Physiology of handcycling: A current sports perspective

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Abstract
Handcycling is a mode of mobility, and sport format within Para-cycling, for those with a lower limb impairment. The exercise modality has been researched extensively in the rehabilitation setting. However, there is an emerging body of evidence detailing the physiological responses to handcycling in the competitive sport domain. Competitive handcyclists utilize equipment that is vastly disparate to that used for rehabilitation or recreation. Furthermore, the transferability of findings from early handcycling research to current international athletes regarding physiological profiles is severely limited. This narrative review aims to map the landscape within handcycling research and document the growing interest at the elite end of the exercise spectrum. From 58 experimental/case studies and four doctoral theses, we provide accounts of the aerobic capacity of handcyclists and the influence training status plays; present research regarding the physiological responses to handcycling performance, including tests of sprint performance; and discuss the finite information on handcyclists’ training habits and efficacy of bespoke interventions. Furthermore, given the wide variety of protocols employed and participants recruited previously, we present considerations for the interpretation of existing research and recommendations for future work, all with a focus on competitive sport. The majority of studies (n = 21) reported aerobic capacity, detailing peak rates of oxygen uptake and power output, with values >3.0 L min⁻¹ and 240 W shown in trained, male H3-H4 classification athletes. Knowledge, though, is lacking for other classifications and female athletes. Similarly, little research is available concerning sprint performance with only one from eight studies recruiting athletes with an impairment.

Keywords
disability, handbike, Paralympic, race, spinal cord injury, threshold, time trial, VO₂

1 | INTRODUCTION

Handcycling is a form of mobility for individuals with lower limb impairments and is a competitive sport and sport discipline within Para-cycling and paratriathlon, respectively. At an international level, handcycling was first included within Para-cycling at the 2004 Paralympic Games, with 19 male athletes competing in three classes across four events.
Twelve years later, at the 2016 Paralympic Games, handcycling contributed to 33% of the events in the road Paracycling schedule and debuted in paratriathlon for the men’s PT1 (now PTWC) class. In total, 75 handcyclists (44 male and 21 female handcyclists and 10 male paratriathletes) competed across ten classes in fourteen events.1

Individuals who are eligible to compete internationally have a diverse range of health conditions, including spinal cord injury (SCI), lower limb deficiencies, cerebral palsy, or other traumatic brain injuries.2 From a competitive sports perspective, athletes will display varying degrees of functional abilities. These will relate to different cardiorespiratory responses to exercise, while muscular strength, coordination, and range of motion of the upper limbs and trunk will be dependent on their impairment. In Paralympic sport, a classification system is used to promote fair competition and to limit the effects of the aforementioned functional differences between athletes on the outcome of events.3 The UCI handcycling classification system consists of five classes: H1 (most impaired) to H5 (least impaired).2 The most noticeable difference between classes is that H1-H4 athletes (athletes unable to kneel) use recumbent handbikes, while H5 athletes (a category that includes athletes with lower level paraplegia and limb deficiencies) use kneeling handbikes (Figure 1).

At the Paralympic Games, handcyclists compete in both time trials (TT) and road races that typically last 20-140 minutes over 15-60 km. Due to different race terrains and tactics, velocities during handcycling TTs average 24-45 km h⁻¹ with peaks of ~ 55 km h⁻¹.4-6 Paralympic medals in Rio 2016 were won within 0.5% margins; for example, differences between winning the 2016 Paralympic gold and silver medal were on average 26 seconds in the TT, and in some classes, 3-s margins were noted (equating to a 0.16% margin; Table 1). The road races were similarly competitive, with each medal being decided by split seconds typically by a sprint finish. In contrast, just two Paralympic Games earlier, the TTs were won with average velocities of 25-37 km h⁻¹ despite a shorter, 12.7 km, distance at the Beijing 2008 Games with winning margins of up to 3.1%.7 These data highlight the rapid progress within elite handcycling and the current competitiveness of the sport with the need for further knowledge regarding handcyclists’ physiology and training for performance optimization.5 As with any sport, there are myriad intrinsic and extrinsic factors that combine and interact to determine performance outcomes and researchers have attempted to visualize these factors in conceptual models.9 Elite handcycling is no different with Figure 2 displaying a non-exhaustive representation of elements that influence performance.

While handcycling has long been studied with respect to rehabilitation or in-patient populations to promote physical activity in those with lower limb impairments (see Kraaijenbrink et al10 for a recent review), this information is of limited use to those working at the elite end of the sports spectrum. Differences in individuals’ physical fitness, training history, age, body mass, and handbike configuration are significantly disparate. Acknowledging the recent interest in studying handcycling from a competitive sports perspective, the present narrative review aims to broadly map evidence of handcycling physiology and identify future research priorities.11 While the contributing factors in handcycling performance are broad (Figure 2), this paper will primarily focus on areas pertaining to athletes’ physiology. Accordingly, the objectives of this review were to (a) present differences in handbike models and their changing prevalence in research; (b) map the evidence of physiological outcome variables and training/pre-event strategies that may influence handcycling performance; and (c) from a practical perspective, highlight methodological considerations with the view to identifying current research gaps and interpretation of existing information. To maximize the application of present knowledge, only studies involving trained participants were included for review. Likewise, studies utilizing arm crank ergometry (ACE) were included if the sample consisted of handcyclists. Studies of able-bodied (AB) participants were only included if they made a novel contribution to the literature.

2 | HANDBIKE TYPES

As with many Paralympic sports,9 handcycling performance relies upon the optimized integration of the athlete

![FIGURE 1](Different handbike types. Adapted from Arnet et al and Stone95,104)
and their equipment. Broadly, handbikes can be split into two classes (Figure 1): the attachable-unit handbike, which are suitable for daily living, and the rigid frame handbikes, which are used in recreation and sports competition.

