30) _____



Appendix K: Training manual for RCT

Guidelines for wheelchair propulsion training for older adults

INTRODUCTION **Participant code: ___________**

Who: My name is _______ and I will be seeing you for the next 3 weeks of this program.

Where and When: We will meet at the Human Mobility Lab on the 3rd floor of the Blusson Spinal Cord Centre for the training sessions.

Why: The goal of this program is to determine the best methods for providing wheelchair propulsion training for aging adults. Although the participants in this study are not wheelchair users, you will simulate a new wheelchair user in terms of your current skill level.

What: There will be a total of six 15-minute sessions in total. You are asked to attend all sessions. The sessions will involve wheeling for two 5-minute trials with a 5-minute rest break. However, the format of each session will change over the course of the training. Each of the sessions will involve techniques to help you learn how to propel a wheelchair effectively.

<u>Session Dates:</u>

1.	4.
2.	5.
3.	6.

PREPARATION FOR TRAINING:

-Have wheelchair configured based on baseline assessment.
-Ensure tires are pumped to 100psi
-Attach SmartWheel to the participant's dominant side and inertia-matched dummy wheel on their non-dominant side.

GLOSSARY:

Braking force: force applied in the opposite direction of the movement that causes the wheel to slow down.

Knowledge of performance: augmented feedback related to the nature of the movement produced (Schmidt and Lee, 2005, p. 465).

Mental imagery: the process of imagining yourself performing a movement either from the perspective of the person performing the movement or from someone watching the movement being performed.

Smooth wheeling: application of the hand to the wheel during the push that provides force in a forward direction and reduced 'braking' force.

Wheeling pattern: the trajectory of the hand and the shape it best represents. Participants should be encouraged to use a circular wheeling pattern to reduce abrupt accelerations and decelerations.

GENERAL RATIONALE FOR TRAINING:

This training program aims to incorporate several principles and theories that are foundational in the field of motor learning. One of the main objectives is to provide variable practice through changes in the structure of each session by modifying speed or generally the focus of attention. The other main objective is to provide sporadic feedback intermittently on several aspects of wheelchair propulsion. Variable practice and sporadic feedback are generally thought to be the most important principles of motor learning. Specifically, extrinsic or augmented feedback (e.g., the effect of a push rather than the individual's movement) is important for motor learning with respect to the individual's knowledge of performance. Other theories incorporated into this training program include mental imagery, applying an external focus of attention, as well as improving the declarative knowledge of the naïve wheelchair user.

The speed selected for baseline testing will be referred to as the 'self-selected speed'.

TRAINING:

Self-selected speed used: ___________________________________

Goal Week 1: Develop a declarative knowledge of the wheelchair propulsion skill (Anderson 1983). Allow participants to explore movement. Provide feedback that encourages participants to focus on intrinsic feedback they are receiving (e.g., tell participants to focus on how the handrim feels on their hand) and begin to introduce extrinsic feedback (e.g., how the chair responds to propulsion).

Session 1.

00:00-00:05-

<u>Wheeling Block 1:</u> The trainer will instruct participants to wheel at their self-selected speed and will provide feedback after minute 1 regarding improving smoothness and propulsion pattern. The trainer will focus on the propulsion pattern during minutes 2 and 3 and provide feedback intermittently during that time. The trainer will encourage the participant to match the speed of their hand with the handrim to minimize braking forces during minutes 4 and 5. The trainer will provide intermittent feedback over the last two minutes.

00:05-00:10-

<u>Rest break:</u> The trainer will provide a general description of manual wheeling. Videos exemplifying positive wheeling characteristics (e.g., smooth pushes, longer push length, circular wheeling patterns) and negative wheeling characteristics (e.g., large decelerations or jerky movements) will be reviewed. The trainers will use this time to discuss the various propulsion patterns. The trainer should make this interactive and ask the participant why an example of efficient wheeling might be better than an example of poor wheeling to ensure understanding. The trainer will describe the negative consequences of braking forces during wheeling.

00:10-00:15-

<u>Wheeling Block 2:</u> Trainers will instruct participants to wheel at their self-selected wheeling speed. Trainers will increase speed by 0.1 m/s (for 1 minute) and decrease speed by 0.1 m/s (for 1 minute). The final 2 minutes will be performed at their self-selected speed. Trainers will provide feedback that highlights their intrinsic feedback 4 times throughout trial relating to cadence and push length.

Session 2.

00:00-00:05-

<u>Wheeling Block 1:</u> The trainers will instruct the participant to wheel at their self-selected wheeling speed. The trainer will increase speed by 0.1 m/s (for 1 minute) and decrease speed by 0.1 m/s (for 1 minute). The final 2 minutes will be performed at their self-

selected speed. The trainers will provide feedback that highlights their intrinsic feedback 4 times throughout the trial relating to cadence and push length.

00:05-00:10-
Rest break: The trainer will lead a general discussion about sensory information during wheeling. The trainer will ask the participant to describe sensations of wheeling. The trainers will use this time to discuss the various wheeling patterns. The trainer should make this interactive and ask participants why one wheeling pattern might be better than another to ensure understanding. The trainer should describe the negative consequences of braking forces.

00:10-00:15-
Wheeling Block 2: The trainer will instruct the participant to wheel at their self-selected wheeling speed for 1 minute. The trainer will increase speed by 0.1 m/s (for 1 minute) and decrease speed by 0.1 m/s (for 1 minute). The final 2 minutes will be performed at the self-selected speed. The trainer will provide extrinsic feedback 4 times throughout the trial on cadence and push length.

Goal Week 2: Use mental imagery, recall sensory information and focus on extrinsic feedback.

Session 3.

00:00-00:05-
Wheeling Block 1: The trainer will instruct participants to wheel at their self-selected speed. During each minute, trainers will guide participants' focus of attention to different aspects of wheeling; (1) placement of hands during contact; (2) location on wheel where hands let go; (3) smoothness of push (changes in velocity- accelerations and decelerations; (4) placement of hands during contact (repeat); and (5) location on wheel where hands let go (repeat). The trainer will provide extrinsic feedback once per minute on each of the different aspects of wheeling.

00:05-00:10-
Rest break: The trainer will watch a video of inefficient wheeling with participant. Have participants comment on potential improvements and discuss why certain changes in propulsion could be beneficial. Discuss areas where energy may be lost (e.g., friction of ground, friction of chair, and braking force).

00:10-00:15-
Wheeling Block 2: The trainer will instruct the participant to wheel at their self-selected wheeling speed for 1 minute. The trainer will increase the speed by 0.1 m/s (for 1 minute) and decrease speed by 0.1 m/s (for 1 minute). The final 2 minutes will be

performed at their self-selected speed. The trainer will provide extrinsic feedback 4 times throughout trial on cadence and push length.

Session 4.

00:00-00:05-
Wheeling Block 1: The trainer will instruct participants to wheel at their self-selected wheeling speed for 1 minute. The trainer will increase the speed by 0.1 m/s (for 1 minute) and decrease speed by 0.1 m/s (for 1 minute). The final 2 minutes will be performed at their self-selected speed. The trainer will provide extrinsic feedback 4 times throughout the trial on cadence and push length.

00:05-00:10-
Rest break: Trainers will ask participants to describe the sensations experienced during wheeling. Trainers will discuss efficient wheeling with the participant and ask the participant to reflect on and imagine wheeling (i.e., perform mental imagery). Trainers will prompt necessary stimuli to trigger memory. Trainers will discuss strategies that can be used to conserve energy during propulsion (build on understanding of energy conservation).

00:10-00:15-
Wheeling Block 2: The trainer will instruct participants to wheel at their self-selected wheeling speed. During each minute, the trainer will prompt participant to focus on the aspect of wheeling; (1) smoothness of push (changes in velocity- accelerations and decelerations; (2) location on wheel where hands let go (place tape on leg); (3) placement of hands during contact; (4) location on wheel where hands let go (place tape on leg) (repeat); and (5) smoothness of push (changes in velocity- accelerations and decelerations (repeat). The trainer will provide extrinsic verbal feedback once per minute on each of the different aspects of wheeling.

