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Human Kinetics
BRIEF REVIEW

The Science of Handcycling: A Narrative Review

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The aim of this narrative review is to provide insight as to the history, biomechanics, and physiological characteristics of competitive handcycling. Furthermore, based upon the limited evidence available, this paper aims to provide practical training suggestions by which to develop competitive handcycling performance. Handbike configuration, individual physiological characteristics, and training history all play a significant role in determining competitive handcycling performance. Optimal handcycling technique is highly dependent upon handbike configuration. As such, seat positioning, crank height, crank fore-aft position, crank length, and handgrip position must all be individually configured. In regard to physiological determinants, power output at a fixed blood lactate concentration of 4 mmol·L^{-1}, relative oxygen consumption, peak aerobic power output, relative upper body strength, and maximal anaerobic power output have all been demonstrated to impact upon handcycling performance capabilities. Therefore, it is suggested that that an emphasis be placed upon the development and frequent monitoring of these parameters. Finally, linked to handcycling training, it is suggested that handcyclists should consider adopting a concurrent strength and endurance training approach, based upon a block periodization model that employs a mixture of endurance, threshold, interval, and strength training sessions. Despite our findings, it is clear that several gaps in our scientific knowledge of handcycling remain and that further research is necessary in order to improve our understanding of factors that determine optimal performance of competitive handcyclists. Finally, further longitudinal research is required across all classifications to study the effects of different training programs upon handcycling performance.

Keywords*:* paralympic sport, handbiking, biomechanics, applied strength and conditioning

Handcycling is a dynamic and liberating form of Paracycling used by individuals who are unable to ride a conventional road bike or tricycle due to either a spinal cord injury (SCI) or lower-extremity physical impairment(s).[1] In addition to being used in both clinical and recreational settings, handcycling is an established Paralympic sport. Over the past 2 decades, changes in rules and regulations have resulted in considerable advancements in handcycling performance with athletes, coaches, and scientists alike continuing to explore ways by which to bring about further improvements. Many interrelated themes of work exist, which necessitates a holistic, interdisciplinary approach. Therefore, the aim of this review is to summarize the latest peer-reviewed research in the field of competitive handcycling and make evidence-based recommendations by which to improve handcycling performance.

Our collective understanding of the determinants of handcycling performance continues to improve. It is clear that equipment design and the interaction of an athlete with their handbike are of paramount importance and, in this respect, the area of ergonomics is advancing. Furthermore, our understanding as to the physiological determinants of handcycling performance has improved. Finally, several recent studies have demonstrated the effectiveness of various training strategies. While we have adopted a systematic approach to the subsection structure of this review, it is important to identify the need for ecologically valid research, where researchers adopt a multidimensional approach in conjunction with internationally classified and experienced competitors. It is likely that collaboration between international research groups will achieve this realistic ambition.

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History/Classification

The first mention of a functional handbike dates back to 1655 when a paraplegic German watchmaker, Stephan Farfler, invented the "manumotive carriage." Handbike design evolved considerably during the 19th and 20th centuries, with disabled individuals employing asynchronous handcycling for the purpose of transportation.[2] In the early 1980s, a group of enthusiasts in the United States developed the first fixed-frame handbike. The advent of solid frame designs permitted a recumbent, long seat position, with legs outstretched in front of individuals who adopted a synchronous crank configuration.

Since that time, handcycling has evolved as a sport and was first included at the Paracycling World Championships in 1998 and then at the 2004 Athens Paralympic Games. The first Paralympic handcycling events consisted of a time trial (TT) and a road race (RR) for male athletes classified in 2 divisions: tetraplegic (men's handcycling [MHC] A) and paraplegic (MHC B/C) with a correction factor applied to athletes in the MHC B/C division. However, it was not until the 2008 Beijing Paralympic Games that females first competed at the Paralympics, with 13 female athletes competing in all divisions (women's handcycling [WHC] A, B, and C). As a member of the Paracycling family, the Union Cycliste Internationale (UCI) govern handcycling. The UCI and the International Paralympic Committee introduced a formal, functional classification system in 2008. This decision extended the number of competitive divisions from 3 (HCA, HCB, and HCC) to 4 (H1, H2, H3, and H4) in 2012, and then 5 in 2016 (H1, H2, H3, H4, and H5).

