The effects of an upper body training program involving resistance exercise and high intensity arm cranking on peak handcycling performance and wheelchair propulsion efficiency in able-bodied males

Abstract

The aim of this study was to determine the training effects of an upper body training program involving resistance exercise and high intensity arm cranking on peak handcycling performance, propulsion efficiency and biomechanical characteristics of wheelchair propulsion in able-bodied males. The training group (n = 10) received a 4-week upper body resistance training (RT), 70% of 1RM, 3 sets of 10 repetitions, 8 exercise stations, 2 times/week, combined with high-intensity interval training (HIIT) 2 times/week. HIIT consisted of arm crank exercise, 7 intervals of 2 minutes at 80-90% of HR_{peak} with 2-minute active rest at 50-60% of HR_{peak}. The control group (n =10) received no training. Both groups performed a pre- and post- incremental handcycling test until volitional exhaustion to evaluate fitness, and a 4-minute submaximal wheelchair propulsion test at comfortable speed (CS), 125% and 145% of CS, to evaluate gross efficiency (GE), fraction of effective force (FEF), percentage of peak oxygen consumption (%$\dot{V}O_{2peak}$) and propulsion characteristics. Repeated measures ANOVA was performed ($p < 0.05$). Training resulted in a 28.2% ± 16.5% increase in PO_{peak}, 13.3% ± 7.5% increase in $\dot{V}O_{2peak}$, 5.6% ± 0.9% increase in HR_{peak}, and 3.8% ± 1.5% decrease in HR_{rest}. No training effects on FEF, GE, %$\dot{V}O_{2peak}$ and push characteristics were identified. In conclusion, the combined RT and arm cranking HIIT improved fitness. However, it appears that this training did not result in improvements in propulsion efficiency and push characteristics. Additional wheelchair skill training may be needed to fully benefit from this advantage in daily life propulsion.

Key words HIIT, upper body exercise, fitness, rehabilitation, performance

The effects of arm cranking upper body training on peak handcycling performance and wheelchair propulsion efficiency in able-bodied males

INTRODUCTION

A lack of physical fitness is a serious obstacle to the maintenance of function and can lead to a loss of independency in wheelchair users (45). In order to prevent wheelchair dependent individuals from undergoing functional degeneration, upper body exercise is necessary and adequate training programs are essential for optimizing mobility as well as health in wheelchair users (46). Because of the lower strain to the upper extremity compared with wheelchair training, arm cranking and handcycling exercise has been proposed to promote physical endurance in this population. Several studies have demonstrated exercise specific improvements of handcycling training programs in peak power output (PO_{peak}) and peak oxygen consumption ($\dot{V}O_{2peak}$) after continuous as well as high-intensity interval training (HIIT) (22, 43), but a combined resistance training and high intensity training protocol has not been investigated. A combined protocol making use of standard indoor gym equipment could benefit people who are interested in improving upper body performance, such as wheelchair users, handcyclists and canoeists The benefit of such a training program compared with previous programs is that such a program is time efficient and no specialized (outdoor) handcycle is needed: standard gym equipment and an indoor arm crank ergometer can be used, allowing training under the supervision of strength and conditioning professionals. Expected improvements in peak handcycling performance are particularly relevant for improving upper body performance and endurance, but combined resistance and arm cranking training might also positively impact on wheelchair mobility, which is highly relevant in rehabilitation settings. The present study will be the first to explore effects of a combined training program, not only on peak handcycling performance, but also on wheelchair propulsion characteristics and mobility. The findings will provide relevant knowledge to strength and conditioning professionals working in rehabilitation settings.

Gross mechanical efficiency (GE) of wheelchair propulsion is low (2 -11%) (23, 51) compared with arm cranking or handcycling (up to 15%) (31, 37) and cycling (18-23%) (9). The fraction of effective force (FEF), a measure of the effectiveness of force application, is relatively low (50-80%) (47) compared with handcycling (79-83%) (21). The lower GE and FEF of wheelchair propulsion are associated with high repetitive and peak loads on the upper extremity leading to upper body strain and injury (13). As a consequence, manual wheelchair users have a high prevalence of upper extremity injuries (50). Theoretically, GE could increase due to adaptations in push characteristics, such as push time (the time duration that the hand applied a positive torque on the hand rim) and push frequency, and/or physiological adaptations caused by upper body exercise training involving high demands of the muscular and cardiorespiratory system (12, 20).