Goal Week 3: Consolidate skill and focus on providing positive feedback on knowledge of performance.

Session 5.

00:00-00:05-
Wheeling Block 1: The trainer will instruct participants to wheel at their self-selected wheeling speed for minute 1 and vary the speed as follows over the following 4 minutes: -0.1 m/s (2 minutes), +0.1 m/s (2 minutes). The trainer will provide feedback on pattern once per minute (performance).

00:05-00:10-
Rest break: The trainer will ask participants to imagine and reflect on themselves wheeling and ask if they can think of anything on which they could improve. Specifically

thinking of the three main variables (circular wheeling pattern, longer push angle, and smooth pushes that eliminate braking forces). Describe how these factors may lead to reduce repetitions.

00:10-00:15-
Wheeling Block 2: The trainer will instruct participants to wheel at their self-selected speed. The trainer will vary the speed of the treadmill as follows over the following 4 minutes: +0.1 m/s (2 minutes), -0.1 m/s (2 minutes). Provide (positive) feedback on wheeling pattern once per minute (performance).

Session 6.

00:00-00:05-
Wheeling Block 1: The trainer will instruct participants to wheel at their self-selected speed. The trainer will vary the speed of the treadmill as follows over the following 4 minutes: +0.1 m/s (2 minutes), -0.1 m/s (2 minutes). Provide (positive) feedback on the wheeling pattern once per minute (performance).

00:05-00:10-
Rest break: The trainer will discuss strategies and tips for conserving energy during propulsion. Specifically, the trainer will focus on decreasing braking forces, reducing the frequency of pushes, increasing the ‘glide’ phase and getting the most out of each push. This will be a review of previous discussions.

00:10-00:15-
Wheeling Block 2: The trainer will instruct the participant to wheel at their self-selected speed for minute 1 and vary the speed as follows over the following 4 minutes: -0.1 m/s (2 minutes), +0.1 m/s (2 minutes). The trainer will provide feedback on the wheeling pattern once per minute (performance).

Appendix L: Practice manual for RCT

Guidelines for wheelchair propulsion practice for older adults

INTRODUCTION **Participant code: ___________**

Who: My name is ___________________ and I will be seeing you for the next 3 weeks of this program.

Where and When: We will meet at the Human Mobility Lab on the 3rd floor of the Blusson Spinal Cord Centre for the training sessions.

Why: The goal of this program is to determine the best methods for providing wheelchair propulsion training for older adults. Although the participants in this study are not wheelchair users, you will simulate a new wheelchair user in terms of your current skill level.

What: There will be a total of six 15-minute sessions in total. You are asked to attend all sessions. The sessions will involve wheeling for two 5-minute trials with a 5-minute rest break.

<u>Session Dates:</u>

1.	4.
2.	5.
3.	6.

PREPARATION FOR TRAINING:

-Have wheelchair configured based on baseline assessment.
-Ensure tires are pumped to 100psi
-Attach SmartWheel to the participant's dominant side and inertia-matched dummy wheel on their non-dominant side.

PRACTICE TRAINING:

All training sessions will consist of blocked practice (wheeling at the same speed) for two 5-minute trials for each session (separated by a 5-minute rest). During the rest break, participants can chat about topics not related to the study or read from a selection of magazines. Participants will wheel at their self-selected speed (i.e., the speed selected for the baseline assessment) for all trials.

Self-selected speed used: ___________________________________

Session 1.
00:00-00:05-
Wheeling Block 1: The trainer will instruct participants to wheel at their self-selected speed.

00:05-00:10- Rest break:

00:10-00:15-
Wheeling Block 2: The trainer will instruct participants to wheel at their self-selected speed.

Session 2.
00:00-00:05-
Wheeling Block 1: The trainer will instruct participants to wheel at their self-selected speed.

00:05-00:15- Rest break:

00:10-00:15-
Wheeling Block 2: The trainer will instruct participants to wheel at their self-selected speed.

Session 3.
00:00-00:05-

Wheeling Block 1: The trainer will instruct participants to wheel at their self-selected speed.

00:05-00:10- Rest break

00:10-00:15-
Wheeling Block 2: The trainer will instruct participants to wheel at their self-selected speed.

Session 4.
00:00-00:05-
Wheeling Block 1: The trainer will instruct participants to wheel at their self-selected speed.

00:05-00:10- Rest break:

00:10-00:15-
Wheeling Block 2: The trainer will instruct participants to wheel at their self-selected speed.

Session 5.
00:00-00:05-
Wheeling Block 1: The trainer will instruct participants to wheel at their self-selected speed.

00:05-00:10- Rest break:

00:10-00:15-
Wheeling Block 2: The trainer will instruct participants to wheel at their self-selected speed.

Session 6.
00:00-00:05-
Wheeling Block 1: The trainer will instruct participants to wheel at their self-selected speed.

00:05-00:10- Rest break:

00:10-00:15-
Wheeling Block 2: The trainer will instruct participants to wheel at their self-selected speed.

Appendix M: RCT participant demographics sheet (Chapters 3, 4, and 5)

Date: ____________________ Participant code: ______________

Demographics

Age: (in years)_____________

Sex: ❑ Male ❑ Female

Measured Height: (cm)_____________ Measured Weight: (kg)_____________

Calculated BMI: _____________

What is your dominant hand (left, right or ambidextrous): ____________________

Are you employed?

- ❑ Yes
- ❑ No

If you are not employed, how would you describe yourself?

- ❑ Homemaker (home duties)
- ❑ Retired
- ❑ Unemployed
- ❑ Student
- ❑ Other ____________________

Education: ❑ Less than high school ❑ High school ❑ College ❑ University ❑ Graduate studies ❑ Post graduate studies

Have you ever had to use a manual wheelchair that you self-propelled?

❑ Yes If so, describe the context?____

❑ No

Do you have any close friends or family members that use a manual wheelchair?

❑ Yes If yes, relation?__________________

❑ No

Appendix N: Participant physical information (Chapters 3, 4, 5, and 6)

Date: ____________________ Participant code: ______________

STRENGTH (measured with hand dynamometer- take average of three)

Grip strength left hand: ______________ Grip strength right hand: ______________

FLEXIBILITY (measured with goniometer)

Shoulder extension:______________ Shoulder flexion:______________

Elbow extension:______________ Elbow flexion:______________

Wrist extension:______________ Wrist flexion:______________

How would you rate your current physical fitness?

- ❑ Excellent
- ❑ Good
- ❑ Average
- ❑ Poor

WHEELCHAIR FITTING

Elbow angle at top dead centre: ______________

Dump (angle): ______________

Weight over castor wheels: ______________

Weight over drive wheels: ______________

Appendix O: Sample size calculations

The sample size has been calculated with G*Power 3.1 software for Mac using the F-test- "ANOVA repeated measures: within-between interactions" statistical test with 3 groups and 3 measurements (Faul, 2007).

Calculation for effect size f (Faul, 2007):

ANOVA: repeated measures between effects:

F tests: $\mu i - \mu = 0$ $i = 1,...,k$ $f = \sigma\mu/\sigma$

($\sigma\mu$ = standard deviation of the effect; σ = standard deviation of the population).

<u>Calculation:</u>

Based on push angle values and standard deviations calculated from the reported standard error (93), the effect size (i.e., Cohen's *d*) was calculated to be 0.26. The calculated sample size is 30 total participants with 10 per group based on the intersession (repeated measures) correlation value of 0.53 (172). The standard deviation of the push angle for the population was extracted from a different study conducted in our lab on able-bodied participants (172).

To plan for a 15% drop out rate, we will recruit 36 participants (12 participants per group).

