Title Page

Title: The Relationship Between Absolute and Relative Upper Body Strength and Handcycling Performance Capabilities

Running Head: Handcycling performance

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Abstract

Purpose: The aim of the present study was to explore the relationship between absolute and relative upper body strength and selected measures of handcycling performance.

Methods: Thirteen, trained H3/H4 classified, male handcyclists (Mean (± *SD*) age 37 ± 11 yrs; body mass 76.6 ±10.1 kg; peak oxygen consumption 2.8 ± 0.6 l·min^{-1}; relative $\dot{V}O_{2peak}$ 36.5 ± 10 ml·kg·min^{-1}) performed a prone bench pull and bench press 1 repetition maximum strength assessment; a 15-km individual time trial; a graded exercise test; and a 15-s all-out sprint test. Relationships between all variables were assessed using Pearson's correlation coefficient.

Results: Absolute strength measures displayed a large correlation with gross mechanical efficiency and maximum anaerobic power output (p = 0.05). However, only a small to moderate relationship was identified with all other measures. In contrast, relative strength measures demonstrated large to very large correlations with gross mechanical efficiency, 15-km time velocity, maximum anaerobic power output, peak aerobic power output, power at a fixed blood lactate concentration of 4 mmol·l^{-1} and peak oxygen consumption (p = 0.05).

Conclusion: Relative upper body strength demonstrates a significant relationship with TT velocity and several handcycling performance measures. Relative strength is the product of one's ability to generate maximal forces relative to body mass. Therefore, the development of one's absolute strength combined with a reduction in body mass may influence real-world handcycling race performance.

Keywords: Paralympic Sport; Handbiking; Upper Body Strength, Arm Crank Ergometry

Introduction

Handcycling is a competitive and recreational sport used by individuals who are unable to ride a conventional road bike or tricycle due to either a spinal cord injury (SCI) and/or other physical impairment of the lower limbs. Competitive handcyclists are classified into one of five categories (H1 - H5) according to the nature of their physical impairment, with H1 athletes having the greatest physical impairment and lowest function.[31] Athletes in the H1 - H4 classes use a recumbent, arm-powered position, whilst athletes in the H5 class adopt a kneeling position and use their arms and trunk to power their handbike. Since its formal recognition by the International Paralympic Committee (IPC) in 1999, the popularity of handcycling has increased considerably, as has the scientific interest and amount the research conducted, which usually focuses upon optimising handbike design and/or the physical preparedness of handcyclists.[25]

Whilst the biomechanics,[6,19,26] handbike-user interface,[2,16,27] and physiological characteristics of handcycling performance,[1,7,13,17] have been extensively investigated few studies have neither considered, nor explored the influence of upper body strength upon handcycling performance. Nevin et al,[17] demonstrated that 8-weeks of concurrent strength and endurance training enhanced handcycling performance to a greater extent than endurance training alone. These novel findings suggested that upper body strength may be an important determinant of handcycling performance. Indeed, maximal upper body strength has been demonstrated to have a significant impact upon performance in several other sports that are upper body dominant including kayaking,[30] wheelchair racing,[28,29] ice sledge hockey,[23] and sailing.[18].

Fundamentally, handcycling performance depends on several external and internal factors. External factors include aerodynamic drag, frictional forces between the tyres and road surface, the gradient of the terrain and total system mass.[5] In addition to these external factors, the primary internal factor which determines handcycling performance is the extent of mechanical power applied to the crank arms.[9] Mechanical power is the product of tangential torque and crank angular velocity. Thus, the greater the mechanical power generated by the rider, the higher the velocity. Based upon this theory it can be postulated that upper body strength may have a significant impact upon handcycling performance as logically, greater upper body strength would allow a rider to generate greater tangential torque during both the pull and push phases of the handcycling propulsion cycle (Fig 1), thereby improving subsequent mechanical power output and effective velocity.[9]

Given the paucity of research linked to the influence of upper body strength on handcycling performance, the aim of the present study was to explore the relationship, between both absolute and relative measures of upper body strength, an ecologically valid 15-km time trial (TT) and selected physiological measures of handcycling performance. It was hypothesized that, both absolute and relative measures of upper body strength would demonstrate significant relationships with handcycling performance capabilities.