HIIT is the most efficient training type to improve wheelchair propulsion capacity (56) as well as upper body sports performance (15, 22, 55). HIIT improves anaerobic and aerobic fitness in athletes and healthy individuals as well as in diseased populations (19). Accumulating evidence has shown that short-term HIIT with a duration of 2-6 weeks improves cardiovascular fitness (15, 16, 25, 44, 55). Moreover, this time-efficient HIIT training is known to be superior to moderate-intensity continuous training for improving peak aerobic capacity (22, 41, 43, 52). In addition, resistance training (RT) is recommended to promote muscle adaptations of strength, power and endurance and optimize wheelchair propulsion capacity (24). A previous study showed that combined RT and rowing training improved push characteristics as defined by increased propulsive moment and decreased push frequency (40). A recent study suggested that adding RT to 4-week HIIT might have greater beneficial effects on canoeing performance and aerobic capacity compared with HIIT alone (55). Thus, it could be hypothesized that combined upper body training could lead to improvements in propulsion efficiency parameters (GE and FEF) and optimization of push characteristics in addition to increasing fitness. Therefore, it is important to study whether, and to what extent, arm cranking and RT that conform to the training guidelines of the American College of Sports Medicine (ACSM) could improve fitness and propulsion efficiency in wheelchair performance as well as push characteristics. The primary objective of this study was therefore to determine the training effects of a combined arm cranking HIIT and RT program on peak handcycling performance, cardiorespiratory fitness, propulsion efficiency in wheelchair performance and wheelchair push characteristics. From a practical point of view, this study will provide insights into effects of a combined training program on upper body endurance, as well as on submaximal wheelchair performance, that makes use of gym equipment that can easily be accessed and supervised by strength and conditioning professionals.

METHODS

Experimental Approach to the Problem

This study was designed to determine the impact of a combined program of arm cranking HIIT and resistance training on peak handcycling performance, efficiency parameters and push characteristics of wheelchair propulsion as well as cardiorespiratory fitness in able-bodied males. The training group (TG) received a 4-

week upper-body RT and a 4-week arm cranking HIIT. The control group (CG) received no training. Before and after the experimental period, participants performed an incremental handcycling test until exhaustion to determine peak handcycling performance (PO_{peak}) and cardiovascular fitness ($\dot{V}O_{2peak}$). In addition, a submaximal wheelchair test was conducted before and after the experimental period to evaluate propulsion efficiency parameters (GE and FEF), percentage of $\dot{V}O_{2peak}$ ($\%\dot{V}O_{2peak}$) and push characteristics (push frequency and push time), over three propulsion velocities. Post-tests were conducted at the same time of the day, and on the same day of the week, four weeks after the pre-tests were completed. All subjects were asked to maintain regular daily physical activity pattern during the study period. The measurement of height using a stadiometer (Seca, Birmingham, UK), body mass using a digital floor scale (Seca Medical 770, German) and percent body fat using a bio-impedance analyser (Bodystat 1500, Douglas, Isle of Man, UK) as well as blood pressure using an automatic blood pressure unit (MX3 plus, Omron, Illinois, USA) were performed pre and post intervention.

Subjects

All procedures of this study were approved by the University of Essex Ethics Committee. Signed informed consent was gained from the participants (20 able-bodied males, aged 26 ± 4 years) after receiving a verbal and a written explanation of the experiment protocol and its possible risks and benefits. The able-bodied individuals were chosen to represent individuals who are naïve to wheelchair propulsion and a homogenous group, meaning differences in type & severity of disability would not interfere with the data. This group is, to some extent, comparable with newly injured persons with intact upper body function. Previous research based on the same philosophy and the use of able-bodied participants to simulate the early rehabilitation phase of individuals new to a wheelchair (5, 12-14, 20, 23, 26-28, 50, 51). Participants were informed that they could withdraw from the study at any time without having to give an explanation and without penalty. Inclusion criteria were; 18-40 years, inexperienced in wheelchair use and absence of any musculoskeletal problems. All participants completed a PAR-Q questionnaire (6), then randomly assigned to an experimental group: TG (n = 10, mean age: 25 ± 4 years, stature: 1.75 ± 0.09 m, body mass: 71.6 ± 9.9 kg) and CG (n = 10, mean age: 27 ± 5 years, stature: 1.74 ± 0.04 m, body mass: 72.2 ± 16.0 kg).