Handbikes have existed since the early 20th century but early bikes were cumbersome with a focus on ambulation rather than competition. Handcycling gained research traction in the 1960s as more mechanically efficient modes of transportation than wheelchair propulsion were sought. Then, in the early 21st century, research emerged with the first attachable-unit handbikes, which consisted of a wheel connected to a crank system, that is attached to the

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**TABLE 1** Handcycling time trial and road race results at the 2016 Paralympics

| Classification | Distance (km) | Gold Velocity (km h⁻¹) | Time (h:min:s) | Silver Time behind (min:s) | Bronze Time behind (min:s) | Fourth Time behind (min:s) |
|----------------|---------------|-------------------------|----------------|-----------------------------|---------------------------|--------------------------|
| Time trial     |               |                         |                |                             |                           |                          |
| MH2            | 20            | 37.4                    | 00:32:07       | 0:06                        | 1:33                      | 3:57                     |
| MH3            | 20            | 42.4                    | 00:28:19       | 1:06                        | 1:07                      | 1:08                     |
| MH4            | 20            | 43.4                    | 00:27:39       | 0:10                        | 1:03                      | 1:16                     |
| MH5            | 20            | 41.9                    | 00:28:37       | 0:03                        | 0:15                      | 0:26                     |
| WH1-H3         | 20            | 35.5                    | 00:33:45       | 0:13                        | 0:36                      | 1:00                     |
| WH4-H5         | 20            | 38.0                    | 00:31:36       | 0:40                        | 1:27                      | 1:38                     |

Road race

| Classification | Distance (km) | Gold Velocity (km h⁻¹) | Time (h:min:s) | Silver Time behind (min:s) | Bronze Time behind (min:s) | Fourth Time behind (min:s) |
|----------------|---------------|-------------------------|----------------|-----------------------------|---------------------------|--------------------------|
| MH2            | 45            | 35.8                    | 01:15:23       | >0:01                       | 7:49                      | 7:51                     |
| MH3            | 60            | 38.6                    | 01:33:17       | >0:01                       | >0:01                     | >0:01                    |
| MH4            | 60            | 40.5                    | 01:28:48       | 0:03                        | 0:06                      | >0:07                    |
| MH5            | 60            | 36.8                    | 01:37:49       | >0:01                       | >0:01                     | 0:02                     |
| WH1-H4         | 45            | 35.8                    | 01:15:56       | 0:02                        | >0:03                     | 0:05                     |
| WH5            | 45            | 27.8                    | 01:37:07       | 0:04                        | >0:03                     | >0:03                    |

Note: M: men; W: women; MH1 classification not included in the 2016 Paralympic program.
front of a wheelchair. Within this set-up, trunk posture is upright, as the participant sits in the wheelchair with backrest angles ranging from 45 to 90°. Coinciding with handcycling joining the Paralympic Games program, studies involving the rigid sporting handbikes emerged in 2003-2004 as greater focus was paid toward positions leveraging power production and lower frontal surface areas.20-23 More recently, studies examining the physiological responses of recumbent and kneeling handcycling were published from 2010 onwards after regulation changes permitted recumbent handbikes to use back support angles less than 45°.24,25 For these studies, the front wheel of a handbike is typically propelled synchronously using a conventional cycle drivetrain, comprising of crank arms, chain rings, derailleur, chain, handgrips (pedals), and gear shifters.14

The position of the crank in relation to the athlete differs drastically between the arm-powered recumbent handbike and the arm-trunk-powered kneeling handbike.14,26 In the recumbent handbike, the athlete lies prone and the cranks are positioned above the height of the shoulders, so that at furthest reach, the arms are near maximal elbow extension. Furthermore, UCI legislation states that the crank axis must not be higher than the athlete’s eye line during competitive recumbent handcycling, whereas, in the kneeling handbike, the cranks are positioned below the shoulders and the horizontal distance between the shoulders and the crank is much smaller, with the athlete assuming a kneeling position. These kneeling handbikes also have longer crank lengths and wider handgrip widths than recumbent handbikes.14 It is noteworthy that due to the upright nature of kneeling handcycling, the athlete’s frontal surface area is greater in a less aerodynamic manner.23 This has resulted in slower race velocities than recumbent handcycling classes (Table 1), despite the potential for greater power production.

3 | EXERCISE TESTING

3.1 | Laboratory testing: aerobic capacity

Outcomes such as the peak rate of oxygen uptake (VO_{2peak}) and power output (PO_{peak}) have been quantified during incremental handcycling exercise tests to exhaustion in a laboratory (Table 2; 21 studies identified covering 235 athletes). A further six studies (216 athletes) reported the aerobic capacity of handcyclists undertaking ACE.27-32 Differences in sex, training history, handbike type, athlete classification, years of involvement in the sport, and exercise protocols (initial load [0-130 W], stage increments [1-20 W], and duration [1 seconds-5 minutes], synchronicity of cycling and athlete posture) may have all contributed to the broad range of values observed. Further, while factors such as abdominal strapping are perceived by athletes to provide stability and more efficient power transfer,12,24 their use is rarely reported in studies with only Meyer et al making note of this in their methods.33