***** Insert Figure 1 Here*****

Methods

Participants

Thirteen, UCI classified male handcyclists with at least one year's recreational handcycling experience took part in this study. All participants were classified as either an H3 or H4 arm-powered handcyclist in accordance with current UCI Paracycling regulations.[31] Six participants were bi-lateral, above knee amputees (H4); one was a triple amputee (H3); and five were paraplegic with impairments corresponding to a spinal lesion between levels T1 to T10 (H3). Mean (± *SD*) participant characteristics were age 37 ± 11 yrs; body mass 76.6 ±10.1 kg; peak oxygen consumption ($\dot{V}O_{2peak}$) 2.8 ± 0.6 l·min^{-1}; relative $\dot{V}O_{2peak}$ 36.5 ± 10 ml·kg·min^{-1}. No medical conditions or upper-body musculoskeletal injuries were reported prior to the study. This study was conducted in accordance with the declaration of Helsinki with approval granted by the Research Ethics Committee of Buckinghamshire New University, High Wycombe, United Kingdom. All participants provided written informed consent to take part in this study

Design

This was a single-cohort, cross-sectional research design that explored the relationship between upper-body strength, 15-km TT velocity and selected physiological measures of handcycling performance. Prone bench pull and bench press 1 repetition maximum (1RM) were assessed and subsequently correlated to 15-km TT velocity, $\dot{V}O_{2peak}$, peak aerobic power (PO_{peak}), power at a fixed blood lactate concentration of 4 mmol·l^{-1} (PO_4), gross mechanical efficiency (GME), and maximum anaerobic power output ($PO_{max,AO15}$). Testing was completed over three consecutive days: 15-km TT (day 1), graded exercise test (GTX), and 15-s all-out sprint test (day 2); and 1 repetition maximum (1RM) strength testing (day 3). A period of 24 hours separated testing sessions in order to limit the impact of fatigue. Before testing, all participants were asked to abstain from strenuous exercise and refrain from consuming caffeine and alcohol for at least 48 hours. TT performance was evaluated outdoors in dry and stable meteorological conditions (19 ± 2° C, <10 km/h wind speed). All laboratory testing was performed indoors, under controlled, ambient conditions (18° C, 50 – 60% relative humidity).

Individual 15-km Time Trial

In order to assess real world handcycling performance of trained participants, a 15-km individual TT was conducted on a closed, cycling racing circuit (Odd Down, Bath, England). This location provided an undulating, 1.5-km smooth tarmac circuit with a total elevation loss and gain of 9 m per lap. Following two familiarisation laps, participants were required to complete ten laps of the 1.5-km circuit as quickly as possible. Participants were monitored by means of a GPS receiver (Garmin Edge

1000, Garmin Ltd, USA). Data were used to establish TT performance in the form of mean velocity ($km \cdot h^{-}1$).

Graded Exercise Test

In all aspects of physiological testing, each participant bike was fitted to a standard, indoor cycling turbo trainer (Fluid 2, CycleOps, USA) Each participant's power output measured using an instrumented front wheel hub (Powertap, G3, CycleOps, USA, 1.5% accuracy between 0 and 1999 W, sample frequency 0.2 Hz). The Powertap has been shown to be a reliable instrument (CV 0.9 – 2.9%) for the measurement of power whilst cycling[3] and was calibrated prior to testing, in accordance with the manufacturer's instructions. Oxygen consumption ($\dot{V}O2$), carbon dioxide production ($\dot{V}CO2$), minute ventilation ($\dot{V}E$), and respiratory exchange ratio (RER) were continuously monitored using a calibrated, online gas analysis system (Oxycon Pro, Jeager, Warwick, Warwickshire, UK) whilst heart rate (HR) was logged using a commercially available receiver (Garmin Edge 1000, Garmin Ltd, USA).

Following a 10-min warm-up at a self-selected power output, participants were requested to start the test protocol at a work rate of 40 W with subsequent 20 W increments every 5-mins until the required mechanical power output could no longer be maintained, or until participants reached volitional exhaustion.[1,19,27] Values of $\dot{V}O_{2peak}$ and PO_{peak} were identified as the highest power output and peak oxygen consumption achieved during the last fully completed 30-s. Throughout the test, participants were free to adjust their gear ratio and/or crank rate as needed in order to achieve and maintain the required mechanical power output. Every 5-mins and upon immediate completion of the test participants were asked to indicate their rating of perceived exertion (RPE) using a 6 to 20 Borg scale.[4] All respiratory parameters were calculated for each breath and averaged at 1-min intervals at rest and every 30-s during each exercise stage.

At the end of each stage and at the point of volitional exhaustion, a small sample of capillary blood was collected from an earlobe to measure blood lactate concentration. These data were used to identify fixed blood lactate concentrations of 2 and 4 mmol·l^{-1}. Once collected, capillary blood samples were treated, analysed, and disposed of immediately using a fully automated analyser (Biosen C-line, EKF Diagostics, Barleban, Germany). Values of GME were calculated as the ratio of external work produced to the amount of energy expended when a fixed blood lactate concentration of 2 mmol·l^{-1} was reached. This metabolic parameter was selected as it represents a consistent, submaximal exercise intensity during which energy production is predominantly achieved via aerobic metabolic pathways. Metabolic energy expenditure was calculated from associated $\dot{V}O_2$ and RER data according to Garby and Astrup[8] and expressed as a percentage value: GME = ((external work done / energy expenditure) x 100) (%). As an approximation of anaerobic threshold, power output corresponding to the onset of blood lactate accumulation (OBLA) at a fixed blood lactate concentration of 4 mmol·l^{-1} was also identified.