Appendix P: GLMM sample R code

```
# Loading nlme package
  library(nlme)

# Variable of interest: Push.Angle
  var <- 'Push.Angle'

# Linear mixed-effect model
# Dependent variable: Push.Angle
# Predictor variable: Group (cat: control, practice, train),
# Time point (cat: time point 1, 2, 3)
# Confounders: Age (continuous), Sex (Cat: F vs M), BMI (continuous)
  dat$Group  <- with(dat,factor(Group, level=c('Control','Practice','Train'))
  dat$TimePt <- with(dat,factor(TimePt,level=c('Trial1','Trial2','Trial3'))

  modLME.Push.Angle <- lme(Push.Angle ~ Age + Sex + BMI + Group + TimePt,
                           data = dat, random = ~ 1 | StudyID)

   # Assessing assumptions:
     qqnorm(modLME.Push.Angle)
     plot(modLME.Push.Angle)

# Examining interactions:
  modLME.Push.Angle.int <- lme(Push.Angle ~ Age + Sex + BMI + Group:TimePt,
                               data = dat, random = ~ 1 | StudyID)

   # Assessing assumptions:
     qqnorm(modLME.Push.Angle.int)
     plot(modLME.Push.Angle.int)

# Testing significance of interactions
  anova(modLME.Push.Angle.int, modLME.Push.Angle)
```

Appendix Q: GLMM R code outputs

The grey box represents the independent variables of interest (i.e., group and time point) relative to the control group and baseline time point. The bolded p-values represent those that met significance (p<0.05). P-values were adjusted for the false discovery rate for the independent variables of interest and are presented in the brackets beside the p-values from each GLMM. The bolded values in the right column (adjusted p-values) represent those that remained significant and those that are underlined, were marginally significant.

Biomechanical variables (Chapter 3)

Push.Angle

	Value	Std.Error	DF	t-value	p-value	
(Intercept)	10.4256	20.4158	58	0.5107	0.6115	
Age	-0.1094	0.2434	28	-0.4497	0.6564	
SexM	3.2625	4.2644	28	0.7651	0.4506	
BMI	1.2060	0.4823	28	2.5007	0.0185	
GroupPractice	2.1897	5.2565	28	0.4166	0.6802	(0.7914)
GroupTrain	21.8414	5.1543	28	4.2375	**0.0002**	**(0.0084)**
TimePtTrial2	9.7455	3.5455	58	2.7487	**0.0080**	(0.0527)
TimePtTrial3	9.4657	3.5267	58	2.6841	**0.0095**	(0.0527)
GroupTPractice	-19.6516	5.6818	28	-3.4587	**0.0018**	**(0.0294)**
TimePt3Trial2	0.2797	3.6392	58	0.0769	0.9390	(0.9770)

Push.Frequency

	Value	Std.Error	DF	t-value	p-value	
(Intercept)	1.4315	0.3321	58	4.3103	0.0001	
Age	0.0018	0.0040	28	0.4612	0.6482	
SexM	0.0449	0.0693	28	0.6480	0.5223	
BMI	-0.0186	0.0078	28	-2.3810	0.0243	
GroupPractice	-0.0050	0.0854	28	-0.0586	0.9537	(0.9770)
GroupTrain	-0.2567	0.0836	28	-3.0693	**0.0047**	**(0.0395)**
TimePtTrial2	-0.1716	0.0656	58	-2.6177	**0.0113**	(0.0527)
TimePtTrial3	-0.1975	0.0652	58	-3.0305	**0.0036**	**(0.0378)**
GroupTPractice	0.2517	0.0921	28	2.7328	**0.0108**	(0.0527)
TimePt3Trial2	0.0259	0.0671	58	0.3850	0.7016	(0.7914)

Mean.Force.Tangential

	Value	Std.Error	DF	t-value	p-value	
(Intercept)	-12.7995	8.1006	58	-1.5801	0.1195	
Age	0.1182	0.0963	28	1.2276	0.2298	
SexM	5.6702	1.6973	28	3.3406	0.0024	
BMI	0.9734	0.1926	28	5.0551	0.0000	
GroupPractice	1.3365	2.0866	28	0.6405	0.5270	(0.7914)
GroupTrain	1.3789	2.0561	28	0.6706	0.5079	(0.7914)
TimePtTrial2	0.4894	0.9119	58	0.5367	0.5936	(0.7914)
TimePtTrial3	-0.0610	0.9093	58	-0.0671	0.9467	(0.9770)
GroupTPractice	-0.0424	2.2734	28	-0.0186	0.9853	(0.9853)
TimePt3Trial2	0.5504	0.9413	58	0.5847	0.5610	(0.7914)

Mean.Force.Total

	Value	Std.Error	DF	t-value	p-value
(Intercept)	-18.5851	12.6737	58	-1.4664	0.1479
Age	0.1512	0.1507	28	1.0036	0.3241

	Value	Std.Error	DF	t-value	p-value	
SexM	6.2517	2.6552	28	2.3545	0.0258	
BMI	1.3371	0.3012	28	4.4394	0.0001	
GroupPractice	2.2274	3.2646	28	0.6823	0.5007	(0.7914)
GroupTrain	4.3554	3.2161	28	1.3542	0.1865	(0.4967)
TimePtTrial2	2.7698	1.4678	58	1.8871	0.0642	(0.2247)
TimePtTrial3	2.1258	1.4633	58	1.4528	0.1517	(0.4551)
GroupTPractice	-2.1280	3.5555	28	-0.5985	0.5543	(0.7914)
TimePt3Trial2	0.6440	1.5146	58	0.4252	0.6723	(0.7914)

Peak.Force.Tangential

	Value	Std.Error	DF	t-value	p-value	
(Intercept)	-26.6590	12.8738	58	-2.0708	0.0428	
Age	0.2174	0.1530	28	1.4209	0.1664	
SexM	9.4606	2.6975	28	3.5071	0.0015	
BMI	1.5120	0.3060	28	4.9406	0.0000	
GroupPractice	1.4027	3.3161	28	0.4230	0.6755	(0.7914)
GroupTrain	3.0821	3.2677	28	0.9432	0.3537	(0.7428)
TimePtTrial2	1.6251	1.4452	58	1.1245	0.2654	(0.6193)
TimePtTrial3	0.7749	1.4410	58	0.5378	0.5928	(0.7914)
GroupTPractice	-1.6794	3.6131	28	-0.4648	0.6457	(0.7914)
TimePt3Trial2	0.8502	1.4917	58	0.5699	0.5709	(0.7914)

Peak.Force.Total

	Value	Std.Error	DF	t-value	p-value	
(Intercept)	-34.3183	18.0706	58	-1.8991	0.0625	
Age	0.2756	0.2148	28	1.2829	0.2101	
SexM	10.1031	3.7857	28	2.6688	0.0125	
BMI	1.8968	0.4294	28	4.4173	0.0001	
GroupPractice	2.1825	4.6549	28	0.4689	0.6428	(0.7914)
GroupTrain	6.1698	4.5851	28	1.3456	0.1892	(0.4967)
TimePtTrial2	4.7952	2.1246	58	2.2570	**0.0278**	(0.1061)
TimePtTrial3	3.1468	2.1179	58	1.4858	0.1427	(0.4551)
GroupTPractice	-3.9873	5.0684	28	-0.7867	0.4381	(0.7914)
TimePt3Trial2	1.6484	2.1920	58	0.7520	0.4551	(0.7914)

Peak.Negative.Force

	Value	Std.Error	DF	t-value	p-value	
(Intercept)	-5.2308	2.4729	58	-2.1153	0.0387	
Age	-0.0181	0.0294	28	-0.6151	0.5434	
SexM	-1.2917	0.5173	28	-2.4967	0.0187	
BMI	0.0720	0.0586	28	1.2292	0.2292	
GroupPractice	-0.2341	0.6370	28	-0.3675	0.7160	(0.7914)
GroupTrain	0.6154	0.6260	28	0.9832	0.3339	(0.7381)
TimePtTrial2	0.8679	0.3636	58	2.3871	**0.0203**	(0.0853)
TimePtTrial3	1.1681	0.3620	58	3.2267	**0.0021**	**(0.0294)**
GroupTPractice	-0.8495	0.6909	28	-1.2296	0.2291	(0.5660)
TimePt3Trial2	-0.3002	0.3741	58	-0.8024	0.4256	(0.7914)