Among trained handcyclists, VO_{2peak} values greater than 3.0 L min^{-1}, or >40.0 ml kg^{-1} min^{-1}, have recently been reported by several researchers during ACE,28 and recumbent34-36 or kneeling37 handcycling; this has been achieved by participants in the H3/H4 and H5 categories, respectively. These values of aerobic capacity are accompanied by 5-6 years of handcycling experience28,36 and 6 ± 2 training sessions per week comprising of 223 ± 57 km wk^{-1}.11,28 Recently, Graham-Paulson et al38 also reported a VO_{2peak} of 3.5 L min^{-1} (44.9 ml kg^{-1} min^{-1}) in a professional PTWC paratriathlete. While there is less information available for athletes in the more impaired H1 and H2 classes, data from these athletes indicate VO_{2peak} values of 1.1 ± 0.4 to 2.0 ± 0.4 L min^{-1} may be achieved with higher values reflected by a longer involvement in the sport.16,29,33,37 Recent work by Flueck et al displayed a clear relationship of aerobic capacity and classification by showing that the H1 class athlete had a much lower VO_{2peak} than the H5 class athlete (1.3 vs. 3.7 L min^{-1} or 17.3 vs. 49.7 ml kg^{-1} min^{-1}),37 with this likely explained by the significantly greater active musculature due to athletes’ impairment. Furthermore, the utilization of trunk muscles for propulsion creates added oxygen demand during kneeling versus recumbent handcycling,14,26,39 again explaining the direct relationship between athletes’ classification and aerobic capacity shown previously.16 Authors have reported PO_{peak} values of 98-150 W, 240-250 W, or 220 W in trained H1/H2, H3/H4, and H5 handcyclists, respectively.5,24,35-37 However, it must be acknowledged that large variability exists in the protocols employed when determining PO_{peak} from maximal incremental tests to exhaustion, especially regarding stage durations and workload increments during incremental tests (Table 2) and definition of PO_{peak}; thus, comparisons between studies are limited.

It is important to note that the heterogeneous proportion of recruitable muscle mass and the potential absence of lower limbs make the comparison of variables such as VO_{2peak} and PO_{peak} between athletes unrepresentative or misleading without scaling parameters.40 To this end, Stephenson et al recently reported greater correlations between lactate thresholds and 20 km handcycling performance within a paratriathlon race when variables were scaled relative to body mass.41 Nevertheless, it has been established that trained handcyclists can display aerobic capacities which are considerably greater than those reported in untrained AB persons, as displayed in Table 2. As such, training status still seems to be one of the strongest determinants of handcycling aerobic capacity; this has been shown in studies comparing handcyclists of varying training histories.28,35

Of the available literature, to the authors’ knowledge, Hutchinson et al42 was the only study that has used a...
| Study                  | Protocol | Handbike | Instrumentation | Initial load | Increment | Stage duration (s) | Classification (n) | Athlete characteristics |
|-----------------------|----------|----------|----------------|--------------|------------|--------------------|---------------------|-------------------------|
| Janssen et al16       | ATU      | MDT      | 28 W           | 5 W          | 60         | H1-2 (10)          | H3-4 (6)            |
| Dallmeijer et al19    | ATU      | MDT      | 25 W           | 10 W         | 60         | H3-4 (9)           | AB (10)             |
| Verellen et al18      | ATU      | ERG      | 50 W           | 10 W         | 180        | H3-4 (9)           |                     |
| Leicht et al27        | ACE      | ERG      | 40-90 W        | 10 W         | 60         | H3-4 (9)           |                     |
| Lovell et al28        | ACE      | ERG      | 45 W           | 1 W          | 10         | H3-4 (10)          |                     |
|                       |          |          | 60 W           | 1 W          | 5          | H3-4 (10)          |                     |
| Fischer et al30       | ACE      | ERG      | 30-50 W        | 1 W          | 4-6        | H3 (7)             |                     |
|                       |          |          | 30-50 W        | 1 W          | 4-6        | H3 (5)             |                     |
| de Groot et al29      | ACE/REC  | ERG/ROL  | 20-30 W        | 8-10 W       | 60         | H1-3 (11)          | H4 (29)             |
|                       |          |          | 40-60 W        | 15-20 W      | 60         |                     |                     |
| Kouwijzer et al32     | ACE (n = 69)/REC (n = 59) | ERG (n = 104)/ROL (n = 24) | 0-30 W       | 1-15 W      | 3-60        | H1-3 (67), H4-5 (57) |                     |
| Knechtle et al22      | TOUR     | MDT      | 10.0 km h⁻¹    | 2.0 km h⁻¹   | 180        | H3-4 (8)           |                     |
| Abel et al58          | TOUR     | ROL      | 12.0 km h⁻¹    | 2.0 km h⁻¹   | 180        | H3 (1)             |                     |
| Meyer et al33         | TOUR     | ROL      | 12.8 km h⁻¹    | 1.6 km h⁻¹   | -          | H1 (1)             |                     |
| Goosney-Tolfrey et al46 | TOUR     | ROL     | 130 ± 40 W     | 10 W         | 60         | H3-4 (8)           |                     |
| Abel et al20          | TOUR     | ERG      | 15 W           | 15 W         | 180        | H1-2 (3), H3-4 (32) |                     |
| Zeller et al47        | TOUR     | ERG      | 20 W           | 20 W         | 300        | AB (11)            |                     |
| Hutchinson et al42    | TOUR     | ERG      | 20-40 W        | 20 W         | 60         | AB (20)            |                     |
| Abel et al24          | REC      | ERG      | PO @ 2.0 mmol l⁻¹ | 15 W       | 15         | H3 (1)             |                     |
|                       |          |          | [BLA⁻]peak −120 W | 20 W       | 180        | H3 (5), H4 (4), H5 (1) |                     |
| de Groot et al48      | REC      | ERG      | 50 W           | 15 W         | 180        | H3-4 (4)           |                     |
| Graham-Paulson et al58| REC      | ERG      | IALT           | 5 W          | 15         | PTWC Paratriathlete (1) |                     |
| Nevin et al49         | REC      | ROL      | 50 W           | 15 W         | 180        | H3-4 (4)           |                     |
| Stangier et al24      | REC      | ERG      | 20 W           | 20 W         | 300        | H3-4 (12)          |                     |
|                       |          |          | 45%PO_peak     | 15 W         | 300        |                     |                     |
| Stone et al36         | REC      | ERG      | IALT           | 5 W          | 15         | H3 (4), H4 (2)     |                     |
|                       |          |          | IALT           | 5 W          | 15         | H3 (5), H4 (2)     |                     |
| Stone et al50         | REC      | ERG      | 40-50 W        | 15 - 20 W    | 60         | H3 (6), H4 (9)     |                     |
| Stephenson et al41    | REC      | ERG      | IALT           | 5 W          | 15         | PTWC Paratriathletes (5) |                     |
| Stone et al35         | REC      | ERG      | IALT           | 5 W          | 15         | H3 (5), H4 (6)     |                     |
| Verellen et al39      | REC      | ERG      | 50 W           | 10 W         | 60         | AB (12)            |                     |
|                       |          |          | KNE            | 50 W         | 10 W       | AB (12)            |                     |
| Flueck et al37        | REC      | ERG      | 20 W           | 10 W         | 60         | H1 (1), H2 (1), H3 (3), H4 (2) | H5 (1)             |
|                       |          |          | KNE            | 20 W         | 10 W       |                     |                     |
| Zeller et al6         | KNE      | ERG      | 20 W           | 20 W         | 300        | H5 (1)             |                     |