Athletes in H1 have the most profound functional impairments; whereas, H5 athletes are least impaired and have the greatest physical function. Initially, the UCI and International Paralympic Committee established guidelines for competitive handcycling classes according to the level and severity of the SCI. As such, H1 athletes demonstrate impairments comparable with a complete C6 lesion or above, while H2 athletes demonstrate impairments equivalent to a complete C7/C8 lesion. H3 athletes typically demonstrate impairments comparable with a complete thoracic (T×) SCI at T×10 or above, while H4 athletes demonstrate impairments equivalent to a complete T×11 lesion or below. Finally, H5 athletes have impairments comparable with a complete T×11 lesion or below.[3] Athletes with H1 to H4 classifications compete in a recumbent position and employ an arm-powered technique. In contrast, athletes in the H5 class adopt a kneeling position and utilize an arm–trunk powered technique.[4]

Weissland and Leprêtre,[5] published findings based on male and female H1 to H4 results, drawing comparisons between TT performances from the London 2012 Paralympic Games. The authors concluded that H1 athletes had a disadvantage based on reduced arm strength, respiratory function, and peak heart rate (HR) caused by impaired or absent supraspinal, sympathoadrenal control. However, it is important to note that acute physiological responses (eg, peak HR) and their potential impact upon performance are not considered in the present classification system which may prove either dis/advantageous to an athlete and their competitors. Muchaxo et al[5] explored whether Paracycling classes truly represent different levels of function and sporting performance. Based on 1807 TT results of 353 elite handcyclists, the authors found a significant difference in performance between H1 and H2, and between H2 and H3 classes. The difference between H3 and H4 classes was significant, but with a small effect size. It has been stated that the difference in classification between H3 and H4 classes principally relates to discrepancies in trunk function.[3] However, Muchaxo et al,[6] recently investigated the impact of trunk function in the context of handcycling performance in H3 and H4 athletes and demonstrated no significant associations between trunk flexion strength and handcycling performance capabilities. These findings suggest that trunk flexion strength may play a limited role in determining handcycling performance; however, further research is required to clarify the full impact of trunk function and to justify the role of trunk function in handcycling classification.

Biomechanics of Handcycling

Biomechanical aspects of handcycling propulsion can be characterized by crank kinetics, joint kinematics, and muscular activity, all of which demonstrate a mutual interdependence. Muscular activation generates the forces and moments of the upper limbs, which result in cyclic joint kinematics of the shoulder and elbow. The cyclical flexion and extension of the elbow and shoulder generate the propulsive torque applied to the handgrips. The torque profile in handcycling demonstrates 2 distinct maxima and minima, which allow for dividing propulsion into a push and pull phase (Figure 1),[7–9] The highest torques are generated during the middle of the push and pull phase in which the arm flexors and extensors are in a favorable position to generate force.[10,11] However, the turnover phases, furthest reach, and closest reach, have been demonstrated to be less favorable positions to generate force.[12]

Whereas able-bodied participants demonstrate an increasing shift toward pull phase propulsion,[9,13–15] trained recumbent handcyclists tend to apply the majority of force during the push phase of the propulsion cycle.[7] Given the fact that the classification of trained handcyclists has been found to impact upon their ability to apply force throughout the crank cycle, it appears that H1 classified handcyclists with a SCI at C6 or above mainly apply force during the pull phase with nearly no force applied during the push phase. Conversely, handcyclists with a spinal lesion at or below C7 (H2–H4) apply force more equally across the push and pull phases, which has been suggested to improve movement efficiency.[9] Hence, differences in torque profiles are likely to be due to differences in individual technique, training status, and strength characteristics.