15-s All-Out Sprint Test

Following the GTX, participants were given a one-hour recovery period prior to completing a 15-s all-out sprint protocol to assess anaerobic performance.[21] Participants were asked to complete a 10-min warm up at a self-selected power output. Prior to commencement of the test the gear ratio was set to 50/11. Once the participant acknowledged that they were ready, the test was initiated. Throughout the test protocol, participants were verbally encouraged to exert maximum, physical effort with the greatest mechanical power output subsequently recorded.

Upper-Body Strength Testing

In order to evaluate maximal upper body strength, measures of prone bench pull (Fig 2) and bench press (Fig 3) 1RM were determined. Strength testing was conducted on a specifically designed, IPC Para-powerlifting bench (Eleiko, Sweden) and a prone pull bench (Pullum Sports, England) using a

20 kg Olympic barbell, 450 mm diameter barbell plates (25, 20, 15 and 10 kg), 200 mm diameter barbell plates (5, 2.5, 2.0, 1.5, 1.0 and 0.5 kg), two safety locks and two Velcro securing straps (Eleiko, Sweden). Both prone bench pull, and bench press 1RM testing was conducted in line with the protocols proposed by Haff and Triplett.[10] Participants were instructed to perform a light warm-up with the bar only, performing 5 – 10 repetitions. Following a 1-min recovery period a second set of 3 – 5 repetitions was performed with an estimated 60% 1RM load. After a 3-min recovery period another set of 2 – 3 repetitions, was performed with an estimated 80% 1RM load. Thereafter, an estimated 1RM load was selected, and the participant asked to perform a single repetition. If successful, the participant was given a 3-min recovery period prior to performing a further 1RM attempt with an increased load. Participants were allowed, to perform 3 to 5 additional 1RM attempts, with 3-min recovery between sets. This pattern continued until each participant's 1RM values had been established within a precision of 1.0 kg.

*****Insert Fig 2 Here*****

***** Insert Fig 3 Here*****

Statistical Analysis

All data are reported as mean (± *SD*) with a level of significance for all statistical analysis set at $p < 0.05$. Statistical analysis were performed using SPSS Version 25.0 (SPSS Inc, Chicago, USA). Parameters were checked for normal distribution using the Shapiro-Wilk test with the Spearman's coefficient used in cases of violation. Pearson's product-moment correlation coefficients (r) were calculated to establish the relationships between absolute and relative values of prone bench pull and bench press strength (dependent variables), 15-km TT velocity, $\dot{V}O_{2peak}$, PO_{peak}, PO_4, GME, $PO_{max,AO15}$, (independent variables). Correlation coefficients were evaluated as follows: >0.1 small; >0.3 moderate; >0.5 large; >0.7 very large; and >0.9 extremely large.[11]

Results

Mean (± *SD*) data from all aspects of the study are summarised in Table 1. Pearson product-moment correlation coefficients were calculated between absolute and relative prone bench pull and bench press strength, 15-km TT velocity, $\dot{V}O_{2peak}$, PO_{peak}, PO_4, GME, and $PO_{max,AO15}$ (Table 2). Absolute prone bench pull, and bench press strength measures demonstrated small to large correlations with $PO_{max,AO15}$, 15-km TT velocity, GME, $\dot{V}O_{2peak}$, PO_4,and PO_{peak}. However, relative prone bench pull, and bench press strength measures demonstrated large to very large correlations with GME, 15-km TT velocity, $PO_{max,AO15}$, PO_{peak}, PO_4, and $\dot{V}O_{2peak}$.

***** Insert Table 1 Here *****

***** Insert Table 2 Here *****

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Discussion

The aim of the present study was to examine the influence of absolute and relative measures of upper body strength upon selected measures of handcycling performance. This objective was achieved by recruiting a sample of trained H3/H4 classified, male handcyclists. The main findings, based upon the data collected, were that relative prone bench pull, and bench press strength demonstrated a significant relationship with 15-km TT velocity (Fig 4) and several physiological determinants of handcycling performance; namely, GME, $PO_{max,AO15}$, PO_{peak}, PO_4, and $\dot{V}O_{2peak}$. To the best of our knowledge, this is the first study to explore the relationship between absolute and relative measures of upper body strength on handcycling performance using a group of UCI-classified participants. Moreover, it is one of only a handful of studies, to date, which have examined the relationship between upper body strength and performance in a group of physically disabled participants.