**Note:** Values are mean ± standard deviation, where appropriate.

\( VO_{peak} \)—peak rate of oxygen uptake; \( PO_{peak} \)—peak aerobic power output; \( HR_{peak} \)—peak heart rate; \[BLA^-\]_{peak}—peak blood lactate concentration; \( RER_{peak} \)—peak respiratory exchange ratio. ATU—attachable unit; ACE—arm crank ergometer; TOUR—touring handbike; REC—recumbent handbike; KNE—kneeling handbike; MDT—motor-driven treadmill; ERG—electromagnetically braked ergometer; ROL—roller system; IALT—individual aerobic lactate threshold; AB—able-bodied; H1-H5—competitive race categories.
### TABLE 2
Outcome measures from studies assessing aerobic capacity in handcycling

| Handcycling experience | VO\textsubscript{peak} (L min\textsuperscript{-1}) | VO\textsubscript{peak} (ml kg min\textsuperscript{-1}) | PO\textsubscript{peak} (W) | HR\textsubscript{peak} (b·min\textsuperscript{-1}) | [BLA\textsubscript{-}peak] (mmol·L\textsuperscript{-1}) | RER\textsubscript{peak} |
|-----------------------|-----------------------------|-----------------------------|-----------------|-----------------|-----------------|-----------------|
| 3.6 ± 1.0 y; 3.0 ± 3.9 h wk\textsuperscript{-1} | 1.7 ± 0.4 | 14.2 ± 3.8 | 55 ± 25 | 118 ± 17 | — | 1.14 ± 0.10 |
| 2.2 ± 1.5 y; 1.2 ± 2.0 h wk\textsuperscript{-1} | 2.1 ± 0.4 | 27.1 ± 6.0 | 129 ± 26 | 182 ± 10 | — | 1.29 ± 0.03 |
| 4.8 ± 4.6 y; 3.8 ± 2.6 h wk\textsuperscript{-1} | 1.9 ± 0.4 | — | 117 ± 32 | 187 ± 7 | — | 1.30 ± 0.06 |
| No experience | 2.2 ± 0.3 | — | 111 ± 19 | 184 ± 13 | — | 1.28 ± 0.06 |
| 4.0 ± 2.1 y; 2.2 ± 1.5 h wk\textsuperscript{-1} | — | 33.3 ± 8.4 | 98 ± 13 | 189 ± 13 | — | 1.15 ± 0.07 |
| 8.2 ± 3.4 h wk\textsuperscript{-1} | 2.3 ± 0.4 | — | 142 ± 21 | 183 ± 9 | 6.4 ± 1.7 | — |
| No experience | 1.7 ± 0.4 | 21.2 ± 4.7 | 121 ± 30 | 172 ± 12 | 10.5 ± 4.0 | 1.16 ± 0.07 |
| 6.0 ± 3.6 y; 6.0 ± 1.5 s wk\textsuperscript{-1} | 3.2 ± 0.4 | 40.4 ± 5.5 | 210 ± 22 | 184 ± 11 | 11.7 ± 2.3 | 1.19 ± 0.06 |
| 6.0 ± 3.0 h wk\textsuperscript{-1} | 2.2 ± 0.6 | 31.7 ± 8.2 | 168 ± 49 | 171 ± 7 | 8.0 ± 2.1 | 1.22 ± 0.11 |
| 7.0 ± 3.0 h wk\textsuperscript{-1} | 2.1 ± 0.6 | 32.0 ± 7.1 | 167 ± 45 | 174 ± 8 | 7.7 ± 1.0 | 1.20 ± 0.03 |
| 7.7 ± 2.6 h wk\textsuperscript{-1} | 2.3 ± 0.5 | 33.6 ± 7.1 | 178 ± 34 | 172 ± 8 | 8.1 ± 2.0 | 1.21 ± 0.10 |
| 9.3 ± 4.8 h wk\textsuperscript{-1} | 2.0 ± 0.4 | 26.5 ± 6.0 | 131 ± 62 | — | — | — |
| 8.3 ± 4.3 h wk\textsuperscript{-1} | 2.6 ± 0.7 | 35.6 ± 10.5 | 146 ± 43 | — | — | — |
| 3.4 ± 3.7 h wk\textsuperscript{-1} | 1.9 ± 0.6 | 24.9 ± 7.9 | 119 ± 34 | 171 ± 22 | — | 1.21 ± 0.12 |
| Trained | 2.6 ± 0.3 | 37.5 ± 7.8 | — | 188 ± 6 | 11.0 ± 2.2 | — |
| Trained | 2.4 | — | — | 169 | 6.1 | 0.99 |
| 4 y | 1.2 | 39.4 | — | 133 | 7.7 | — |
| 2.0 ± 2.0 y; 3.0 ± 2.0 h wk\textsuperscript{-1} | 2.6 ± 0.4 | 33.8 ± 5.9 | 165 ± 47 | 191 ± 8 | 6.9 ± 1.4 | 1.24 ± 0.06 |
| 5.0 ± 3.3 h wk\textsuperscript{-1} | 1.9 ± 0.7 | — | 101 ± 45 | 165 ± 22 | 7.1 ± 2.6 | — |
| No experience | 2.7 ± 0.4 | — | 135 ± 18 | 150 ± 20 | 8.9 ± 2.3 | 1.03 ± 0.07 |
| No experience | 1.8 ± 0.5 | 24.3 ± 4.0 | 122 ± 34 | 163 ± 17 | 7.4 ± 1.9 | 1.48 ± 0.14 |
| Elite | — | 42.3 | 240 | — | — | — |
| Trained | 2.4 ± 0.5 | 32.2 ± 6.9 | 159 ± 29 | 178 ± 12 | 10.6 ± 2.2 | 1.18 ± 0.13 |
| Elite | 3.5 | 44.9 | — | — | — | — |
| >1 y | — | 41.0 ± 16.4 | 170 ± 28 | — | — | — |
| | — | 34.1 ± 8.2 | 148 ± 21 | — | — | — |
| Elite | 3.0 ± 0.5 | 40.5 ± 6.2 | 192 ± 29 | 183 ± 12 | 11.5 ± 2.8 | 1.03 ± 0.05 |
| | 3.0 ± 0.5 | 40.7 ± 6.7 | 228 ± 30 | 174 ± 10 | 8.2 ± 1.5 | 1.18 ± 0.14 |
| Elite | 3.2 ± 0.3 | 45.0 ± 5.8 | 247 ± 20 | 188 ± 7 | — | — |
| Recreational | 2.6 ± 0.2 | 37.3 ± 6.5 | 198 ± 21 | 183 ± 9 | — | — |
| 3.6 ± 2.4 y; 7 ± 3 h wk\textsuperscript{-1} | — | — | 207 ± 42 | — | — | — |
| Trained | 2.6 ± 0.6 | 39.4 ± 7.7 | 182 ± 35 | — | — | — |
| 5.4 ± 5.6 y; 7 ± 3 h wk\textsuperscript{-1} | 3.3 ± 0.4 | 47.0 ± 6.8 | 252 ± 19 | 188 ± 11 | 10.9 ± 2.5 | 1.15 ± 0.07 |
| No experience | 2.7 ± 0.5 | — | 171 ± 15 | 163 ± 18 | 11.5 ± 1.9 | 1.22 ± 0.12 |
| No experience | 3.3 ± 0.7 | — | 188 ± 21 | 168 ± 17 | 11.8 ± 1.9 | 1.16 ± 0.06 |
| > 3 h wk\textsuperscript{-1} | 2.3 ± 0.6 | 37.0 ± 10.3 | 172 ± 42 | — | — | — |
| >3 h wk\textsuperscript{-1} | 3.7 | 49.7 | 222 | — | — | — |
| 9.4 ± 4.5 h wk\textsuperscript{-1} | — | — | 220 | 181 | 11.3 | — |
verification stage to confirm the attainment of the highest VO2peak value recorded during handcycling, albeit in AB participants. Moreover, all four recommended secondary parameters at volitional exhaustion (ie, HRpeak, ratings of perceived exertion [RPE], peak blood lactate concentration ([BLA]peak), and peak respiratory exchange ratio [RERpeak]) were also noted, as discussed by Midgley et al., to improve confidence in the measurement of VO2peak.