Incremental Exercise Test Protocol

To evaluate the changes in cardiorespiratory fitness, peak physiological parameters were determined by a maximal incremental handcycle exercise test, performed on a motor-driven treadmill (Saturn, HP-Cosmos, Nussdorf, Germany, 1.0 x 2.7 m) using a standard sports wheelchair (Morriën, Morriën BV, Nijkerk, Netherlands) with an attached handcycling unit. This test was conducted before and after the training period for both groups.

To measure power output (PO), the cranks of the add-on handcycling unit were fixed at the lightest gear and were instrumented with a power sensor SRM-system (Schoberer Rad Messtechnik, Welldorf, Germany, Rotor 3D+ compact; accuracy 0.5%, sample frequency 1Hz). PO was continuously measured by the SRM and data were recorded on the SRM power controller 7. The SRM system produces a valid and reliable measurement of PO (18).

The exercise load was increased by adding a load of 0.5% of body weight to the pulley system at the back of the handcycle every minute until volitional exhaustion as described in previous studies (11, 22). The peak respiratory exchange ratio (RER_{peak}) and $\dot{V}O_{2peak}$ were derived from an open circuit spirometer (CPX, Jaeger, Hoechberg, Germany). The peak heart rate (HR_{peak}) and PO_{peak} were collected from the SRM system.

Data selected for analysis depended on how long a participant could continue in the final minute of the test. If the final stage lasted more than 50 seconds, data collected over the 20th – the 50th second of the final stage were averaged to calculate peak values. If the final stage lasted between 30-50 seconds, data obtained over the final 20-second period were analyzed. If the final stage lasted less than 30 seconds, data collected over the 20th – the 50th second of the previous stage were analyzed.

Wheelchair Sub-Maximal Protocol

In addition to the incremental handcycling test, a submaximal wheelchair test was conducted before and after the training period. All participants were tested in the same wheelchair of 14 kg total mass. A non-folding ultra light wheelchair (Quickie, USA) was mounted with a force- and torque-sensing SMART^{Wheel} (3 Rivers Holdings, Mesa, AZ) to the right wheel to collect kinetic data. The characteristics and properties of the SMART^{Wheel} are described in more detail elsewhere (39). No individual adjustments relative to anthropometrics of the participants were made.

Prior to the submaximal wheelchair test, resting oxygen consumption was measured breath by breath, using an open-circuit spirometer (CPX, Jaeger, Hoechberg, Germany) for 5 minutes. The gas analyzer was calibrated using room air, a Jaeger 31-syring and a calibration gas (16.0% O_2, 5.0% CO_2). Participants completed a four x 3-minute familiarization and performed an overground wheelchair test to investigate their preferred comfortable speed using SMART^{Wheel} Standard Clinical Evaluation Protocol, a propulsion assessment that requires users to propel a manual wheelchair on a level tile floor for 2 x 10 second trials of propulsion at their comfortable speed (CS). The average comfortable speed from the 2 trials was used for further testing.

In the present study, 3 propulsion speeds were included and wheelchair propulsion efficiency was determined for all three speeds, as described in our previous study (5). We adopted a propulsion speed protocol that demonstrated 54%-64% $\dot{V}O_{2peak}$ and ratings of perceived exertion (RPE) of 7-13 (38). RPE scores were obtained using a 15-point Borg scale of perceived exertion, where 6 represents ‘extremely light’ and 20 represents ‘extremely hard’(3). The RPE scores were reported immediately after each trial by nodding when the experimenter was pointing to their RPE. CS and 125% of CS were selected to represent typical of everyday functional propulsion (38). The speed of 145% of CS was used to represent a relatively challenging speed (34, 38). A 4-minute familiarization period was included to allow the subject to become accustomed to the set speeds (CS, 125% and 145% of CS) to be employed during the 4-minute test period on the motor-driven treadmill (Saturn, HP-Cosmos, Nussdorf, Germany, 1.0 x 2.7 m). After an 8-minute rest period, participants propelled the wheelchair on the driven motor treadmill at 3 different imposed speeds. Each exercise bout consisted of 4 minutes of exercise following 8 minutes of rest to allow for heart rate to return close to baseline. Participants did not receive specific instructions on wheelchair propulsion style other than to stay in the middle of the treadmill using the handrims. The uninstructed practice was used to minimize a motor learning bias, which could affect propulsion efficiency and focus primarily on the upper body training effects (12).