Elbow and shoulder flexion and extension are the primary kinematics driving handcycling propulsion.[9,10,13,16,17] In recumbent handcycling, peak elbow extension and shoulder adduction occur at furthest reach, as the arms are maximally extended, while peak elbow flexion and shoulder abduction occur at closest reach, as the arm is maximally flexed, and the handgrips are closest to the shoulders (Figure 1).[10,14,17,18] Peak shoulder flexion and extension occurs when the handgrips are vertically in their highest and lowest position.[16] Kinematic investigations have also investigated the

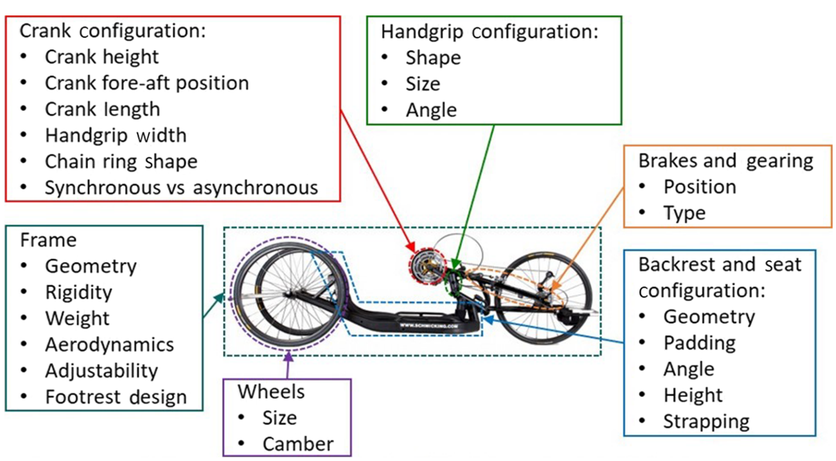

Figure 1 — Handbike configuration variables.

motion of the thorax, scapular, and wrist.[7,16] Shoulder internal and external rotation, thorax, scapular, and wrist kinematics do not follow a smooth parabolic pattern.[10,13–15,19] Indeed, when compared with novice able-bodied riders, trained handcyclists demonstrate less shoulder internal rotation suggesting that there may be technical differences between users of different skill levels, independent of handbike configuration.[13–15]

In terms of muscle activation, the pull phase of the propulsion cycle is initiated by the posterior part of the shoulder muscle (M. *deltoideus, pars spinalis*). Around the foremost position, the elbow flexors (M. *biceps brachii*) start their activation to increase crank torque. At the lowest crank position, the anterior part of the shoulder muscle (M. *deltoideus, pars clavicularis*) is activated to lift the handgrips upward.[8,10,15] The second half of the pull-up is then initiated by activation of the chest muscle (M. *pectoralis major*) which is supported by the elbow extensors (M. *triceps brachii*) which are activated shortly afterward. The period of co-contraction between elbow flexors and extensors and the anterior and posterior parts of the M. *deltoideus* lasts approximately 15° to 20°, respectively.[8,10,15] In summary, the M. *deltoideus* initiates and mediates the different phases of the crank cycle while the large upper body muscle groups are used to generate propulsive forces.

Handbike Configuration

The configuration of a handbike is complex as numerous components can be manipulated in line with UCI regulations (Figure 2). In recent years, several studies have investigated the configuration of the recumbent handbike and how it affects performance. These studies have suggested that crank axis, determined by the crank fore-aft position and crank height, and the trajectories of the handgrips, determined, by the crank length and handgrip angle may have a significant impact on handcycling technique.[7,9,16,18,20] Elite handcyclists understand the importance of handbike configuration on technique and performance, yet large differences exist between individuals, due to personal preference and a trial-and-error approach employed by many handcyclists.

Positioning of the crank arms to a horizontal fore-aft position of between 97% and 100% of recumbent handcyclists' arm length has been identified as being the most efficient configuration for the musculature of the upper limb to produce force economically.[16] The influence of crank length has also been investigated in highly trained recumbent handcyclists. Manipulating crank length is an interesting phenomenon, as both cadence and handgrip speed are concurrently affected by changes in crank length. It has been proposed shorter crank length (150 or 160 mm) may be more economical at a higher cadence (>90 rpm), while longer crank length (170 or 180 mm) may be more economical at a lower cadence (<90 rpm).[17] However, Mason et al,[7] studied the effects of varying crank lengths between 150 and 180 mm at a constant handgrip speed and identified no differences in handcycling economy (in milliliters per minute per Watt) suggesting that handcyclists should adopt a crank length of between 150 and 180 mm dependent upon personal preference. Finally, considering handgrip position, Krämer et al,[20] demonstrated that a pronated handgrip angle of +30° may be the optimal position from which to generate power.