Upper Body Strength and Physiological Determinants of Handcycling Performance

Performance testing in handcycling typically includes the determination of $\dot{V}O_{2peak}$,[13,17,19] PO_{peak},[7,13,17] lactate threshold,[1] and GME.[13,17] Findings of the present study suggest a strong relationship between relative upper body strength, $\dot{V}O_{2peak}$, PO_{peak}, and lactate threshold defined as power output at OBLA. Interestingly GME demonstrated a significant relationship with relative upper body strength. This is in agreement with previous studies which have suggested that improvements in maximal upper body strength can enhance GME in both handcyclists[17] and wheelchair users.[28] Improvements in GME may be of particular importance to handcyclists as improvements in mechanical efficiency will likely translate to a reduction in relative workload at a given mechanical power output. Theoretically, this would enable a rider to either produce a higher power output for an equivalent amount of energy expended (*i.e.*, improved performance capacity) or, extended time to exhaustion at a given work rate (*i.e.*, improved endurance capacity) with both scenarios enhancing an athlete's performance potential. Altered muscle fibre type recruitment and changes in musculotendinous stiffness have been proposed as likely mechanisms linked to improvements in GME in endurance athletes following strength training. Ronnestad and Mujika[22] suggested that greater muscular strength may postpone time to exhaustion of type I fibres thereby, delaying the recruitment of less efficient, but more powerful, type IIA fibres. The latter may also have a glycogen sparing effect which might further contribute to improved endurance. Another potential mechanism related to muscle fibre recruitment is an increased proportion of the more fatigue resistant, yet high power output type IIA fibres at the expense of type IIX fibres. Finally, strength training may also result in enhanced musculotendinous stiffness, leading to improved force transmission.[22]

Upper Body Strength and Handcycling Propulsive Forces

Handcycling consists of a repetitive, synchronised, closed-chain motion, which involves alternating pulling and pushing of the upper limbs. These co-ordinated movements create effective, propulsive forces that are transferred to the crank arms.[19] The propulsion cycle in handcycling can be split into 6 distinct sectors (Fig 1), press-down (0° - 45°), pull-down (45 - 90°) pull-up (90° - 180°), lift-up (180° - 225°), push-up (225° - 270°), and push-down (270° - 360°).[15,19] These sectors in turn can be viewed as two phases, each having three complementary sectors. The pull phase (press-down, pull-down and pull-up) and the push phase (lift-up, push-up and push-down). Several authors have demonstrated that novice handcyclists tend to apply a greater proportion of work during the pull phase, with an increase in pulling torque and a concomitant reduction in pushing torque; observed at higher power outputs.[2,6,20,31,26] During the pull/push phase transition, Quittmann et al,[19] noted a reduction in torque, crank angular velocity, and power output within the pull-up and lift-up sectors (Fig 1: 90° - 225°). Based upon this observation, the authors postulated that riders attempt to minimise a loss of torque and velocity near the 180° crank angle by initiating a more powerful pulling action during the preceding pull phase. However, it must be noted that participants in this study were able-bodied and it has been suggested that trained handcyclists may display a more evenly distributed torque profile across the push and pull phases.[15,32] Findings of the present study support the view that both pulling and pushing torque has a significant influence upon handcycling performance as both relative prone bench pull, and relative bench press strength were strongly correlated with 15-km TT velocity. Finally, it is important to note that a handcyclists functional classification level may also impact upon their torque profile with those with a SCI at C6 or above (H1) applying force mainly during the pull phase and those with a lesion at or below C7 (H2 - H4) able to apply force more equally across the push and pull phases.[32]

Upper Body Strength and 15-s All-Out Sprint Ability

Another important factor to consider in regard to handcycling performance is the ability, in a racing context, to close a gap, break away from other riders, or perform well in a sprint. It can be argued the outcome of these crucial moments can be decided by force production capability, as the ability to generate greater tangential torque will result in a higher power output for a short period of time. The present study used a 15-s all-out sprint protocol to measure maximal power output. A significant correlation was demonstrated between relative prone bench pull strength, relative bench press strength and $PO_{max,AO15.}$ These finding suggest a strong relationship between relative strength and the ability to generate a high-power output. These findings should come as no real surprise, as in most contexts, greater muscular strength is associated with enhanced force-time characteristics such as rate of force development and power output.

Relative Upper Body Strength

Relative strength is the product of one's ability to generate maximal forces relative to body mass therefore, a handcyclists ability to generate force, relative to the combined mass of their own body and bike, is arguably more important in the context of competitive performance than maximal strength, *per se*. However, it must be borne in mind that relative strength is highly dependent upon an individual's maximum strength. Therefore, it can be inferred that, for a given body mass, greater maximal upper body strength, in combination with a reduction in non-functional body mass (*i.e.*, reduced body fat) should theoretically improve an athlete's handcycling performance.