Oxygen consumption and heart rate were continuously collected during the 4-minute submaximal wheelchair tests and were calculated as an average value over 20 seconds of the last minute. Participants' %$\dot{V}O_{2peak}$ at each speed pre and post intervention was calculated. In addition, push characteristics were determined from the torque signal as defined in De Groot et al. (14). Push frequency was defined as the number of pushes per minute. Push time was defined as the time duration that the hand applied a positive torque on the handrim.

Using the measured torque and wheel velocity, which were derived from SMART^{Wheel}, PO on each wheel was calculated as:

$$PO = Mz \cdot V_W \cdot r_W^{-1} \qquad \text{(Eq 1) (35)}$$

where M_z is the torque around the axle, V_W the velocity of the wheel and r_W is the wheel radius (0.318 m).

Mean power output (PO_{mean}) was calculated from the torque applied to the wheel axis (Mz) and angular velocity (ω) (35) and was calculated as an average value over the final 20 seconds.

$$PO_{mean}\ (W) = ([\sum(Mz\ (N \cdot m) \cdot \omega\ ({}^{\circ} \cdot s^{-1}))] \cdot 2)/Samples \qquad \text{(Eq 2)(35)}$$

As the SMART^{Wheel} measured the right side only, symmetry was assumed. To determine PO, thus, the values of the right wheel were multiplied by 2. The recovery period was accounted for with Mz (being ≤1 Nm) and the angular velocity of the hub, time averaged from the onset of the first push to the end of the recovery phase.

Kinetic Measures

The forces and moments were collected over the final 20 seconds of each trial.

Kinetic data were obtained via an infrared wireless transmitter at 240Hz using the SMARTWheel. Kinetic data were filtered using the SMARTWheel manufacturer's 32-tap finite impulse response (FIR) low-pass digital filter with a cut-off frequency of 20 Hz. The beginning and end of the pushes were derived from the M_z and were identified by the absolute value of 1Nm. The push started when M_z was > 1 Nm and ended when ≤1 Nm. Matlab[c] was used to identify cycles and compute variables.

The fraction effective force (FEF) on the handrim was calculated from the total force applied to the handrim (F_{tot}) and tangential force (F_t) for each workload and expressed as a percentage:

$$FEF = F_t \cdot F_{tot}^{-1} \cdot 100\ (\%) \qquad \text{(Eq 3)(8)}$$

The FEF was expressed as the time average FEF over the last 20-second measurement period.

Gross Mechanical Efficiency

Gross mechanical efficiency (GE) was calculated as the ratio of the external work to energy expended during exercise. External work done was determined from the PO_{mean} values derived from the SMARTWheel during the handrim wheelchair propulsion. The metabolic energy expenditure (En) was calculated by multiply oxygen uptake with the oxygen equivalent:

$$E_n\ (W) = \dot{V}O_2\ (l.min^{-1}) \cdot ((4940) \cdot RER + 16040/60) \qquad \text{(Eq 4)(17)}$$

The following equation was used to calculate GE

$$GE = PO_{mean} \cdot En^{-1} \cdot 100\ (\%) \qquad \text{(Eq 5)(53)}$$

Training Protocol

In the 4-week training period, TG performed 2 RT sessions and 2 HIIT per week. The load of RT was 70% of 1 repetition maximum (1RM). 1 RM was determined by weight and number of repetitions using Brzyck equation (4).

$$1RM = Weight/(1.0278 - (0.0278 \times \text{Number of repetitions})) \qquad \text{(Eq 6)(4)}$$

Participants performed RT in accordance with ACSM guidelines. They completed 3 sets of 10 repetitions at 8 different exercise stations consisting of exercise on machines (Life Fitness, Franklin Park, Illinois, USA) for seated chest press, chest fly, lateral pull down, seated row, seated shoulder press, overhead cable for triceps extension, and dumbbell exercise for side lateral raise and biceps curl. Muscles worked were pectorals, deltoids, biceps, triceps, rhomboids and latissimus dorsi (32).

HIIT consisted of handcycling exercise using an arm crank ergometer (Angio, Lode, Groningen, the Netherlands). The HIIT program of exercise intensity, frequency and work-rest ratio was based on intervention by Nybo et al (36). Participants carried out a 2-minute warm -up period prior to arm cranking training comprising 7 intervals of 2 minutes at 80-90% of HR_{max}. Between intervals, a 2-minute arm cranking active recovery period was performed at 50-60% of HR_{max}. The arm cranking training concluded with a 2-minute cool down period at 50-60% of HR_{max}. Training sessions took place on separate days of the week.