Physiology of Handcycling

In recent years, handcycling research has generated a considerable amount of information linked to physiological characteristics of participants in laboratory settings. Heterogeneity of participants and variations in study designs has resulted in a broad range of reference values, making interstudy comparison and interpretation difficult. Other factors, such as disability, classification, sex, age, and protocol type add layers to what is an already complex picture. Finally, one must also consider the general development of an athlete's performance capabilities over numerous competitive seasons, which requires a longitudinal, multifactorial perspective.

Peak oxygen uptake (VO_2peak) and peak aerobic power (PO_{peak}) have been demonstrated to be significant determinants of performance in both able-bodied and recreational handcyclists.[21] Table 1 summarizes absolute and relative values of aerobic parameters of trained competitive handcyclists. While a considerable body of evidence exists for H3, H4, and H5 classified handcyclists, limited research has been conducted with H1 or H2 classified riders. Indeed, only 2 studies have reported the aerobic parameters for H1 and H2 athletes. Flueck et al[30] reported an average value of absolute and relative PO_{peak} for a trained H1 (tetraplegic) athlete of 98 W and 1.3 $W·kg^{-1}$, respectively with an associated value of VO_2peak of 1.3 $L·min^{-1}$ or 17.3 $mL·kg^{-1}·min^{-1}$. Furthermore, Meyer et al[23] reported a VO_2peak of 1.2 $L·min^{-1}$ for a trained H1 athlete with a tetraplegia. In contrast to aerobic capacity, fewer reports of maximal anaerobic capacity exist. Although information relating to handcycle-specific sprint tests with able-bodied

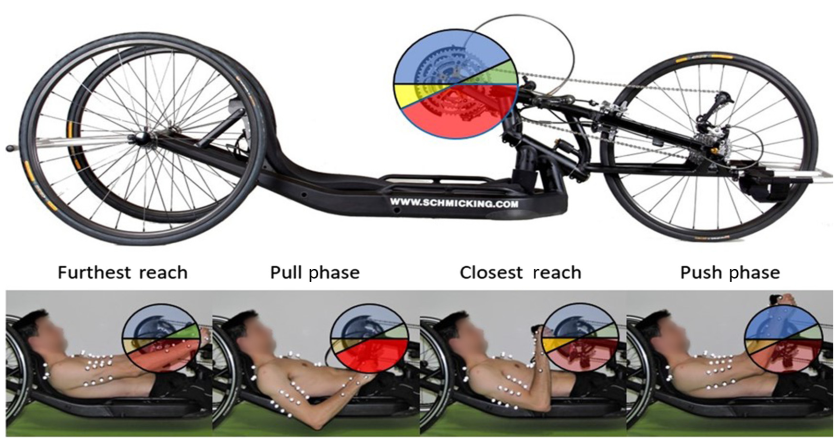

Figure 2 — Handcyling propulsion cycle.

Table 1 Studies Assessing Aerobic Capacity With Specifically Trained, Competitive Handcyclists