Upper Body Strength Testing

Several authors have investigated muscular effort and muscle activation characteristics during the handcycling propulsion cycle. Faupin et al,[6] showed that m. biceps brachialis and m. trapezius surface electromyography (sEMG) activity was highest during the pull phase of the propulsion cycle whilst, m. anterior deltoid and m. pectoralis major sEMG activity increased during the initial sectors of the push phase. In support of these finding, Quittmann et al,[20,21] demonstrated that m. biceps brachialis, m. trapezius, along with m. medial deltoid and m. posterior deltoid sEMG activity increased at progressively higher workloads during the pull phase. In contrast, m. anterior deltoid, m. triceps brachialis and m. pectoralis major activity showed an increase during the initial sectors of the push phase. Interestingly, Quittmann et al,[20,21] observed that m. latissimus dorsi activity was relatively consistent during both the pull and push phases. These findings are somewhat surprising as m. latissimus dorsi is considered to be a major force generating muscle group during upper body pulling movements.[12] However, Quittmann et al,[20] suggested that m. latissimus dorsi may perform more of a stabilising function during the handcycling propulsion cycle. The m. biceps brachialis, m. trapezius and m. latissimus dorsi have all been shown to have high sEMG activity during horizontal upper body pulling exercises.[12] Conversely, m. pectoralis major, m. triceps brachialis and m. anterior deltoid have been found to be highly active during the bench press.[24] Nevin et al,[17] suggested that the prone bench pull, and bench press exercises closely mimic the synchronistic, horizontal pull/push force production movement pattern observed during handcycling. Therefore, given the similarity of muscle activation and movement pattern characteristics both the prone bench pull, and bench press can be seen as suitable exercises by which to assess handcycling specific, upper body strength.

Limitations

The findings of this study provide a novel insight into the influence of absolute and relative upper body strength upon handcycling performance in trained H3/H4 handcyclists. However, it must be noted that there are several limitations associated with the design of the study. Firstly, the sample size was relatively small and heterogeneous in terms of age, performance level, and disability, which resulted in considerable variance within the group. Secondly, seven of the participants were lower limb amputees and five had a SCI. Individuals with a SCI have been shown to have a reduced physiological performance capability as a result of direct motor control loss and sympathetic activity below the level of their spinal lesion.[29] Therefore, participants with a SCI may not have been able to brace themselves or express as much force during 1RM testing due to reduced core stability. Finally, the amputee participants were slightly lighter due to the loss of body mass sustained as a result of their amputations. Therefore, in terms of relative measures they displayed generally higher results.

Practical Applications

In order to optimise handcycling performance capabilities it is recommended that handcyclists include regular upper body strength training designed to enhance horizontal pulling and pushing strength as part of a concurrent strength and endurance training programme. Furthermore, it is recommended that handcyclists augment their current performance testing regimes with regular upper body 1RM strength testing using the prone bench pull and bench press exercises in order to monitor, adjust, and effectively adapt individual strength training loads.

Conclusion

In conclusion, findings from the present study indicate that relative upper body strength demonstrates a significant relationship with 15-km TT velocity and therefore, may influence real-world handcycling race performance. Furthermore, relative upper body strength demonstrates a strong relationship with several physiological measures that can be used to monitor training progress and/or predict handcycling performance – namely GME, $PO_{max,AO15}$, PO_{peak}, PO_4, and $\dot{V}O_{2peak}$. This study used a participant group of trained, H3/ H4 UCI classified handcyclists consisting of both SCI and amputee participants. It could be argued that the amputee participants may have a performance advantage over individuals with an SCI due to potentially greater physiological function and lower body mass. Therefore, it is recommended that further research be conducted to investigate the influence of upper body strength upon handcycling performance capabilities in specific disability groups (e.g., SCI, amputee).

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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References

1. Abel T, Schneider S, Platen P. Struder HK. Performance diagnostics in handcycling during competition. *Spinal Cord*. 2006; 44(4): 211 – 216.
2. Arnet U, Van Drongelen S, Van Der Woude LHV., et al. Shoulder load during handcycling at different incline and speed positions. *Clin Biomech*. 2012; 27(1): 1 – 6.
3. Bertucci W, Duc S, Villerius V, Pernin JN, & Grappe F. Validity and reliability of the Powertap mobile cycling power meter when compared with the SRM device. *Int J Sports Med.* 2015; 26(10): 868 – 873.
4. Borg, GA. Psychophysical based of perceived exertion. *Med Sci Sports Exer.* 1981; 4: 377 – 388.
5. Faria EW, Parker DL, & Faria IE. The science of cycling factors affecting performance – Part 2. *Sports Medicine.* 2005; 35(4): 313 – 337.
6. Faupin A, Gorce P, Watelain E, Meyer C, & Thevenon, A. A biomechanical analysis of handcycling: A case study. *J of Appl Biomech.* 2010; 2, 240 – 245.
7. Fischer G, Ardigo L, & Figueiredo P. Physiological performance determinants of a 22-km handbiking time trail. *Int J Sports Physiol Perf*. 2016; 10: 965 – 971.
8. Garby L, & Astrup A. The relationship between the respiratory quotient and the equivalent of oxygen during simultaneous glucose and lipid oxidation and lipogenesis. *Acta Physiol Scandi.* 1987; 129(3): 443 – 444.