In addition to VO2peak, 21 studies reported HRpeak, 16 reported [BLA]peak, and 15 reported RERpeak with values of > 180 b min−1, 1.20, and 10.0 mmol L−1 shown, respectively (Table 2). That said, upper body exercise has the potential to evoke different cardiorespiratory responses compared to lower body exercise. Research in AB persons has shown ACE to elicit higher mean arterial pressures with lower systemic vascular conductance, cardiac outputs, and local fractional oxygen extraction at exhaustion versus leg cycling. These differences are further affected by the potentially disrupted autonomic innervation of persons with a SCI eligible to compete in the sport of handcycling; thus, variability again exists between participant cohorts depending on their impairment. Finally, as the vast majority of studies have recruited male handcyclists, little information is available detailing female athletes’ aerobic capacity. In fact, of the 450 athletes noted in Table 2, only 51 are female. Research in AB endurance athletes has demonstrated that as the contribution of the upper body toward propulsion increases, sex differences in performance level are augmented with this not solely explained by variance in VO2peak or fat-free mass. Therefore, relative sex differences are expected to be greater during handcycling than lower body endurance exercise. While work by Kouwijzer et al did provide VO2peak and POpeak reference values for both males and females, even their large-scale study was not evenly balanced across sexes. Consequently, information is still lacking on female handcyclists’ aerobic capacity.

### 3.2 | Laboratory Testing: Anaerobic Performance

Only a limited number of reviewed studies have documented output parameters related to anaerobic performance during handcycling (Table 3; 114 athletes including 19 females). Further, while research exists concerning the anaerobic capabilities of athletes with a physical impairment during ACE, no studies have recruited trained handcyclists. Of the studies shown in Table 3, only one recruited recumbent handcyclists with the rest studying AB participants, commonly in a touring configuration. The lack of research is surprising since a sprint finish often determines the result of the road races (Table 1). That said, in AB participants, maximum and average PO during sprint handcycling ranged from 409 ± 100 to 873 ± 293 W and 281 ± 96 to 435 ± 51 W, respectively (Table 3). The large range in POs are most likely influenced by differences in protocol durations (3-20 s), cadences (isokinetic protocols limited between 110 and 140 rev min−1), resistance applied (20-4.4 Nm), gear ratios (2.86-4.45), ergometers used (inertial load flywheel or electromagnetically braked) as well as participants’ sex and upper body training history (Table 3). Further, while studies accepted maximum PO as the peak value recorded during tests, Kramer et al utilized the apex of the PO versus cadence curve by second-order polynomial curve, and some studies do not state their method of calculating maximum PO. Moreover, there is scant reporting of the use of strapping in studies, despite evidence showing its use in providing a closed chain movement pattern significantly benefits PO production.