Statistical Analyses

The data were analyzed using the Predictive Analytics Software (SPSS for Mac Version 19; SPSS Inc., Chicago, USA). Standard descriptive statistics (mean ± SD) were calculated for all physiological and kinetic variables. An independent t-test was applied to subject characteristics to detect baseline differences between the groups. A repeated measures ANOVA, with time (pre- and post-test) as the within factor, and group (TG and CG) as the between factor, was applied to detect significant differences over time for efficiency parameters (FEF and GE), push characteristics (push frequency and push time), peak exercise parameters and percentage of $\dot{V}O_{2peak}$, at each of the 3 speeds. Significance level was set at $p < 0.05$ for all statistical procedures. Effect size was calculated using partial eta-squared (η_p^2) and interpreted as small (≥ 0.01), medium (≥ 0.06) or large (≥ 0.14) (7).

RESULTS

Subject characteristics in TG and CG

There was no significant difference in CS between TG (0.92 ± 0.3 m/s) and CG (0.96 ± 0.2 m/s). No baseline differences in body mass, HR_{rest}, body fat and blood pressure between groups were detected, see **Table 1**. A significant main time effect (decrease) was found for % body fat. A significant interaction effect was detected for HR_{rest}. Training resulted in a 3.8% ± 1.5% decrease in HR_{rest}

Peak Physiological Fitness

Training resulted in a 28.2% ± 16.5% increase in PO_{peak}, 13.3% ± 7.5% increase in $\dot{V}O_{2peak}$ and 5.6% ± 0.9% increase in HR_{peak}. Comparisons of peak values obtained during maximal incremental tests before and after training are presented in **Table 2**. Significant group x time interactions were found for PO_{peak}, $\dot{V}O_{2peak}$ ($l \cdot min^{-1}$) and $\dot{V}O_{2peak}$ ($ml \cdot kg^{-1} \cdot min^{-1}$) with greater increases occurring in the TG for each variable.

Significant main effects of time (increases) were found in PO_{peak}, $\dot{V}O_{2peak}$ ($l \cdot min^{-1}$) and $\dot{V}O_{2peak}$ ($ml \cdot kg^{-1} \cdot min^{-1}$). No significant interactions or main effects of time were detected in RER_{peak}.

Push characteristics and efficiency parameters

Comparisons of push characteristics, efficiency parameters and % $\dot{V}O_{2peak}$ at each speed, pre and post intervention according to group are presented in **Table 3**. No significant interactions were detected in the percentage of push frequency or push time at any speed ($p > 0.05$). However, significant main time effects were found showing a decrease in push frequency at CS and 125%. There was no change in FEF or GE over time or between groups at any speed ($p < 0.05$). There were no significant main effects or interactions for the change in % $\dot{V}O_{2peak}$, but moderate effect sizes (partial eta squared) of 0.078 and 0.129 at CS and 125% of CS, respectively, were found, and a small effect size of 0.016 at 145% of CS.

DISCUSSION

This was the first study to examine the effects of a 4-week combined upper body RT and 7x2 min handcycling HIIT program on handcycling peak performance, wheelchair propulsion efficiency, force effectiveness, push characteristics and cardiorespiratory fitness. We hypothesized that this combined upper body training program would improve peak performance and peak oxygen consumption, and would lead to improved submaximal wheelchair performance in able- bodied men.