9. Groen WG, Van Der Woude LHV, & De Koning JJ. A power balance model for handcycling. *Disabil Rehabil.* 2010; 32(26): 2165 – 217.

10. Haff GG, & Triplett NT. Essentials of Strength Training and Conditioning (4th Ed). Champaign, Il: Human Kinetics. 2016.

11. Hopkins WG, Marshall SW, Batterham AM, & Hanin J. Progressive statistics for studies in sport medicine and exercise science. *Med Sci Sports Exer.* 2019; 41(1): 3 – 12.

12. Lehman G, Buchan DD, Lundy A, Myres N, & Nalborcyzk A. Variations in muscle activation levels during traditional latissimus dorsi weight training exercises: An experimental study. *Dyn Med.* 2004; 3(4): doi: 10.1186/1476-5918-3-4.

13. Lovell D, Sheilds D, Beck B, Cuneo R, & McLellan C. The aerobic performance of training and untrained handcyclists with spina cord injury. *Euro J Appl Physiol.* 2012; 112(9): 3431 – 3437.

14. Jacobs PL. Effects of resistance and endurance training in persons with paraplegia. *Med Sci Sports Exer.* 2009; 41(9): 687-708.

15. Krämer C, Hilker L, & Böhm H. Influence of crank length and crank width on maximal hand cycling power and cadence. Eur J Appl Physiol. 2009; 106: 749–757. doi:10.1007/s00421-009-1062-1

16. Mannion P, Toparlar Y, Clifford E, Hajdukiewicz M., Andrainne T, & Blocken B. The impact of arm-crank position on the drag of a Paralympic hand-cyclist. *Comp Methods in Biomech and Biomech Engr.* 2019; 22(4): 386 – 395.

17. Nevin JP, Smith P, Waldron M, Patterson S, Price M, Hunt A, & Blagrove R. Efficacy of an 8-week concurrent strength and endurance training programme on hand cycling performance. *J Str Cond Res.* 2018; 32(7): 1861 – 1868.

18. Pearson SN, Hume PA, Cronin JB, & Slyfield D. Strength and power determinants of grinding performance in Americas cup sailors. *J Str Cond Res.* 2009; 23(6): 1883 – 1889.

19. Quittmann OJ, Meskemper J, Abel T, Albrecht K, Foitschik T, Rojas-Vega S, & Strüder HK. Kinematics and kinetics of handcycling propulsion at increasing workloads in able-bodied subjects. *Sports Eng.* 2018; 21(4), 283 – 294.
20. Quittmann OJ, Abel T, Albrecht K, & Strüder HK. Reliability of muscular activation patterns and their alterations during incremental handcycling in able-bodied participants. *Sports Biomech*. 2019; https://doi.org/doi:10.1080/14763141.2020.1745266
21. Quittmann OJ, Abel T, Albrecht K, & Strüder HK. Biomechanics of all-out handcycling exercise: kinetics, kinematics, and muscular activity of a 15-s sprint test in able-bodied participants. *Sports Biomech.* 2020; https://doi.org/10.1080/14763141.2020.1745266.
22. Ronnestad BR, & Mujika I. Optimizing strength training for running and cycling endurance performance: A review. *Scand J Med Sci Sport.* 2014; 24: 603 – 612.
23. Skovering K, Ettema G, Welde B, & Sandbakk O. On the relationship between upper-body strength, power, and sprint performance in ice sledge hockey. *J Str Cond Res.* 2013; 27(12): 3461 – 3466.
24. Stastny P, Golas A, Blazek, D, Maszczyk M, Wilk M, Pietraszewski P, Petr M, Uhlir P, & Zajac A. A systematic review of surface electromyography analysis on the bench press movement task. *PloS one.* 2017; 12(2): doi: 10.1371/journal.pone.0171632.
25. Stone B, Mason BS, Bundon A, & Goosey-Tolfrey VL. Elite handcycling: A qualitative analysis of recumbent handbike configuration for optimal sports performance. *Ergo.* 2019; 62(3): 449 – 458.
26. Stone B, Mason BS, Warner MB, & Goosey-Tolfrey, VL. Shoulder and thorax kinematics contribute to increased power output of competitive handcyclists. *Scand J Med Sci Sport.* 2019; 29(6): 843 – 853.
27. Stone, B, Mason, BS, Warner MB, & Goosey-Tolfrey VL. Horizontal crank position affects economy and upper limb kinematics of recumbent handcyclists. *Med Sci Sports Exer.* 2019; 251(11): 2265 – 2273.