Study	Setup	Protocol	Classification (n)	Sex	Training, h·wk^{-1}	VO_2peak, L·min^{-1}	VO_2peak, mL·kg^{-1}·min^{-1}	PO_{peak}, W	PO_{peak}, W·kg^{-1}	VO_2 at VT1, mL·kg^{-1}·min^{-1}	VO_2 at VT2, mL·kg^{-1}·min^{-1}	PO at VT1, W	PO at VT2, W
Knechtle et al[22]	Treadmill	10 km·h^{-1} + 2 km·h^{-1} per 3 min	H3–H4 (8)	Male	Not reported	2.6 (0.3)	37.5 (7.8)	—	—	—	—	—	—
Meyer et al[23]	Turbo trainer	Stage 12.8 km·h^{-1} + 1.6 km·h^{-1}	H1 (1)	Male	>15	1.2	18.4	—	—	—	—	—	—
Abel et al[24]	Cyclus2	Ramp PO at 2 mmol + 15 W/15 s	H3 (1)	Male	Not reported		42.3	240	—	—	—	—	—
Lovell et al[25]	ACE	Ramp 60 W + 12 W·min^{-1}	H3–H4 (10)	Male	6 (1.5) sessions	3.2 (0.4)	40.4 (5.5)	210 (22)	—	2.3 (0.3) L·min^{-1}	—	—	—
Fischer et al[26]	ACE	Ramp 50 W + 15 W·min^{-1}	H3 (7)	Male	7.7 (2.6)	2.3 (0.5)	33.6 (7.06)	178 (34)	—	28.0 (6.7)	31.4 (6.5)	137 (26)	162 (25)
Zeller et al[27]	Cyclus 2	Stage 20 W + 20 W per 5 min	H5 (1)	Female	9.6 (4.8)			220	3.23	—	—	—	181 at 4 mmol
Graham-Paulson et al[28]	Not reported	Not reported	Paratriathlete (1)	Male	Not reported	3.5	44.9		—	—	—	—	—
Nevin et al[29]	Turbo Trainer	Ramp 50 W +15 W per 3 min	H3–H4 (10)	Male	>5		41 (16.4)	170 (28.4)	—	—	—	—	—
Flueck et al[30]	Cyclus2	Ramp 20 W + 10 W·min^{-1}	H1 (1), H2 (1), H3 (3), H4 (2), H5 (1)	Male	11 (4)	2.5 (0.7)	38.6 (10.5)	178 (44)	2.79 (0.71)	—	—	—	—
Stangier et al[31]	Cyclus 2	Stage 20 W + 20 W per 5 min	H3–H4 (12)	Male	Not reported		40.5 (6.2)	192 (29)	—	—	32.2 (6.3) at 4 mmol	—	149 (34) at 4 mmol
Stone et al[16]	Cyclus 2	Male: 50 W + 20 W·min^{-1} Female: 40 W + 15 W·min^{-1}	H3 (6), H4 (9)	Male (13), Female (2)	7 (3)			207 (42)	—	—	—	—	—
Stone et al[17]	Cyclus 2	Stage PO at AeLT + 5 W per 15 s	H3 (5), H4 (2)	Male	13 (2)	3.2 (0.3)	45.0 (5.8)	247 (20)	—	—	—	98 (19) at AeLT	137 (15) at AnT
Stone et al[32]	Cyclus 2	Stage PO at AeLT + 5 W per 15 s	H3 (5), H4 (6)	Male	7 (3)	3.3 (0.4)	47.0 (6.8)	252 (19)	—	1.5 (0.1) L·min^{-1} at AeLT	2.4 (0.4) L·min^{-1} at 4 mmol	87 (13) at AeLT	154 (14) at 4 mmol
Mason et al[7]	Cyclus 2	Stage PO at AeLT + 5 W per 15 s (males) or 5 W per 20 s (females)	H3 (4), H4 (5)	Male (8), Female (1)	9 (4)			232 (44)	—	—	—	—	—
Nevin and Smith[33]	Turbo trainer	Ramp 40 W + 20 W per 5 min	H3–H4 (13)	Male	>5	2.8 (0.5)	36.8 (10)	160 (26.7)	2.2 (0.7)	—	—	—	—

Abbreviations: ACE, arm-crank ergometer; AeLT, aerobic lactate threshold; PO, power output; PO_{peak}, peak aerobic power; VO_2peak, peak oxygen uptake; VT, ventilatory threshold.

participants is available,[8,13,24,27,34] research findings linked to sprint performance in trained, competitive handcyclists is scarce. Table 2 summarizes sprint performance test results for both recreational[36] and trained handcyclists.[6,17,35]

Ideally, any ecologically valid evaluation of handcycling performance should represent the demands of either an individual TT or a mass start RR. In this respect, one may view sterile, laboratory-based testing as being somewhat less suitable compared with field-based testing. A laboratory-based performance test usually requires a participant to undertake a continuous, self-paced effort to complete a set distance as quickly as possible. This allows standardized conditions to be established; however, this is not what is experienced during a typical race effort. During a TT or RR on an undulating course, an athlete may potentially encounter challenging environmental conditions, sections with steep de/ascents and other technical sections that require phases of de/acceleration. Together, these factors would result in a more stochastic power production profile, which may present a greater metabolic and overall performance challenge.