Stone et al reported maximum PO values of 334 ± 18 and 377 ± 59 W in recreational and elite handcyclists, respectively. The fact that AB persons can generate greater sprinting power is not surprising; it is likely to do with not only the experimental set-up (touring vs. recumbent bike position) but also the physical impairment of the handcycling athletes (eg, potential disrupted abdominal function due to paralysis). Trunk function has been identified as a central component determining sports performance (eg, wheelchair sports classification). Research has noted that by increasing the contribution of trunk muscles during wheelchair sprinting, via manipulations in seat angles, the acceleration and sprinting capabilities in a group of AB participants significantly increased. While the contribution of the trunk muscles to handcycling propulsion may be questioned, especially at workloads below POpeak, due to the recumbent position of athletes, recent work by Quittman et al have highlighted their significant involvement with progressive workloads in AB individuals. Further, Kouwijzer et al clearly show great POs are achieved during arm and trunk power kneeling handcycling compared to recumbent handcycling. As such, it appears that, conversely to aerobic performance, functional capacity predicates over skill level or efficiency when assessing outcomes measures pertaining to anaerobic performance.

### 3.3 | Physiological responses to handcycling performance

Only a few studies in the literature (n = 12) have investigated the physiological responses during handcycling competition or simulated TT performance, ranging from 10 to 540 km, while a further study investigated 10-km road race performance. The two earliest case studies measured the metabolic profile (VO2 and [BLA]) during a marathon (42.2 km) and an ultra-endurance event (540 km)
using a touring handbike. These studies identified that aerobic metabolism was unsurprisingly the predominant energy system. Abel et al showed that the studied athlete completed the 42.2-km race in under 1:49 h at an average 66% VO₂peak, 3.4 mmol L⁻¹ [BLa⁻] and 0.88 RER, while later work presented a 540 km TT completed over 38:52 h at 46% POpeak and 1.99-2.30 mmol L⁻¹ [BLa⁻]. More recent work studying TTs closer to Paralympic distances (10-22 km) has suggested that both aerobic and anaerobic metabolism significantly contribute to successful performance in recumbent handcycling. For example, seven male H3 handcyclists completed an over-ground 22 km TT at 29.9 ± 3.6 km h⁻¹, equivalent to 86 ± 10% VO₂peak with an RER of 1.07 ± 0.17 and an average [BLa⁻] of 8.07 ± 1.95 mmol L⁻¹. Reported HRpeak is around 190 b min⁻¹ and average VO₂ of 2.0 L in⁻¹ during over-ground TTs in H1-3 handcyclists. During simulated 10 and 16 km TT performance on a Cyclus 2 ergometer (RBM electronic automation GmbH), average velocities of ~33 km h⁻¹, equating to 142 ± 49 to 174 ± 15 W, ~170 b min⁻¹, and ~10.0 mmol L⁻¹ [BLa⁻] have recently been documented in trained handcyclists. The average velocities reported for the TT distances of 10-22 km, ranging from 4.9 km h⁻¹ in a 20.2 km mountain climb TT with 863 m elevation gain to 34.5 km h⁻¹ over self-reported best 20 km time. However, it is noted that these velocities are considerably lower than the 43.4 km h⁻¹ achieved by a male H4 handcyclist in the 20 km 2016 Paralympic TT, which suggests that more research is warranted in this area for sports scientists and coaches to fully appreciate the performance diagnostics of truly elite athletes competing currently.

To our knowledge, six studies have sought to determine correlates to handcycling performance in a TT, road race, or within a paratriathlon race. While some studies have shown high correlations (r = ~0.90) between VO₂peak and handcycling performance, it is noteworthy that these studies concerned athletes of a lower aerobic capacity (1.1 ± 0.4 to 2.3 ± 0.5 L min⁻¹) and recent work in handcyclists of a higher training status (VO₂peak: 3.3 ± 0.4 L min⁻¹) showed no significant correlation to 16 km simulated TT performance. That VO₂peak does not differentiate performance potential within groups of higher-trained athletes is not surprising, and such a paradigm has long been understood in AB endurance sport. Instead, the fractional utilization of VO₂peak (ie, work rate at ventilatory or lactate thresholds) is considered a better performance predictor and has recently been shown to correlate more strongly to handcycling performance. Nonetheless, POpeak appears to consistently relate closely to handcycling performance across studies. Similarly, in AB cycling, POpeak regularly correlates to performance, regardless of the test duration. While PO data during representative handcycling TTs are sparse, the limited information available suggests athletes compete between 70% and 80% POpeak with the tolerable limit of POpeak being well below TT durations. However, that POpeak is a consistent performance determinant likely relates to the fact that it is a function of both aerobic and anaerobic energy provision and mechanical efficiency (ME), similar to the demands of handcycling TTs, as mentioned previously. As such, testing athletes’ POpeak may offer the most insight into performance potential without the necessity for measuring gas exchange or blood metabolite variables which

### Table 3: Sprint performance in handcycling

| Study            | Protocol | Handbike | Duration (s) | Resistance | Athlete characteristics | Sprint performance |
|------------------|----------|----------|--------------|------------|-------------------------|--------------------|
|                 |          |          |              |            | Handcycling experience   | Peak power output (W) | Mean power output (W) | Peak cadence (r·min⁻¹) |
| Krämer et al⁵¹   | TOUR     | 3-4      | 20.7-24.2 Nm | No experience | AB (25) | 873 ± 293 | — | 107 ± 16 |
| Abel et al⁵²     | TOUR     | 20       | —            | No experience | AB (15) | 590 ± 191 | 350 ± 126 | — |
| Zeller et al⁵⁷   | TOUR     | 20       | 20 Nm        | No experience | AB (11) | ~500 ± -100 | ~400 ± -75 | <110* |
| Zeller et al⁵⁷   | KNE      | 20       | 20 Nm        | No experience | AB (10) | 415 ± 163 | 281 ± 96 | <110* |
| Kouwijzer et al²⁶| TOUR     | 20       | 20 Nm        | No experience | AB (10) | 628 ± 231 | 391 ± 121 | <80* |
| Stone et al³⁴    | REC      | 20       | 5% body mass | Elite       | H3 (4), H4 (2) | 377 ± 59 | — | 100 ± 13 |
| Stone et al³⁴    | REC      | 20       | —            | Recreational | H3 (5), H4 (2) | 334 ± 18 | — | 92 ± 13 |
| Quittmann et al⁵³| REC      | 15       | 20 Nm        | No experience | AB (10) | 546 ± 70 | 435 ± 51 | <140* |
| Quittmann et al⁵⁴| REC      | 15       | 0.5 N·kg body mass⁻¹ | No experience | AB (18) | 409 ± 100 | 334 ± 84 | <130* |
| Quittmann et al⁵⁵| REC      | 15       | 20 Nm        | No experience | AB (12) | 578 ± 78 | — | <140* |