28. Torhaug T, Brurok B, Hoff J, Helgerud J, & Leivseth G. The effect from maximal bench press strength training on work economy during wheelchair propulsion in men with spinal cord injury. *Spinal Cord.* 2016; 54: 838 – 842.
29. Turbanki S, & Schmidtbleicher D. Effects of heavy resistance training on strength and power in upper extremities in wheelchair athletes. *J Str Cond Res.* 2010; 24(1): 8 – 16.
30. Uali I, Herrero AJ, Garatachea N, Marin PJ, Alvear-Ordenes I, & Garcia-Lopez D. Maximal strength training on different resistance training rowing exercises predicts start phase performance in elite kayakers. *J Str Cond Res.* 2012; 26(4): 941 – 946.
31. Union Cycliste Internationale. Cycling Regulations, Part 16 Para-Cycling. 2019.
32. Verellen J, Janssens L, Meyer C, & Vanlandewijck Y. Development and application of a handbike ergometer to measure the 3D force generation pattern during arm crank propulsion in realistic handcycling conditions. *Sport Technol*. 2012; 5: 65–73. doi: 10.1080/19346182.2012.754894

Fig 1. Handcycling propulsion cycle and a typical H3/H4 hand bike set-up.

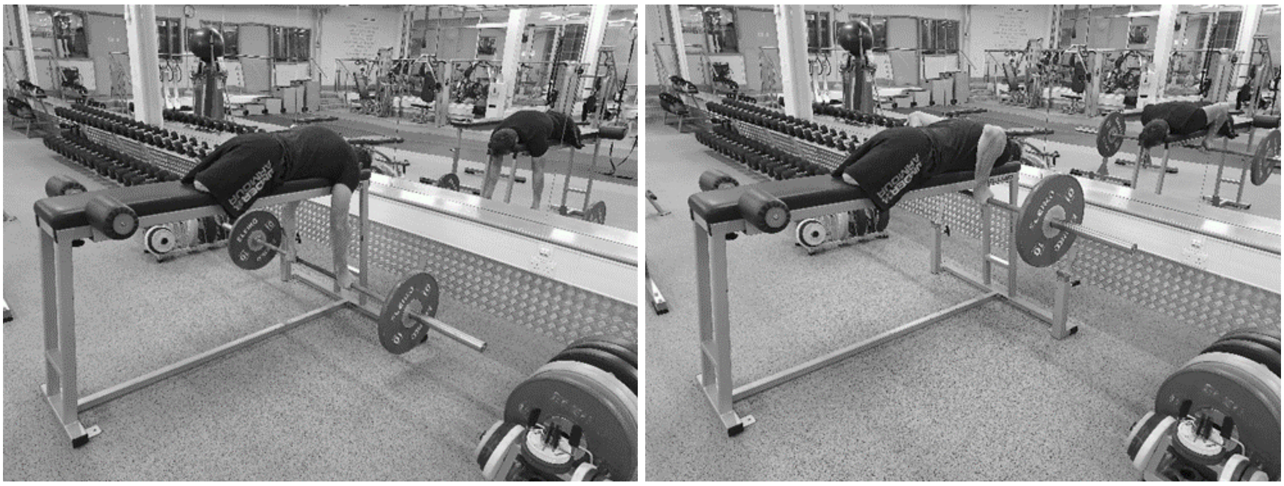

Fig 2. Prone Bench Pull – With Barbell

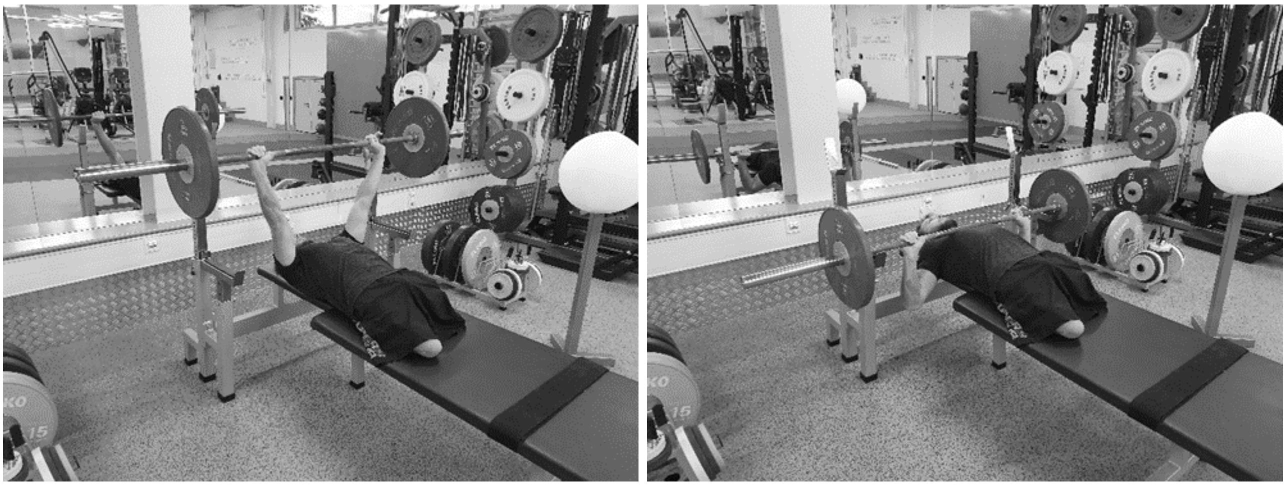

Fig 3. Bench Press – With Barbell

Table 1. Mean (± *SD*) values of participant testing data

Prone Bench Pull 1RM (kg)	77.8 ±13.2
Relative Prone Bench Pull Strength ($kg \cdot kg^{-1}$)	1.0 ± 0.3
Bench Press 1RM (kg)	90.2 ±16.7
Relative Bench Press Strength ($kg \cdot kg^{-1}$)	1.2 ± 0.3
15 km Time Trial Time (mins:secs)	32:29 ± 6.06