A recent study assessed average velocities from 1807 TT results from 2014 to 2018. Average velocity ranged from 13.0 to 26.1 km·h^{-1} (H1), 18.8 to 34.4 km·h^{-1} (H2), 26.2 to 38.7 km·h^{-1} (H3), 28.4 to 40.4 km·h^{-1} (H4), and 29.6 to 39.9 km·h^{-1} (H5), respectively for male athletes. Average velocity for female athletes was 15.6 to 27.0 km·h^{-1} (H2), 21.9 to 34.2 km·h^{-1} (H3), 23.3 to 33.8 km·h^{-1} (H4), and 26.9 to 37.5 km·h^{-1} (H5), respectively.[5] Researchers have employed in/outdoor TTs to simulate competitive events.[26,28–30,32,33] During an outdoor 22-km TT, average speeds of 29.3 to 30.4 km·h^{-1}; VO_2, 28.5 to 30.7 mL·kg^{-1}·min^{-1} (82%–89% VO_2peak); HR, 166 to 172 bpm; and respiratory exchange ratio, 1.03 to 1.14, were reported in H3 athletes.[26] Using H1 to H5 participants, Flueck et al,[30] demonstrated laboratory-based 10 km TT times of 18.4 (4.1) minutes, average power output (PO) of 142 (49) (~80% PO_{peak}), and average HR responses of 162 (27) bpm; however, information relating to performance differences between athlete classifications was not reported. A recent study with H3/H4 athletes reported on a simulated 16-km TT. During a self-paced effort, athletes attained average speeds ranging from 31.4 to 34.3 km·h^{-1}; PO, 152 to 190 W; and HR, 154 to 194 bpm. They cycled at 80% to 93% VO_2peak, 87% to 98% HR_{peak}, and 65% to 75% PO_{peak}.[32]

The overarching question remains: which physiological parameters should athletes and coaches target during training to optimize competitive handcycling performance? Unsurprisingly, PO_{peak} (in Watts and Watts per kilogram) and VO_2peak (in liters per minute and milliliters per kilogram per minute) have been shown to be highly associated with race performance in both recreational,[37] and trained handcyclists.[25,26] Two recent studies with trained handcyclists found no significant associations between race performance and VO_2peak.[21,32] However, PO_{peak} (in Watts), relative PO_{peak} (in Watts per kilogram), and PO at a fixed blood lactate concentration of 4 mmol·L^{-1} (PO_4) have been shown to be highly associated with race performance.[21,32] Indeed, PO_4 was shown to be the strongest predictor of performance in a simulated 16 km TT accounting for 59.3% of total variance.[33] More recently, Nevin and Smith,[33] demonstrated very large correlations between 15-km TT velocity and measures of PO_4, VO_2peak (in milliliter per kilogram per minute), PO_{peak} (in Watts per kilogram), body mass, and maximal anaerobic power. In the context of performance determinants, recent findings have also pointed to the importance of absolute and relative values of upper body strength.[36] Even though the number of scientific studies relating to handcycling has increased in the last decade, it is critical to note that there are very few studies involving athletes with high SCI. Equally important is the fact that little if any information exists for female athletes, which represents a clear gap in scientific knowledge that warrants further exploration.