Note: TOUR—touring handbike; KNE—kneeling handbike; REC—recumbent handbike; AB—able-bodied, H3-H4—handcycling classification. * Cadence limited isokinetically. Values are mean ± standard deviation.
are needed to calculate ventilatory or lactate thresholds. Although these latter physiological landmarks are more representative of the relative intensities sustained during TTs, there is significantly more heterogeneity in methods used and large inter-individual variability in association with performance.62

### 3.4 Training monitoring

To date, little focus has been paid to the monitoring and reporting of handcyclists’ training habits in the published literature. The case studies of Abel et al. and Zeller et al. remain the sole source of peer-reviewed information on the training habits of elite handcyclists.6,24 While training reporting was not the focus of Abel et al.,24 they note that in preparation for the 540 km TT mentioned previously, the athlete covered 6000 km using a 3:1 macrocycle periodization of aerobic orientated to recovery training weeks. Furthermore, over the training period, the athlete spent 56.5% of time at an intensity below 2.6 mmol L\(^{-1}\) [BLa\(^{-}\)], 10.2% between 2.6 and 3.4 mmol L\(^{-1}\), 23.6% between 3.4 and 6.0 mmol L\(^{-1}\), and 9.7% above 6.0 mmol L\(^{-1}\). Zeller et al. meanwhile followed a female H5, four-time Paralympic medalist over 45 weeks and presented her training load and training intensity distribution.6 Over the study period, the athlete completed 194 handcycling sessions, totaling >433 h and 10,100 km, with weekly averages of 9.38 ± 4.50 h during 4.3 ± 1.5 sessions. Her maximal week comprised of eight training sessions in 23:12 h.6

Zeller et al. adapted the methods of Lucía et al. by reporting the athlete’s training intensity distribution based on the time spent in training zones derived from cycling PO rather than HR.6,63 From this, Zeller et al. report ~65% to 80% of time was spent in zone 1 (below PO associated with 2.0 mmol L\(^{-1}\) [BLa\(^{-}\)]), with this percentage increasing across “Preparation,” “Pre-competition,” and “Competition” training phases.6 Concurrent to this, the time in zone 2 (2.0 mmol L\(^{-1}\) ≤ [BLa\(^{-}\)] <4.0 mmol L\(^{-1}\)) decreased across phases, while the time in zone 3 (≥4 mmol L\(^{-1}\)) was consistent at ~12%. These changes in training intensity distribution indicate a progressive transition from a “threshold” to “polarized” intensity distribution across the study period when considering contemporary models; the authors attribute this to concurrent increases in training volume.6 It is noteworthy that a polarized training intensity has been advocated as the preferred model for endurance athletes with Zeller et al reporting this approach in this first account for elite handcyclists.6 Moreover, although limited information is available on the study’s training metrics, Nevin et al report that the addition of strength training, concurrent to endurance training, can result in greater improvements in determinants on handcycling performance than endurance training alone in already trained athletes.49 This aligns with finding from AB athletes,65 and taken with the work of Zeller et al.6 shows how trained handcyclists are now following training practices common in athletes without impairments.

While the case studies of Abel et al. and Zeller et al. remain the only work in elite handcyclists,5,24 de Groot et al. did research the training load of ten trained athletes over a 12-week period.48 Athletes reported 5-47 training sessions with a mean intensity of 85 ± 20 W (PO\(^{\text{peak}}\): 159 ± 29 W) and 132 b min\(^{-1}\) (HR\(^{\text{peak}}\): 178 ± 12 b min\(^{-1}\)). Furthermore, de Groot et al. noted high correlations between external training load,48 when calculated as a “Training Stress Score,” and internal training load using session RPE and HR training impulse methods. This adds to the work of Goosey-Tolfrey et al. who also found RPE to be a valid means for monitoring handcycling training intensity.46

### 3.5 Environmental, nutritional, and other pre-event considerations

Competitive handcycling that takes place at an international level present many environmental challenges for athletes. To date, the authors are only aware of two studies that have reported the thermoregulatory responses to handcycling.58,67 Abel et al. reported a peak core temperature (T\(_{c}\)) of 40.4°C at the end of a 42-km race, even in temperate conditions (20.0-22.0°C), in a single, male, H3 handcyclist with an SCI.58 Stephenson et al. tracked the T\(_{c}\) of nine paratriathletes within the handcycling discipline following a 750 m open water lake swim in air temperature of ~33°C.67 The PTWC athletes displayed a greater T\(_{c}\) change during the bike segment compared to other ambulant race categories, with many athletes reaching T\(_{c}\) above 40.0°C. This was likely to result from a lower surface area and air density for convective heat loss, a closer proximity to the road surface for radiant heat gain and longer segment durations when handcycling.67 Furthermore, athletes eligible to compete in handcycling or PTWC para-triathlon likely have significant impairments in thermoregulatory function, even relative to other Paralympic athlete cohorts, inherently raising their risk of thermoregulatory strain regardless of exercise modality. With this emerging evidence, it is apparent that athletes competing in the sport of handcycling face significant thermal strain depending upon their health or race conditions. The reader is directed to the work of Griggs et al. for a comprehensive overview of suitable cooling techniques and the thermoregulatory challenges of Paralympic sport.68,69