Physiological variables (Chapter 4)

Relative.Power.Output

	Value	Std.Error	DF	t-value	p-value

```
(Intercept)    0.0579    0.0697 56  0.8308  0.4096
Age            0.0009    0.0008 28  1.1371  0.2651
SexM           0.0315    0.0146 28  2.1514  0.0402
BMI           -0.0005    0.0017 28 -0.2922  0.7723
GroupPractice  0.0136    0.0179 28  0.7557  0.4561 (0.7742)
GroupTrain    -0.0012    0.0178 28 -0.0696  0.9450 (0.9745)
TimePtTrial2   0.0026    0.0050 56  0.5078  0.6136 (0.7941)
TimePtTrial3   0.0007    0.0051 56  0.1281  0.8985 (0.9745)
GroupTPractice 0.0148    0.0197 28  0.7524  0.4581 (0.7742)
TimePt3Trial2  0.0019    0.0052 56  0.3648  0.7166 (0.8760)

Power.Output
                Value Std.Error DF t-value p-value
(Intercept)   -4.8705    6.1309 56 -0.7944  0.4303
Age            0.0830    0.0729 28  1.1396  0.2641
SexM           4.3661    1.2870 28  3.3926  0.0021
BMI            0.3128    0.1461 28  2.1413  0.0411
GroupPractice  1.1413    1.5786 28  0.7230  0.4757 (0.7742)
GroupTrain     0.5575    1.5620 28  0.3569  0.7238 (0.8760)
TimePtTrial2   0.3162    0.4583 56  0.6899  0.4931 (0.7742)
TimePtTrial3   0.0385    0.4635 56  0.0830  0.9341 (0.9745)
GroupTPractice 0.5839    1.7296 28  0.3375  0.7382 (0.8760)
TimePt3Trial2  0.2777    0.4751 56  0.5845  0.5612 (0.7742)

Work
                 Value Std.Error DF t-value p-value
(Intercept)   -23.8723    9.6367 56 -2.4772  0.0163
Age             0.1244    0.1153 28  1.0788  0.2899
SexM            6.5867    2.0189 28  3.2625  0.0029
BMI             0.8358    0.2273 28  3.6766  0.0010
GroupPractice   1.6003    2.4828 28  0.6445  0.5245 (0.7742)
GroupTrain      9.2678    2.4528 28  3.7784  0.0008 (0.0528)
TimePtTrial2    4.5155    1.7815 56  2.5346  0.0141 (0.1163)
TimePtTrial3    4.6748    1.7908 56  2.6104  0.0116 (0.1163)
GroupTPractice -7.6675    2.6941 28 -2.8460  0.0082 (0.1163)
TimePt3Trial2  -0.1593    1.8295 56 -0.0871  0.9309 (0.9745)

Energy.Expenditure
                 Value Std.Error DF t-value p-value
(Intercept)    23.0039   74.7189 57  0.3079  0.7593
Age             1.1852    0.9027 27  1.3129  0.2003
SexM           45.0706   15.7712 27  2.8578  0.0081
BMI             2.7211    1.7766 27  1.5316  0.1372
GroupPractice  -4.8769   19.1049 27 -0.2553  0.8005 (0.9109)
GroupTrain    -20.5774   19.6668 27 -1.0463  0.3047 (0.7448)
TimePtTrial2   -5.2009    7.2552 57 -0.7168  0.4764 (0.7742)
TimePtTrial3  -20.0487    7.1836 57 -2.7909  0.0071 (0.1163)
GroupTPractice 15.7006   21.7161 27  0.7230  0.4759 (0.7742)
TimePt3Trial2  14.8478    7.4305 57  1.9982  0.0505 (0.2664)

Mechanical.Effectiveness
                Value Std.Error DF t-value p-value
(Intercept)    0.8006    0.1302 58  6.1484  0.0000
Age            0.0002    0.0015 28  0.1360  0.8928
SexM           0.0286    0.0273 28  1.0503  0.3026
BMI           -0.0015    0.0031 28 -0.4933  0.6257
GroupPractice -0.0187    0.0335 28 -0.5578  0.5814 (0.7742)
```

GroupTrain	-0.0399	0.0330	28	-1.2077	0.2373	(0.6265)
TimePtTrial2	-0.0313	0.0161	58	-1.9463	0.0565	(0.2664)
TimePtTrial3	-0.0362	0.0160	58	-2.2618	**0.0275**	(0.1815)
GroupTPractice	0.0212	0.0365	28	0.5801	0.5665	(0.7742)
TimePt3Trial2	0.0050	0.0166	58	0.2986	0.7663	(0.8873)

Gross.Mechanical.Efficiency

	Value	Std.Error	DF	t-value	p-value	
(Intercept)	1.5373	3.3084	53	0.4647	0.6441	
Age	0.0313	0.0400	27	0.7828	0.4406	
SexM	0.8745	0.6999	27	1.2495	0.2222	
BMI	0.0722	0.0788	27	0.9161	0.3677	
GroupPractice	0.8308	0.8503	27	0.9771	0.3372	(0.7524)
GroupTrain	1.4780	0.8709	27	1.6971	0.1012	(0.3929)
TimePtTrial2	0.1989	0.3305	53	0.6019	0.5498	(0.7742)
TimePtTrial3	0.4759	0.3262	53	1.4592	0.1504	(0.5224)
GroupTPractice	-0.6471	0.9604	27	-0.6738	0.5062	(0.7742)
TimePt3Trial2	-0.2770	0.3425	53	-0.8089	0.4222	(0.7742)

VO2

	Value	Std.Error	DF	t-value	p-value	
(Intercept)	9.4291	2.3241	57	4.0572	0.0002	
Age	0.0328	0.0281	27	1.1679	0.2531	
SexM	0.3475	0.4901	27	0.7091	0.4843	
BMI	-0.1621	0.0552	27	-2.9383	0.0067	
GroupPractice	-0.1964	0.5935	27	-0.3309	0.7433	(0.8760)
GroupTrain	-0.7971	0.6112	27	-1.3041	0.2032	(0.5999)
TimePtTrial2	-0.1615	0.2693	57	-0.5996	0.5511	(0.7742)
TimePtTrial3	-0.7071	0.2669	57	-2.6490	**0.0104**	(0.1163)
GroupTPractice	0.6008	0.6742	27	0.8911	0.3808	(0.7742)
TimePt3Trial2	0.5456	0.2757	57	1.9791	0.0526	(0.2664)

Respiratory.Exchange.Ratio

	Value	Std.Error	DF	t-value	p-value	
(Intercept)	1.0140	0.1243	57	8.1582	0.0000	
Age	0.0015	0.0015	27	0.9760	0.3378	
SexM	0.0120	0.0262	27	0.4571	0.6513	
BMI	-0.0051	0.0029	27	-1.7237	0.0962	
GroupPractice	-0.0004	0.0317	27	-0.0112	0.9912	(0.9912)
GroupTrain	-0.0807	0.0326	27	-2.4728	**0.0200**	(0.1467)
TimePtTrial2	-0.0013	0.0175	57	-0.0759	0.9398	(0.9745)
TimePtTrial3	-0.0122	0.0174	57	-0.7011	0.4861	(0.7742)
GroupTPractice	0.0804	0.0340	27	2.2355	**0.0339**	(0.2031)
TimePt3Trial2	0.0109	0.0179	57	0.6061	0.5469	(0.7742)

Ventilation.Exchange

	Value	Std.Error	DF	t-value	p-value	
(Intercept)	2.7816	7.8100	57	0.3562	0.7230	
Age	0.1707	0.0944	27	1.8090	0.0816	
SexM	4.2159	1.6487	27	2.5571	0.0165	
BMI	0.1265	0.1858	27	0.6810	0.5017	
GroupPractice	0.0767	1.9974	27	0.0384	0.9697	(0.9846)
GroupTrain	-2.8385	2.0559	27	-1.3807	0.1787	(0.5897)
TimePtTrial2	-0.9175	0.7309	57	-1.2552	0.2145	(0.5999)
TimePtTrial3	-1.8498	0.7236	57	-2.5564	**0.0133**	(0.1163)
GroupTPractice	2.9152	2.2706	27	1.2839	0.2101	(0.5999)
TimePt3Trial2	0.9323	0.7487	57	1.2453	0.2180	(0.5999)