The primary outcomes of this study are indeed the significant improvements in PO_{peak} (+28.2%), $\dot{V}O_{2peak}$ (+13.3%) and HR_{peak} (+5.6%) after 4 weeks of training. Our results therefore clearly illustrate the effectiveness of the combined upper body training program on peak handcycling performance as well as cardiorespiratory fitness. According to previous investigations, upper body training can be categorized into at least 3 modes: handcycle or arm cranking training, wheelchair training and RT (46). The magnitude of improvement in PO_{peak} and $\dot{V}O_{2peak}$ after our combined upper body training was higher than average change values found in spinal cord injured persons performing RT and aerobic exercise with the use of a rowing machine (40). Weight lifting combined with handcycling or other aerobic exercises has been evaluated, as well as handcycle training or wheelchair exercise only, demonstrating mean values of 26.1% for PO_{peak} (ranged from 10.1% to 57.2%) and 17.6% for $\dot{V}O_{2peak}$ (ranged from 5.1% to 33.5%) across these training modes (46). However, improvements in the current were lower than found after a 7 week handcycling HIIT protocol in which participant complete a very demanding 4x4 HIIT protocol 3 times per week. In that study, also using able-bodied subjects, large improvements in PO_{peak} (+47.1%) and $\dot{V}O_{2peak}$ (+22.2%) were noted (43). When compared to the equivalent HIIT protocol of 4 weeks, 2 times per week by Yang et al. (55), our combined RT and HIIT protocol showed greater improvements. Yang reported a small increase in $\dot{V}O_{2peak}$ (+7%) and PO_{peak} (+15%) after training. Our findings support the notion that adding RT to a standard HIIT program could have greater beneficial effects on peak canoeing capacities and performance compared to HIIT alone (55). From a practical viewpoint, the present combined protocol using indoor gym equipment and arm crank ergometer improved peak physiological outcomes, indicating the effectiveness of the combined upper body training strategy in the design of an optimal strength and endurance training program for upper body exercise. These findings are particularly applicable to wheelchair racers, handcyclists and canoeists, who require high values for both maximal aerobic and anaerobic capacities as well as a high level of upper body muscle strength. Similarly, athletes who are interested in ‘off-feet conditioning’, due to injury or periodised rest will find these findings valuable.

The mechanisms underlying the improvements in aerobic power and peak oxygen uptake of arm cranking HIIT programs have been explained through peripheral adaptations as well as central factors. Mitochondrial oxidative capacity is improved following training due to increases in PGC-1α and Ca^{2+} reuptake into the sarcoplasmic reticulum, resulting in a reduction exercising muscle fatigue (29). These oxidative adaptations enhance muscle function and contribute to the improvement in cardiorespiratory fitness (52). Also, central factors are likely to underlie the improvement in $\dot{V}O_{2peak}$ following arm cranking HIIT. It has previously been found that myocardial contractility and ejection fraction are improved with HIIT (54). The upper body HIIT may result in different physiological response compared with lower body training due to the differences in muscle size, strength, relative mean repetition velocity and oxygen uptake kinetics (42).

The limited data available on combined training suggested that RT combined with aerobic training on a rowing machine at 60% of maximal heart rate reserve for 30 minutes 3 times weekly for 6 weeks improved propulsion (defined by a decreased push frequency and increased propulsive moment) (40). In the current study, no force or push adaptations were found as a result of training. The difference with previous literature may be due to the different subject groups participating in the various studies. Subjects in previous studies frequently had clinical conditions and experience using a manual wheelchair, compared with novice able-bodied users in the present study. However, improvements in peak physiological capacity in the study of Rodgers et al. (40), whose participants were experienced wheelchair users with spinal cord injury or lower limb dysfunction, were lower (14.6+% for PO_{peak} and +6.8% for

$\dot{V}O_{2peak}$.) than the improvements reported in the present study, As there are differences in physiology between able-bodied and disabled individuals (2), the effect of the training on the clinical population may differ. Some level of caution must be used when transferring data to wheelchair users. However, it is important to evaluate how data collected in able-bodied individuals compares with individuals with different disabilities. The use of a homogenous group of able-bodied participants allowed us to better understand the training effect of the concurrent upper body training. This provided useful data to be able to interpret any deviations from this able-bodied pattern due to disabilities. Previous evidence showed that able-bodied individuals are to some extent comparable with newly injured individuals with intact upper body function (30). Therefore, our findings could be, at least, transferable to the newly injured population with intact upper body function in the initial stages of rehabilitation.