15 km Time Trial Velocity ($km \cdot h^{-1}$)	28.6 ± 6.3
$\dot{V}O_{2peak}$ ($l \cdot min^{-1}$)	2.8 ± 0.6
Relative $\dot{V}O_{2peak}$ ($ml \cdot kg \cdot min^{-1}$)	36.8 ± 10
PO_{peak} (W)	160 ± 26.7
PO_4 (W)	119 ± 26
GME (%)	13.4 ± 2.7
$PO_{max,AO15}$ (W)	547 ± 120

Table 2. Correlation Matrix of Upper Body Strength and Selected Physiological Performance Measures

	Prone Bench Pull 1RM (kg)	Relative Prone Bench Pull Strength ($kg \cdot kg^{-1}$)	Bench Press 1RM (kg)	Relative Bench Press Strength ($kg \cdot kg^{-1}$)	Velocity ($km \cdot h^{-1}$)	$\dot{V}O_{2peak}$ ($l \cdot min^{-1}$)	PO_{peak} (W)	PO_4 (W)	GME (%)	$PO_{max,AO15}$ (W)
Prone Bench Pull 1RM (kg)	-	.								
Relative Prone Bench Pull Strength ($kg \cdot kg^{-1}$)	.843**	-								
Bench Press 1RM (kg)	.865**	.852**	-							
Relative Bench Press Strength ($kg \cdot kg^{-1}$)	.728**	.949**	.899**	-						
Velocity ($km \cdot h^{-1}$)	.447	.770**	.423	.703*	-					
$\dot{V}O_{2peak}$ ($l \cdot min^{-1}$)	.464	.612*	.600	.663*	.651*	-				
PO_{peak} (W)	.275	.671*	.310	.647*	.851**	.479	-			
PO_4 (W)	.358	.661*	.346	.615*	.927**	.687*	.842**	-		
GME (%)	.498	.811**	.686*	.871**	.733**	.651*	.717**	.709**	-	
$PO_{max,AO15}$ (W)	.566	.701*	.684*	.734**	.678*	.806**	.572	.595*	.641*	-

** Correlation significant at the <0.01 level (2-tailed)
* Correlation significant at the <0.05 level (2-tailed)

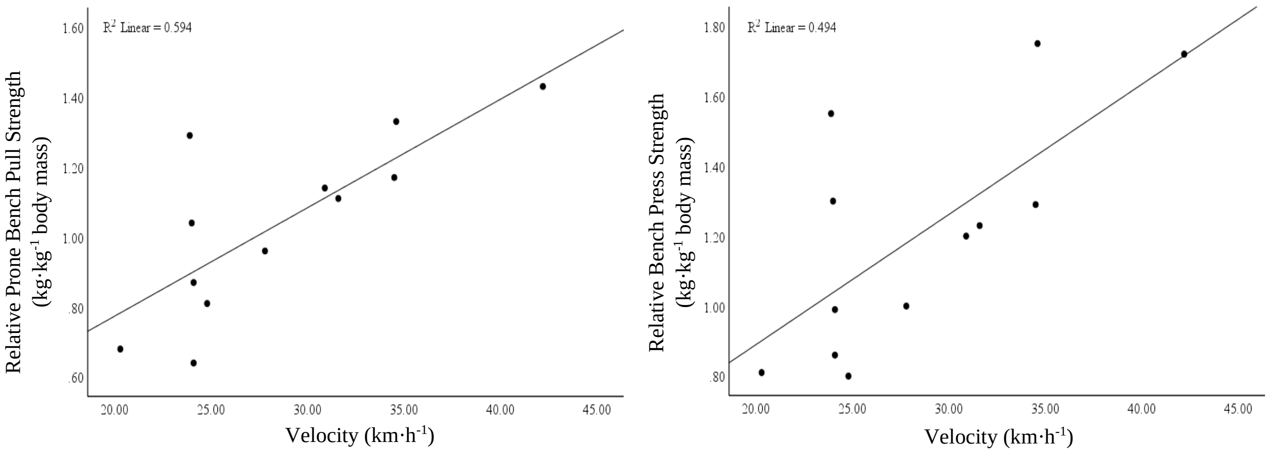

Fig 4. Correlation plots between relative prone bench pull strength, relative bench press strength and 15-km TT velocity.