Heart.Rate

	Value	Std.Error	DF	t-value	p-value	
(Intercept)	75.7363	16.8422	54	4.4968	0.0000	
Age	-0.1323	0.1961	25	-0.6745	0.5062	
SexM	-3.3956	3.6013	25	-0.9429	0.3548	
BMI	0.6274	0.3923	25	1.5992	0.1223	
GroupPractice	7.8467	4.4741	25	1.7538	0.0917	(0.3929)
GroupTrain	3.5038	4.3145	25	0.8121	0.4244	(0.7742)
TimePtTrial2	0.3091	1.6534	54	0.1869	0.8524	(0.9535)
TimePtTrial3	-0.8937	1.6332	54	-0.5472	0.5865	(0.7742)
GroupTPractice	4.3429	4.4835	25	0.9686	0.3420	(0.7524)
TimePt3Trial2	1.2028	1.6577	54	0.7256	0.4712	(0.7742)

Max.Power.output

	Value	Std.Error	DF	t-value	p-value	
(Intercept)	25.4018	69.6597	63	0.3647	0.7166	
Age	-1.1421	0.8278	28	-1.3797	0.1786	
SexM	67.6593	14.6165	28	4.6290	0.0001	
BMI	4.6562	1.6599	28	2.8051	0.0090	
GroupPractice	27.3613	17.9214	28	1.5267	0.1380	(0.5060)
GroupTrain	17.7098	17.7266	28	0.9991	0.3263	(0.7524)
TimePtTrial2	5.4753	4.9629	63	1.1032	0.2741	(0.6958)
TimePtTrial3	13.7484	4.9627	63	2.7703	**0.0073**	(0.1163)
GroupTPractice	9.6514	19.6975	28	0.4900	0.6280	(0.7970)
TimePt3Trial2	-8.2731	4.9634	63	-1.6668	0.1005	(0.3929)

COV variables (Chapter 5)

Push.Angle.COV

	Value	Std.Error	DF	t-value	p-value	
(Intercept)	0.2110	0.0484	58	4.3600	0.0001	
Age	-0.0003	0.0006	28	-0.4796	0.6352	
SexM	0.0121	0.0101	28	1.1970	0.2413	
BMI	-0.0025	0.0011	28	-2.1982	0.0364	
GroupPractice	-0.0489	0.0125	28	-3.9218	**0.0005**	**(0.0192)**
GroupTrain	-0.0464	0.0123	28	-3.7814	**0.0008**	**(0.0192)**
TimePtTrial2	-0.0048	0.0065	58	-0.7376	0.4638	(0.6746)
TimePtTrial3	-0.0055	0.0065	58	-0.8566	0.3952	(0.6746)
GroupTPractice	-0.0025	0.0135	28	-0.1860	0.8538	(0.9206)
TimePt3Trial2	0.0008	0.0067	58	0.1124	0.9109	(0.9206)

Push.Frequency.COV

	Value	Std.Error	DF	t-value	p-value	
(Intercept)	0.0664	0.0401	58	1.6569	0.1029	
Age	-0.0008	0.0005	28	-1.5950	0.1219	
SexM	0.0177	0.0083	28	2.1214	0.0429	
BMI	0.0018	0.0009	28	1.8655	0.0726	
GroupPractice	-0.0256	0.0103	28	-2.4839	**0.0192**	(0.1152)
GroupTrain	-0.0083	0.0101	28	-0.8261	0.4157	(0.6746)
TimePtTrial2	0.0104	0.0091	58	1.1448	0.2570	(0.5535)
TimePtTrial3	0.0131	0.0090	58	1.4601	0.1496	(0.3779)
GroupTPractice	-0.0173	0.0111	28	-1.5613	0.1297	(0.3662)
TimePt3Trial2	-0.0028	0.0093	58	-0.2989	0.7661	(0.9193)

Mean.Force.Tangential.COV

	Value	Std.Error	DF	t-value	p-value	
(Intercept)	0.1384	0.0388	58	3.5676	0.0007	
Age	0.0003	0.0005	28	0.7530	0.4577	
SexM	0.0066	0.0081	28	0.8175	0.4206	
BMI	-0.0009	0.0009	28	-1.0099	0.3212	
GroupPractice	-0.0339	0.0100	28	-3.4004	**0.0020**	**(0.0320)**
GroupTrain	-0.0250	0.0098	28	-2.5584	**0.0162**	(0.1111)
TimePtTrial2	-0.0016	0.0082	58	-0.1897	0.8502	(0.9206)
TimePtTrial3	-0.0061	0.0081	58	-0.7539	0.4540	(0.6746)
GroupTPractice	-0.0090	0.0107	28	-0.8358	0.4103	(0.6746)
TimePt3Trial2	0.0046	0.0084	58	0.5468	0.5866	(0.6746)

Mean.Force.Total.COV

	Value	Std.Error	DF	t-value	p-value	
(Intercept)	0.1489	0.0471	58	3.1623	0.0025	
Age	0.0007	0.0006	28	1.1982	0.2409	
SexM	-0.0007	0.0098	28	-0.0684	0.9460	
BMI	-0.0012	0.0011	28	-1.1092	0.2768	
GroupPractice	-0.0390	0.0121	28	-3.2211	**0.0032**	**(0.0346)**
GroupTrain	-0.0264	0.0119	28	-2.2190	**0.0348**	(0.1670)
TimePtTrial2	0.0088	0.0084	58	1.0489	0.2986	(0.5972)
TimePtTrial3	0.0011	0.0084	58	0.1344	0.8935	(0.9206)
GroupTPractice	-0.0127	0.0131	28	-0.9684	0.3411	(0.6550)
TimePt3Trial2	0.0077	0.0086	58	0.8921	0.3760	(0.6746)

Peak.Force.Tangential.COV

	Value	Std.Error	DF	t-value	p-value
(Intercept)	0.1286	0.0474	58	2.7122	0.0088

Age	0.0008	0.0006	28	1.4576	0.1561	
SexM	0.0090	0.0099	28	0.9148	0.3681	
BMI	-0.0007	0.0011	28	-0.5999	0.5534	
GroupPractice	-0.0387	0.0122	28	-3.1742	**0.0036**	**(0.0346)**
GroupTrain	-0.0234	0.0119	28	-1.9625	0.0597	(0.2252)
TimePtTrial2	-0.0021	0.0094	58	-0.2196	0.8269	(0.9206)
TimePtTrial3	-0.0035	0.0101	58	-0.3474	0.7296	(0.8980)
GroupTPractice	-0.0153	0.0131	28	-1.1633	0.2545	(0.5535)
TimePt3Trial2	0.0050	0.0096	58	0.5147	0.6087	(0.8116)

Peak.Force.Total.COV

	Value	Std.Error	DF	t-value	p-value	
(Intercept)	0.1401	0.0529	58	2.6465	0.0105	
Age	0.0012	0.0006	28	1.9660	0.0593	
SexM	-0.0032	0.0110	28	-0.2885	0.7751	
BMI	-0.0014	0.0012	28	-1.1465	0.2613	
GroupPractice	-0.0384	0.0136	28	-2.8211	**0.0087**	(0.0696)
GroupTrain	-0.0152	0.0133	28	-1.1370	0.2652	(0.5535)
TimePtTrial2	0.0037	0.0102	58	0.3644	0.7169	(0.8980)
TimePtTrial3	-0.0026	0.0101	58	-0.2607	0.7953	(0.9206)
GroupTPractice	-0.0233	0.0147	28	-1.5838	0.1245	(0.3662)
TimePt3Trial2	0.0064	0.0104	58	0.6086	0.5452	(0.7696)