Handcycling Training

Several studies have demonstrated the effectiveness of handcycling training in clinical rehabilitation settings.[37–39] Furthermore, a number of studies have shown that handcycling can be effective in improving upper body fitness parameters in both male and female, able-bodied participants.[40–43,44] However, only a handful of studies have investigated the effectiveness of structured training

Table 2 Studies Assessing Anaerobic Capacity With Recreational or Specifically Trained, Competitive Handcyclists

Study	Setup	Protocol	Classification (n)	Sex	Training, h·wk^{-1}	Peak cadence, rpm	PO_{max}, W	PO_{mean}, W
Stone et al[16]	Cyclus 2	20-s sprint, 5% body weight	H3 (4), H4 (2)	Male	13 (2)	109 (13)	377 (59)	—
Nevin and Smith[33]	Turbo trainer	15-s sprint	H3 (6), H4 (6)	Male	Not reported		547 (120)	—
Nooijen et al[35]	Cyclus 2	20-s sprint (isokinetic), 20-N initial load	H1–H4 (56), H5 (7)	Male (47), female (16)	13 (4) (H1–H4) 15 (9) (H5)	Limit: 100 rpm for H1–H2 130 rpm for H3–H4 110 rpm for H5	—	303 (122) (H1–H4) 445 (113) (H5)
Muchaxo et al[6]	Cyclus 2	20-s sprint (isokinetic), 20-N initial load	H3 (17) H4 (12)	Male (22), Female (7)	13 (4)	Limit: 130 rpm	453 (H3) 435 (H4)	358 (H3) 361 (H4)

Abbreviations: PO_{max}, maximal anaerobic power; PO_{mean}, mean anaerobic power.

interventions using UCI classified handcyclists.[24,27,29,45] From a competitive perspective, the aim of handcycling training is to elicit homeostatic perturbations, which promote physiological adaptation and improvements in one's performance potential.[46] Typically, handcyclists will utilize a range of training sessions including endurance rides, threshold training, interval training, and upper body strength training.[24,27,29,45]

The prescription of handcycling training can be manipulated by altering several variables including training frequency, volume, and intensity. Prescribing training frequency or volume is relatively simple as these factors can be altered by manipulating the number of training sessions per week and/or by changing the duration of a session. However, the manipulation of training intensity is more complex due to several candidate anchor measurements that can be used to guide training intensity. In the context of handcycling, rating of perceived exertion,[38] percentage of maximum heart rate,[41,42,47] PO_4,[24,27,45] and percentage PO_{peak},[29] have all been employed to prescribe training intensity. Another important consideration is the concept of training intensity distribution (TID). Seiler[43] proposed a conceptual 3-zone TID model whereby, PO at a given blood lactate concentration is used to guide training intensity. In this model, zone 1 (Z1) is defined as low intensity training at a PO associated with a blood lactate concentration of $<2\ mmol{\cdot}L^{-1}$; zone 2 (Z2) or LT1 is defined as moderate intensity training, performed at a PO between a blood lactate concentration of $2\ mmol{\cdot}L^{-1}$ and $4\ mmol{\cdot}L^{-1}$; while zone 3 (Z3) or LT2 is defined as high intensity training, performed at a PO which results in a blood lactate concentration of $>4\ mmol{\cdot}L^{-1}$. Described as polarized training, several authors have suggested that a TID of 80% Z1 and 20% Z2/3 may result in the optimal development of endurance performance in both able-bodied cyclists[43,48] and handcyclists.[27,45]

During a competitive handcycling event, riders require a high anaerobic capacity to repeatedly generate propulsive forces and recover from the production of high POs over short periods of time. For example, this will allow a rider to close a gap on an opponent, break away from other riders, or win in a sprint finish. Anaerobic capacity can be defined as the difference between maximal anaerobic power and PO_{peak}.[33] Known as the anaerobic power reserve (APR), this measure has been demonstrated to have a considerable relationship with handcycling performance.[33] Indeed, handcyclists frequently use various forms of interval training which tap into their APR to enhance both aerobic and anaerobic capacity.[24,29,42]

It has been reported that handcyclists frequently perform upper body strength training as part of a concurrent strength and endurance training regime.[24,27,29,36,40,47] The ability to generate a high PO is dependent upon tangential torque and crank angular velocity. Greater upper body strength will allow a rider to generate a larger tangential torque during both the pull and push phases of the handcycling propulsion cycle, potentially improving mechanical PO and effective velocity.[49] Indeed, Nevin and Smith,[37] reported a strong correlation between relative upper body horizontal pulling and pushing strength and handcycling performance. Relative strength is the product of one's ability to generate maximal forces relative to body mass. Therefore, it can be inferred that, for a given body mass, greater maximal upper body strength would improve handcycling performance.