The improvements in peak handcycling performance are particularly relevant for improving upper body health and endurance (22, 43), but whether combined resistance and arm cranking training also impact on wheelchair propulsion, is of interest in rehabilitation settings. Results of the present study showed that training adaptations after handcycling training were exercise specific, since no improvement in the propulsion efficiency, force application or push characteristics during wheelchair exercise were found. This may be due to the differences in the nature of arm cranking/handcycling and wheelchair propulsion. An arm cranking/handcycling exercise does not reproduce the pushing movements required for propelling a wheelchair. This speculation could be supported by previous work by Hettinga et al., which highlighted the importance of specificity of training to improve upper body performance and physiological capacity (22). Arnet et al. (1) indicated that compared with wheelchair propulsion, peak relative muscle forces and glenohumeral contact forces were lower during handcycling. The peak relative muscle forces of supraspinatus, infraspinatus and biceps were 3.3 times, 2.8 times and 2.3 times, respectively, higher during wheelchair propulsion compared with handcycling. In addition, the nature of force application between handcycling and wheelchair propulsion is different. During handcycling, continuous force is evenly applied throughout the full motion cycle with the peak forces observed at the end of cycle. Conversely, wheelchair propulsion is a discontinuous motion (actively work around 30-40% of the cycle), with peak forces found in the middle of the push phase (90° vertical) with smaller peaks at the early and late of the recovery phase (1). Further, since the most effective direction of exerted forces is tangential to the pushrim, both agonistic and antagonistic muscles of shoulders and arms are required for an optimally directed force during the propulsive phase with the need for coupling-uncoupling actions in handrim propulsion (48). Muscle activity and force application differences between arm cranking/handcycling and wheelchair propulsion may be responsible for the lack of improvement in wheelchair propulsion characteristics after arm cranking training in the present study.

Interestingly, at the 3 speeds, % $\dot{V}O_{2peak}$ of the TG reduced in response to the intervention compared with CG, who demonstrated an increase in % $\dot{V}O_{2peak}$. Even though there were no significant interactions, moderate to large effect sizes were seen in several cases. The training group worked at a lower (not significant) percentage of $\dot{V}O_{2peak}$ after intervention compared with the control group. Though they were not significantly different, the relative exercise intensities varied between subjects and between conditions. At lower % $\dot{V}O_{2peak}$, as seen in TG post, GE is usually lower because of the relatively large contribution of basal metabolism (33). GE in our study ranged between 4-6%, and the FEF ranged between 60-75%, ranges that are consistent with previous studies (2%-11% and 57%-80% for GE and FEF respectively) (10, 49, 51). The present study also found that the efficiency parameters increased, associated with increasing speed in both groups in agreement with previous studies (5, 13, 49).

The lack of adaptation in wheelchair push characteristics after arm cranking training might result in a lack of improvement in muscle work which relates to efficiency parameters (28). It has been suggested that an optimal push frequency at CS correlated with oxygen consumption and GE (20). Consistent with previous studies, push frequency in this study ranged from 42-57 pushes/minute at CS (27) with a similar push time to that reported in the literature (0.27s- 0.31s) (26). Lower push frequency provides adequate time to generate higher force and apply to the handrim, which results in higher propulsive moments (27, 40). Consequently, this would allow wheelchair users to improve their propulsion economy. It could be suggested that a longer push time as well as lower push frequency could improve efficiency.

PRACTICAL APPLICATIONS

In the current intervention, 4-weeks of combined upper body training improved peak handcycling performance as well as cardiorespiratory fitness expressed as $\dot{V}O_{2peak}$, which could practically benefit people who are interested in improving upper body sports performance e.g. experienced wheelchair racers, handcyclists and canoeists. For individuals who are new to wheelchair use, however, intervention did not translate into an improved wheelchair propulsion efficiency or effect push characteristics. Strength and conditioning professionals working in rehabilitation settings may consider additional wheelchair skill training during rehabilitation to fully benefit from this advantage in daily life propulsion.

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Table 1. Body mass, resting heart rate, body fat and blood pressure for the two groups in pre- and post-test. Significance values for main effects of time, and group x time interaction are shown (Mean ± *SD*).[*]

Variable	TG		CG		*P*	*P*
	Pre-test	Post-test	Pre-test	Post-test	pre- post-test	*Group x Time*
Body mass (kg)	71.6±9.9	71.6±9.3	72.2±16.0	72.4±14.6	0.899	0.761
HR_{rest} (bpm)	73.6±12.0	70.8±17.2	73.4±7.5	83.0±8.6	0.117	0.008[‡]
Body fat (%)	15.2±3.1	13.3±2.9	15.6±5.6	15.1±5.6	0.007[†]	0.120
SBP (mmHg)	122.7±17.6	118.6±10.7	118.1±2.6	126.5±10.5	0.481	0.051
DBP (mmHg)	71.3±14.5	68.7±9.3	71.1±7.2	70.9±4.5	0.590	0.644

[*] HR_{rest} = resting heart rate; SBP = systolic blood pressure; DBP = diastolic blood pressure; TG = training group, CG = control group. [†]significant main time effect ($p < 0.05$). [‡]significant interaction effect ($p < 0.05$).