Peak.Negative.Force.COV

	Value	Std.Error	DF	t-value	p-value	
(Intercept)	-0.1073	0.0958	58	-1.1195	0.2675	
Age	-0.0021	0.0011	28	-1.8003	0.0826	
SexM	-0.0240	0.0200	28	-1.1978	0.2410	
BMI	-0.0027	0.0023	28	-1.1839	0.2464	
GroupPractice	0.0508	0.0247	28	2.0579	**0.0490**	(0.2138)
GroupTrain	0.0473	0.0242	28	1.9524	0.0610	(0.2252)
TimePtTrial2	-0.0358	0.0158	58	-2.2647	**0.0273**	(0.1456)
TimePtTrial3	-0.0121	0.0157	58	-0.7672	0.4461	(0.6746)
GroupTPractice	0.0035	0.0267	28	0.1314	0.8964	(0.9206)
TimePt3Trial2	-0.0238	0.0163	58	-1.4614	0.1493	(0.3779)

Mechanical.Effectiveness.COV

	Value	Std.Error	DF	t-value	p-value	
(Intercept)	0.0957	0.0333	58	2.8771	0.0056	
Age	0.0002	0.0004	28	0.4550	0.6526	
SexM	-0.0092	0.0070	28	-1.3145	0.1993	
BMI	-0.0011	0.0008	28	-1.3408	0.1908	
GroupPractice	-0.0100	0.0086	28	-1.1634	0.2545	(0.5535)
GroupTrain	-0.0063	0.0084	28	-0.7517	0.4585	(0.6746)
TimePtTrial2	0.0078	0.0043	58	1.7894	0.0788	(0.2702)
TimePtTrial3	0.0073	0.0043	58	1.6924	0.0959	(0.3069)
GroupTPractice	-0.0036	0.0093	28	-0.3898	0.6997	(0.8980)
TimePt3Trial2	0.0004	0.0045	58	0.1001	0.9206	(0.9206)

Appendix R: GLMM estimations of effect size

Estimating effect size

Sample size was calculated based on the primary outcome variable, push angle (Appendix O). Exact calculations of effect size are not possible with the GLMM analyses (Appendices P and Q) because we only have standard error (SE) and not standard deviation (SD) or variance for each variable from this model; however, effect size can be estimated by using the standard error.

Standard deviation can be approximated as SD = sqrt(n)*SE. This equation is only an estimation because it ignores the correlation structure of the data and the uncertainty association with random factors in the model. Therefore, the ES's produced using this equation are comparable within a study but not between studies. Random effects are consistent within a study and thus comparable. The following ES's are computed using the SE values for training group relative to the control group.

Cohen's *d* estimated equation: $d = \frac{\beta}{SE(\beta)\cdot\sqrt{n}}$

Variable	**Estimation of Cohen's *d*** (training group relative to control group)
Biomechanical variables (Chapter 3)	
Push angle (°)	0.70
Push frequency (Hz)	-0.51
Mean force tangential (N)	0.11
Mean force total (N)	0.22
Peak force tangential (N)	0.16
Peak force total (N)	0.22
Peak negative force (N)	0.16
Physiological variables (Chapter 4)	
Relative power output (W/kg)	-0.01
Power output (W)	0.06
Work/ push (Joules/ push)	0.62
Energy expenditure (W)	-0.17
Mechanical effectiveness	-0.20
GME (%)	0.28
$\dot{V}O_2$ (ml/min/kg)	-0.21
RER	-0.41
$\dot{V}_E$ (l/min)	-0.23
Heart rate (bpm)	0.13
Max power output (W)	0.16
COV variables (Chapter 5)	
Push angle (°)	-0.62
Push frequency (Hz)	-0.14
Mean force tangential (N)	-0.42
Mean force total (N)	-0.37
Peak force tangential (N)	-0.32
Peak Force total (N)	-0.19
Peak negative force (N)	0.32
Mechanical Effectiveness	-0.12

Appendix S: SCRIBE checklist

The Single-Case Reporting guideline In BEhavioural interventions (SCRIBE) 2016 Checklist

Item number	Topic	Item description	Notes
TITLE and ABSTRACT			
1	Title	Identify the research as a single-case experimental design in the title	135
2	Abstract	Summarise the research question, population, design, methods including intervention/s (independent variable/s) and target behaviour/s and any other outcome/s (dependent variable/s), results, and conclusions	-
INTRODUCTION			
3	Scientific background	Describe the scientific background to identify issue/s under analysis, current scientific knowledge, and gaps in that knowledge base	135-137
4	Aims	State the purpose/aims of the study, research question/s, and, if applicable, hypotheses	137
METHODS			
	DESIGN		
5	Design	Identify the design (e.g., withdrawal/reversal, multiple-baseline, alternating-treatments, changing-criterion, some combination thereof, or adaptive design) and describe the phases and phase sequence (whether determined *a priori* or data-driven) and, if applicable, criteria for phase change	138
6	Procedural changes	Describe any procedural changes that occurred during the course of the investigation after the start of the study	-
7	Replication	Describe any planned replication	-
8	Randomisation	State whether randomisation was used, and if so, describe the randomisation method and the elements of the study that were randomized	-
9	Blinding	State whether blinding/masking was used, and if so, describe who was blinded/masked	139
	PARTICIPANT/S or UNIT/S		
10	Selection criteria	State the inclusion and exclusion criteria, if applicable, and the method of recruitment	138-139
11	Participant characteristics	For each participant, describe the demographic characteristics and clinical (or other) features relevant to the research question, such that anonymity is ensured	146-
	CONTEXT		
12	Setting	Describe characteristics of the setting and location where the study was conducted	146
	APPROVALS		
13	Ethics	State whether ethics approval was obtained and indicate if and how informed consent and/or assent were obtained	146
	MEASURES and MATERIALS		
14	Measures	Operationally define all target behaviours and outcome measures, describe reliability and validity, state how they were selected, and how and when they were measured	144
15	Equipment	Clearly describe any equipment and/or materials (e.g., technological aids, biofeedback, computer programs, intervention manuals or other material resources) used to measure target behaviour/s and other outcome/s or deliver the interventions	140-142
	INTERVENTIONS		
16	Intervention	Describe intervention and control condition in each phase, including how and when they were actually administered, with as much detail as possible to facilitate attempts at replication	140-142

17	Procedural fidelity	Describe how procedural fidelity was evaluated in each phase	
	ANALYSIS		
18	Analyses	Describe and justify all methods used to analyse data	145
RESULTS			
19	Sequence completed	For each participant, report the sequence actually completed, including the number of trials for each session for each case. For participant/s who did not complete, state when they stopped and the reasons	146-154
20	Outcomes and estimation	For each participant, report results, including raw data, for each target behaviour and other outcome/s	146-154
21	Adverse events	State whether or not any adverse events occurred for any participant and the phase in which they occurred	
DISCUSSION			
22	Interpretation	Summarise findings and interpret the results in the context of current evidence	154
23	Limitations	Discuss limitations, addressing sources of potential bias and imprecision	157
24	Applicability	Discuss applicability and implications of the study findings	158
DOCUMENTATION			
25	Protocol	If available, state where a study protocol can be accessed	-
26	Funding	Identify source/s of funding and other support; describe the role of funders	-

Appendix T: Wheelchair Users Shoulder Pain Index

Date: ___________________ Participant code: _____________

Place an "X" on the scale to estimate your level of pain with the following activities. Check box at right if the activity was not performed in the past week.