The combination of training frequency, volume, and intensity is commonly referred to as training load (TL). Monitoring and quantification of both external and internal TLs has been recognized as an important factor in the long-term development of handcyclists as it allows for the regulation of training as part of a periodized program.[27,45] Commonly used methods of determining TL's in handcycling include arbitrary units which can be calculated by session rating of perceived exertion × time,[27] training impulse which can be calculated as average session heart rate × time,[38] and the training stress score (TSS), which takes into consideration the duration and average PO of a training session to provide a single estimate of overall TL.[37,45] Each method has its inherent strengths and limitations; arbitrary units and training impulse are relatively simple and cheap methods of monitoring TL's. However, TSS is extensively used in able-bodied cycling and may prove a useful tool for handcyclists to accurately quantify and monitor TLs.

Practical Recommendations

Based on the limited evidence available, concurrent strength and endurance training may represent the most favorable approach by which to develop handcycling performance capabilities.[24,27,29,36,40,47] Therefore, it is suggested that handcyclists consider adopting a concurrent approach to training utilizing a block periodization model.[29,44] Such a model will allow for the focused development of specific physiological characteristics (ie, VO_2peak, lactate threshold, anaerobic capacity) during a given mesocycle, while simultaneously maintaining other physiological characteristics albeit, at a reduced TL.[29,45] With respect to training type, frequency, and volume, it is suggested that a mixture of endurance, threshold, and interval training sessions should be performed 3 to 4 times per week with complementary, upper body strength training performed twice a week.[27,29] However, this may vary dependent upon the training history and status of the athlete. From a training intensity perspective, it is suggested that where possible, the 3-zone conceptual model based upon PO associated with a fixed blood lactate concentration of $4\ mmol{\cdot}L^{-1}$ be utilized for endurance and threshold training.[24,27,36] In regard to interval training, it is suggested that a rider's APR be established in order to develop appropriately structured interval training sessions.[33] If preparing for shorter duration events, such as RR and TT, a polarized TID approach, consisting of 70% Z1, 20% Z2, and 10% Z3 should be considered.[27] However, if preparing for ultra-endurance events, a 90% Z1, 8% Z2, and 2% Z3 TID model may prove more efficacious.[36] Finally, based upon the limited evidence available the use of either arbitrary units,[27] training impulse,[38] or TSS,[37,44] as a measurement of TL's may also be prudent for handcyclists.

Conclusion

Findings of this review suggest that handcycle configuration, physiological characteristics, and training history all play a significant role in determining handcycling performance. Optimal handcycling technique and movement efficiency are highly depended upon handbike configuration. As such seat positioning, crank height, crank fore-aft position, crank length, and handgrip position must all be individually configured. In regard to physiological determinants of performance PO_4, relative $\dot{V}O_2$peak, PO_{peak}, relative upper body strength, and maximal anaerobic power have all been demonstrated to impact upon handcycling performance capabilities. Therefore, it is suggested that an emphasis be placed upon the development and frequent monitoring of these parameters. Related to handcycling training, there is currently a paucity of research as to the optimal approach by which to develop handcycling performance capabilities. However, based upon the limited evidence available, it is suggested that handcyclists should consider a concurrent training approach based upon a block periodization model. It is important to note that training adaptations are subject to highly variable interindividual responses which compounds the "training suggestions" challenge. This is especially prevalent in disability sports where athletes have a heterogeneous mix of disabilities, leading to variations in functional capacity and performance potential. Therefore, it is recommended that an individualized approach be used to develop and implement effective training programs for handcyclists. Despite the findings of this review, it is clear that several gaps in our scientific knowledge of handcycling remain. Further research is necessary to explain the full impact of trunk function and muscle activation profiles upon handcycling performance. Moreover, additional research is required to establish physiological responses and functionality of male H1 and H2 athletes, as well as female handcyclists, across all competitive divisions. Finally, further longitudinal research is required across all classifications to study the effects of different training programs upon handcycling performance.

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