Table 2. Peak exercise parameters using handcycling incremental submaximal test for the two groups in pre- and post-test (Mean ± *SD*).*

Variable	TG		CG		*P*	*P*
	Pre-test	Post-test	Pre-test	Post-test	pre- posttest	*Group x Time*
PO_{peak} (W)	81.8 ± 24.9	104.9 ± 29.5	95.2 ± 29.5	89.5 ± 30.7	0.006†	<0.001‡
HR_{peak} (bpm)	152.3 ± 13.7	160.8 ± 14.1	165.8 ± 12.2	164.9 ± 17.0	0.068	0.027‡
$\dot{V}O_{2peak}$ ($l \cdot min^{-1}$)	1.7 ± 0.5	1.9 ± 0.5	1.8 ± 0.4	1.7 ± 0.4	0.040†	<0.001‡
$\dot{V}O_{2peak}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	24.2 ± 5.7	27.4 ± 6.2	25.3 ± 5.5	24.4 ± 5.4	0.040†	<0.001‡
RER_{peak}	1.15 ± 0.07	1.19 ± 0.08	1.17 ± 0.09	1.14 ± 0.08	0.767	0.172

*TG = training group; CG = control group; PO_{peak} = peak power output; HR_{peak} = peak heart rate; $\dot{V}O_{2peak}$ = peak oxygen consumption; RER_{peak} = peak respiratory exchange ratio. †significant main time effect ($p < 0.05$). ‡significant interaction effect ($p < 0.05$).

Table 3. Wheelchair push characteristics, levels of FEF, GE and % $\dot{V}O_{2\ Peak}$ for the two groups in pre- and post-test (Mean ± *SD*).[*]

Variable	Speed	TG		CG		*P*	*P*
		Pre-test	Post-test	Pre-test	Post-test	pre- posttest	*Group x Time*
Push frequency (pushes/min)	CS	57.0 ± 9.6	49.5 ± 15.8	59.4 ± 11.6	42.6 ± 12.9	0.001[†]	0.169
	125%	59.1 ± 12.8	51.0 ± 18.5	55.5 ± 15.5	47.4 ± 16.4	0.007[†]	1.000
	145%	68.4 ± 22.7	62.1 ± 21.4	57.9 ± 17.4	48.0 ± 13.7	0.070	0.674
Push time (s)	CS	0.30 ± 0.08	0.28 ± 0.12	0.33 ± 0.09	0.30 ± 0.06	0.262	0.927
	125%	0.27 ± 0.27	0.28 ± 0.08	0.25 ± 0.06	0.26 ± 0.06	0.366	0.744
	145%	0.25 ± 0.11	0.25 ± 0.06	0.23 ± 0.06	0.24 ± 0.05	0.882	0.472
FEF (%)	CS	70.0 ± 14.0	62.3 ± 12.9	65.5 ± 15.2	60.8 ± 14.1	0.137	0.707
	125%	68.7 ± 12.7	63.9 ± 13.4	69.6 ± 10.7	68.4 ± 15.1	0.457	0.660
	145%	74.4 ± 10.3	66.6 ± 15.2	72.8 ± 12.5	75.7 ± 16.2	0.485	0.124
GE (%)	CS	4.8 ± 1.3	4.0 ± 1.0	4.9 ± 2.0	4.6 ± 1.9	0.118	0.620
	125%	5.2 ± 1.6	4.6 ± 1.3	5.5 ± 1.7	5.1 ± 2.2	0.173	0.771
	145%	5.9 ± 1.3	5.4 ± 1.3	6.0 ± 1.7	5.8 ± 2.3	0.364	0.700
% $\dot{V}O_{2\ Peak}$ (%)	CS	40.4 ± 5.1	38.1 ± 2.8	36.4 ± 5.1	42.0 ± 2.8	0.624	0.232
	125%	43.0 ± 3.8	41.6 ± 3.2	40.5 ± 3.8	48.5 ± 3.2	0.265	0.121
	145%	46.9 ± 3.1	46.3 ± 4.1	48.1 ± 3.1	50.4 ± 4.1	0.761	0.599

[*]TG = training group; CG = control group; FEF = fraction of effective force; GE = gross mechanical efficiency; % $\dot{V}O_{2peak}$ = percentage of peak oxygen consumption; CS = comfortable speed. [†]significant main time effect ($p < 0.05$). [‡]significant interaction effect ($p < 0.05$).