Based on your experiences in the **past week**, how much shoulder pain do you experience when:

1. Transferring from a bed to a wheelchair?

   No Pain [ ]____[ ]Worst Pain Ever Experienced [ ] Activity Not Performed

2. Transferring from a wheelchair to a car?

   No Pain [ ]____[ ]Worst Pain Ever Experienced [ ] Activity Not Performed

3. Transferring from a wheelchair to the tub or shower?

   No Pain [ ]____[ ]Worst Pain Ever Experienced [ ] Activity Not Performed

4. Loading your wheelchair into a car?

   No Pain [ ]____[ ]Worst Pain Ever Experienced [ ] Activity Not Performed

5. Pushing your chair for 10 minutes or more?

   No Pain [ ]____[ ]Worst Pain Ever Experienced [ ] Activity Not Performed

6. Pushing up ramps or inclines outdoors?

   No Pain [ ]____[ ]Worst Pain Ever Experienced [ ] Activity Not Performed

7. Lifting objects down from an overhead shelf?

   No Pain [ ]____[ ]Worst Pain Ever Experienced [ ] Activity Not Performed

8. Putting on pants?

No Pain [ ]____[ ]Worst Pain Ever
Experienced [ ] Activity Not Performed

9. Putting on a t-shirt or pullover?

No Pain [ ]____[ ]Worst Pain Ever
Experienced [ ] Activity Not Performed

10. Putting on a button down shirt?

No Pain [ ]____[ ]Worst Pain Ever
Experienced [ ] Activity Not Performed

11. Washing your back?

No Pain [ ]____[ ]Worst Pain Ever
Experienced [ ] Activity Not Performed

12. Usual daily activities at work or school?

No Pain [ ]____[ ]Worst Pain Ever
Experienced [ ] Activity Not Performed

13. Driving?

No Pain [ ]____[ ]Worst Pain Ever
Experienced [ ] Activity Not Performed

14. Performing household chores?

No Pain [ ]____[ ]Worst Pain Ever
Experienced [ ] Activity Not Performed

15. Sleeping?

No Pain [ ]____[ ]Worst Pain Ever
Experienced [ ] Activity Not Performed

Appendix U: Training Manual for SSRD

INTRODUCTION **Participant code: ___________**

Who: My name is MEGAN and I will be seeing you for the next 6 weeks of this program.

Where and When: We will meet at the Human Mobility Lab on the 3rd floor of the Blusson Spinal Cord Centre for the training sessions.

Why: The goal of this program is to determine the best methods for providing wheelchair propulsion training for aging adults.

What: There will be a total of twelve 15-minute sessions in total. You are asked to attend all sessions. The sessions will involve wheeling for two 5-minute trials with a 5-minute rest break. However, the format of each session will change over the course of the training. Visits 1, 6 and 12 will include additional data collection, which is described in the consent form.

Session Dates:

Phase 1-

1.	4.
2.	5.
3.	6.

Phase 2-

7.	8.
9.	10.
11.	12.

PREPARATION FOR TRAINING:

-Have wheelchair configured based on baseline assessment.
-Ensure tires are pumped to 100psi
-Attach SmartWheel to the participant's dominant side and inertia-matched dummy wheel on their non-dominant side.

PRACTICE TRAINING:

All training sessions will consist of blocked practice (wheeling at the same speed) for two 5-minute trials for each session (separated by a 5-minute rest). During the rest break, participants can chat about topics not related to the study or read from a selection of magazines. Participants will wheel at their self-selected speed (i.e., the speed selected for the baseline assessment) for all trials.

Self-selected speed used: ___________________________________

Session 1.
00:00-00:05-
Wheeling Block 1: The trainer will instruct participants to wheel at their self-selected speed.

00:05-00:10- Rest break:

00:10-00:15-
Wheeling Block 2: The trainer will instruct participants to wheel at their self-selected speed.

Session 2.
00:00-00:05-
Wheeling Block 1: The trainer will instruct participants to wheel at their self-selected speed.

00:05-00:15- Rest break:

00:10-00:15-
Wheeling Block 2: The trainer will instruct participants to wheel at their self-selected speed.

Session 3.
00:00-00:05-
Wheeling Block 1: The trainer will instruct participants to wheel at their self-selected speed.

00:05-00:10- Rest break

00:10-00:15-
Wheeling Block 2: The trainer will instruct participants to wheel at their self-selected speed.

Session 4.
00:00-00:05-
Wheeling Block 1: The trainer will instruct participants to wheel at their self-selected speed.

00:05-00:10- Rest break:

00:10-00:15-
Wheeling Block 2: The trainer will instruct participants to wheel at their self-selected speed.

Session 5.
00:00-00:05-
Wheeling Block 1: The trainer will instruct participants to wheel at their self-selected speed.

00:05-00:10- Rest break:

00:10-00:15-
Wheeling Block 2: The trainer will instruct participants to wheel at their self-selected speed.

Session 6.
00:00-00:05-
Wheeling Block 1: The trainer will instruct participants to wheel at their self-selected speed.

00:05-00:10- Rest break:

00:10-00:15-
Wheeling Block 2: The trainer will instruct participants to wheel at their self-selected speed.

PREPARATION FOR TRAINING:

-Have wheelchair configured based on baseline assessment.
-Ensure tires are pumped to 100psi
-Attach SmartWheel to the participant's dominant side and inertia-matched dummy wheel on their non-dominant side.

GLOSSARY:

Braking force: force applied in the opposite direction of the movement that causes the wheel to slow down.

Knowledge of performance: augmented feedback related to the nature of the movement produced (Schmidt and Lee, 2005, p. 465).

Mental imagery: the process of imagining yourself performing a movement either from the perspective of the person performing the movement or from someone watching the movement being performed.

Smooth wheeling: application of the hand to the wheel during the push that provides force in a forward direction and reduced 'braking' force.

Wheeling pattern: the trajectory of the hand and the shape it best represents. Participants should be encouraged to use a circular wheeling pattern to reduce abrupt accelerations and decelerations.

GENERAL RATIONALE FOR TRAINING:

This training program aims to incorporate several principles and theories that are foundational in the field of motor learning. One of the main objectives is to provide variable practice through changes in the structure of each session by modifying speed or generally the focus of attention. The other main objective is to provide sporadic feedback intermittently on several aspects of wheelchair propulsion. Variable practice and sporadic feedback are generally thought to be the most important principles of motor learning. Specifically, extrinsic or augmented feedback (e.g., the effect of a push rather than the individual's movement) is important for motor learning with respect to the individual's knowledge of performance. Other theories incorporated into this training program include mental imagery, applying an external focus of attention, as well as improving the declarative knowledge of the naïve wheelchair user.

The speed selected for baseline testing will be referred to as the 'self-selected speed'.

Self-selected speed used: ___________________________________

Goal Week 1: Develop a declarative knowledge of the wheelchair propulsion skill (Anderson 1983). Allow participants to explore movement. Provide feedback that encourages participants to focus on intrinsic feedback they are receiving (e.g., tell participants to focus on how the handrim feels on their hand) and begin to introduce extrinsic feedback (e.g., how the chair responds to propulsion).

Session 1.
00:00-00:05-
<u>Wheeling Block 1:</u> The trainer will instruct participants to wheel at their self-selected speed and will provide feedback after minute 1 regarding improving smoothness and propulsion pattern. The trainer will focus on the propulsion pattern during minutes 2 and 3 and provide feedback intermittently during that time. The trainer will encourage the participant to match the speed of their hand with the handrim to minimize braking forces during minutes 4 and 5. The trainer will provide intermittent feedback over the last two minutes.

00:05-00:10-
<u>Rest break:</u> The trainer will provide a general description of manual wheeling. Videos exemplifying positive wheeling characteristics (e.g., smooth pushes, longer push length, circular wheeling patterns) and negative wheeling characteristics (e.g., large decelerations or jerky movements) will be reviewed. The trainers will use this time to discuss the various propulsion patterns. The trainer should make this interactive and ask the participant why an example of efficient wheeling might be better than an example of poor wheeling to ensure understanding. The trainer will describe the negative consequences of braking forces during wheeling.

00:10-00:15-
<u>Wheeling Block 2:</u> Trainers will instruct participants to wheel at their self-selected wheeling speed. Trainers will increase speed by 0.1 m/s (for 1 minute) and decrease speed by 0.1 m/s (for 1 minute). The final 2 minutes will be performed at their self-selected speed. Trainers will provide feedback that highlights their intrinsic feedback 4 times throughout trial relating to cadence and push length (excluding the final minute).

Session 2.

00:00-00:05-
<u>Wheeling Block 1:</u> The trainers will instruct the participant to wheel at their self-selected wheeling speed. The trainer will increase speed by 0.1 m/s (for 1 minute) and decrease speed by 0.1 m/s (for 1 minute). The final 2 minutes will be performed at their self-selected speed. The trainers will provide feedback that highlights their intrinsic feedback 4 times throughout the trial relating to cadence and push length.

00:05-00:10-

Rest break: The trainer will lead a general discussion about sensory information during wheeling. The trainer will ask the participant to describe sensations of wheeling. The trainers will use this time to discuss the various wheeling patterns. The trainer should make this interactive and ask participants why one wheeling pattern might be better than another to ensure understanding. The trainer should describe the negative consequences of braking forces.

00:10-00:15-
Wheeling Block 2: The trainer will instruct the participant to wheel at their self-selected wheeling speed for 1 minute. The trainer will increase speed by 0.1 m/s (for 1 minute) and decrease speed by 0.1 m/s (for 1 minute). The final 2 minutes will be performed at their self-selected speed. The trainer will provide extrinsic feedback 4 times throughout the trial on cadence and push length (excluding the final minute).

Goal Week 2: Use mental imagery, recall sensory information and focus on extrinsic feedback.

Session 3.

00:00-00:05-
Wheeling Block 1: The trainer will instruct participants to wheel at their self-selected speed. During each minute, trainers will guide participants' focus of attention to different aspects of wheeling; (1) placement of hands during contact; (2) location on wheel where hands let go; (3) smoothness of push (changes in velocity- accelerations and decelerations; (4) placement of hands during contact (repeat); and (5) location on wheel where hands let go (repeat). The trainer will provide extrinsic feedback once per minute on each of the different aspects of wheeling.

00:05-00:10-
Rest break: The trainer will watch a video of inefficient wheeling with participant. Have participants comment on potential improvements and discuss why certain changes in propulsion could be beneficial. Discuss areas where energy may be lost (e.g., friction of ground, friction of chair, and braking force).

00:10-00:15-
Wheeling Block 2: The trainer will instruct the participant to wheel at their self-selected wheeling speed for 1 minute. The trainer will increase the speed by 0.1 m/s (for 1 minute) and decrease speed by 0.1 m/s (for 1 minute). The final 2 minutes will be performed at their self-selected speed. The trainer will provide extrinsic feedback 4 times throughout trial on cadence and push length (excluding the final minute).

Session 4.

00:00-00:05-
Wheeling Block 1: The trainer will instruct participants to wheel at their self-selected wheeling speed for 1 minute. The trainer will increase the speed by 0.1 m/s (for 1 minute) and decrease speed by 0.1 m/s (for 1 minute). The final 2 minutes will be performed at their self-selected speed. The trainer will provide extrinsic feedback 4 times throughout the trial on cadence and push length.

00:05-00:10-
Rest break: Trainers will ask participants to describe the sensations experienced during wheeling. Trainers will discuss efficient wheeling with the participant and ask the participant to reflect on and imagine wheeling (i.e., perform mental imagery). Trainers will prompt necessary stimuli to trigger memory. Trainers will discuss strategies that can be used to conserve energy during propulsion (build on understanding of energy conservation).

00:10-00:15-
Wheeling Block 2: The trainer will instruct participants to wheel at their self-selected wheeling speed. During each minute, the trainer will prompt participant to focus on the aspect of wheeling; (1) smoothness of push (changes in velocity- accelerations and decelerations; (2) location on wheel where hands let go (place tape on leg); (3) placement of hands during contact; (4) location on wheel where hands let go (place tape on leg) (repeat); and (5) smoothness of push (changes in velocity- accelerations and decelerations (repeat). The trainer will provide extrinsic verbal feedback once per minute on each of the different aspects of wheeling (excluding the final minute).

Goal Week 3: Consolidate skill and focus on providing positive feedback on knowledge of performance.

Session 5.

00:00-00:05-
Wheeling Block 1: The trainer will instruct participants to wheel at their self-selected wheeling speed for minute 1 and vary the speed as follows over the following 4 minutes: -0.1 m/s (2 minutes), +0.1 m/s (2 minutes). The trainer will provide feedback on pattern once per minute (performance).

00:05-00:10-
Rest break: The trainer will ask participants to imagine and reflect on themselves wheeling and ask if they can think of anything on which they could improve. Specifically thinking of the three main variables (circular wheeling pattern, longer push angle, and smooth pushes that eliminate braking forces). Describe how these factors may lead to reduce repetitions.

00:10-00:15-

Wheeling Block 2: The trainer will instruct participants to wheel at their self-selected speed. The trainer will vary the speed of the treadmill as follows over the following 2 minutes: +0.1 m/s (1 minute), -0.1 m/s (1 minute). The final 2 minutes will be completed at their self-selected wheeling speed. Provide (positive) feedback on wheeling pattern once per minute (performance) (excluding the final minute).

Session 6.

00:00-00:05-
Wheeling Block 1: The trainer will instruct participants to wheel at their self-selected speed. The trainer will vary the speed of the treadmill as follows over the following four minutes: +0.1 m/s (2 minutes), -0.1 m/s (2 minutes). Provide (positive) feedback on the wheeling pattern once per minute (performance).

00:05-00:10-
Rest break: The trainer will discuss strategies and tips for conserving energy during propulsion. Specifically, the trainer will focus on decreasing braking forces, reducing the frequency of pushes, increasing the 'glide' phase and getting the most out of each push. This will be a review of previous discussions.

00:10-00:15-
Wheeling Block 2: The trainer will instruct the participant to wheel at their self-selected speed for minute 1 and vary the speed as follows over the following 2 minutes: -0.1 m/s (1 minute), +0.1 m/s (1 minute). The final 2 minutes will be completed at their self-selected wheeling speed. The trainer will provide feedback on the wheeling pattern once per minute (performance) (excluding the final minute).

Appendix V: Participant Demographics Sheet (Study 3- SSRD)

Date: ____________________ Participant code: ______________

Demographics

Age: (in years)_____________

Sex: ❑ Male ❑ Female

Height: (cm)_____________ Measured Weight: (kg)_____________

How would you rate your current physical fitness?

- ❑ Excellent
- ❑ Good
- ❑ Average
- ❑ Poor

Are you employed?

- ❑ Yes
- ❑ No

If you are not employed, how would you describe yourself?

- ❑ Homemaker (home duties)
- ❑ Retired
- ❑ Unemployed
- ❑ Student
- ❑ Other ____________________

Education: ❑ Less than high school ❑ High school ❑ College ❑ University ❑ Graduate studies ❑ Post graduate studies

Background Information

Primary reason for using a wheelchair: ____

Secondary Diagnoses: ____

How long have you been using a manual wheelchair? ____________________________

How long have you used your current wheelchair? _______________________

Do you use your wheelchair daily? □ Yes □ No

What is the make and model of your wheelchair? ___________________________

How much does your wheelchair weigh? ___________________________

How many hours per day do you spend in your wheelchair?

□ < 2 hours □ 2-5 hours □ <5-8 hours □ > 8 hours

Where do you use your wheelchair?

□ home □ work □ recreation or sports □ work □ school □ community (restaurants/shopping)

□ other___________

Did you ever receive any wheelchair training?

❑ Yes If so, where?_________________ When? ___________________

❑ No

If yes, did the wheelchair training focus on:

- ❑ Propulsion (how to push the handrims to manoeuvre your wheelchair)
- ❑ Community skills
- ❑ Other ___________________

Appendix W: Exit survey

Date: ___________________ Participant code: _____________

- Did you find the 6 training sessions *stressful* or *uncomfortable*?

  Yes ____ No ____

  Comment: ____

- Do you feel that you *improved* your ability to perform wheelchair propulsion from these 6 training sessions? Yes ____ No ____

  Comment: ____

- Would you *recommend* these training sessions to a new wheelchair user?

  Yes ____ No ____

  Comment: ____

- What did you like the *least* about these training sessions?

  ____

- What did you like the *most* about these training sessions?

  ____

- How might this training be modified to make it more effective?

  ____

  ____

  ____

- Other comments?

  ____