Only two studies have manipulated dietary supplements and examined TT performance outcomes within the sport of handcycling.37,38 At a group level, Flueck et al. demonstrated that acute nitrate supplementation either by 6 mmol
| Study                          | Protocol | Handbike type | Power (W) | Cadence (rev min⁻¹) | Steady-state duration (min) | Handcycling experience | Classification (n) | ME (%) | RER       |
|-------------------------------|----------|---------------|-----------|---------------------|-----------------------------|------------------------|-------------------|--------|-----------|
| van der Woude et al¹⁷         | ATU      | 8 ± 2-48 ± 6  | 24-44     | 3                   | No experience               | AB (12)                | 3.8 ± 0.4-12.2    | <1.00  |
| Verellen et al¹⁸              | ATU      | 50            | 60-90     | 3                   | 4.0 ± 2.1 y; 2.2 ± 1.5 h wk⁻¹ | H3-4 (9)               | 12.3 ± 1.4-12.9 ± 1.2 | 0.99 ± 0.06-1.00 ± 0.07 |
|                              |          | 60            | 60-90     | 3                   |                             |                        | 12.9 ± 1.0-13.2 ± 0.9 | 1.02 ± 0.04-1.02 ± 0.09 |
|                              |          | 70            | 60-90     | 3                   |                             |                        | 13.3 ± 1.6-13.7 ± 1.3 | 1.04 ± 0.06-1.05 ± 0.08 |
|                              |          | 80            | 60-90     | 3                   |                             |                        | 12.9 ± 1.8-14.4 ± 1.3 | 1.05 ± 0.07-1.07 ± 0.09 |
|                              |          | 90            | 60-90     | 3                   |                             |                        | 13.4 ± 1.9-14.5 ± 1.4 | 1.07 ± 0.07-1.16 ± 0.09 |
| Bafghi et al⁸⁴               | ATU      | 14 ± 3        | 27        | 3                   | No experience               | AB (9)                 | 5.9 ± 1.1         | —      |
|                              |          | 35 ± 7        | 67        | 3                   |                             |                        | 8.7 ± 1.3         | —      |
| Kraaijenbrink et al⁸⁶        | ATU      | 16 ± 3        | 52 ± 1-69 ± 1 | 4               | No experience               | AB (12)                | 4.0 ± 0.2         | 0.93 ± 0.07|
|                              |          | 26 ± 4        | 52 ± 1-69 ± 1 | 4               |                             |                        | 6.0 ± 0.3         | —      |
|                              |          | 36 ± 4        | 52 ± 1-69 ± 1 | 4               |                             |                        | 7.0 ± 0.2         | —      |
| Dallmeijer et al¹⁹           | ATU      | 25            | 50-70     | 4                   | No experience               | AB (10)                | 8.2                  | 0.96 ± 0.08|
| TOUR                         |          | 35            | 50-70     | 4                   |                             |                        | 9.8                  | 0.95 ± 0.05|
|                              |          | 25            | 50-70     | 4                   | 4.8 ± 4.6 y; 3.8 ± 2.6 h wk⁻¹ | H3-4 (9)               | 10.2                  | 0.93 ± 0.08|
|                              |          | 35            | 50-70     | 4                   |                             |                        | 12.2                  | 0.95 ± 0.07|
| Goosey-Tolfrey & Sindall⁸²   | ACE      | 60            | 60        | 4                   | Trained                     | H1 (2), H3-4 (11)      | 14.7 ± 2.4-16.9 ± 2.0 | —      |
|                              |          | 80            | 60        | 4                   |                             |                        | 15.9 ± 2.6-17.5 ± 1.8 | —      |
| van Drongelen et al⁸⁵        | ACE      | 20-25         | 70 ± 3    | 3                   | No experience               | AB (12)                | 7.0 ± 0.6          | 0.92 ± 0.05|
|                              |          | 25-35         | 70 ± 3    | 3                   |                             |                        | 9.0 ± 1.2           | 0.95 ± 0.05|
| Abel et al⁵⁸                 | TOUR     | 84            | 79        | —                   | Trained                     | H3(1)                  | 15.3                  | 0.88    |
| Goosey-Tolfrey et al⁸³       | TOUR     | 90            | 85        | 4                   | Trained                     | H3-4 (8)               | 21.4 ± 3.0          | 0.92 ± 0.11|
| Arnet et al⁵⁵                | TOUR     | 60 ± 17       | 69        | 3.5                 | 5.5 ± 5.2 h wk⁻¹            | H3-4 (13)              | 10.1 ± 1.0          | 87% <1.00|

(Continues)
nitrate as beetroot juice or sodium nitrate did not improve 10 km handcycling TT performance in a group of 8 trained handcyclists. Yet, from an individual perspective, and different supplementation, ingestion of caffeine (6 mg kg⁻¹) improved simulated 20 km TT performance by 2.7% of an elite male PTWC paratriathlete.³⁸ It was noted that the improvements may have been related to greater arousal and an increased PO for a given RPE.³⁸ When discussing the use of supplementation by individuals with a physical impairment during handcycling, one must consider the impact of the physical impairment. As stated within the PhD thesis of Graham-Paulson,⁷⁰ the impact of a SCI, for example, on caffeine’s ergogenic potential may be related to autonomic dysfunction, slowed gastrointestinal transit times and changes in muscle fiber type distribution.⁷¹-⁷³ It would therefore be unreasonable to directly translate the results from AB studies to handcycling scenarios and, furthermore, AB findings to individuals with a physical impairment such as a SCI. Thus, many questions regarding supplementation and handcycling remain to be addressed.

There is still a lot of work needed to explore beyond just nutritional strategies but also other training interventions. For example, Leicht et al²⁷ examined the use of a respiratory warm-up via a respiratory loading device within a group of well-trained handcyclists. They found that ACE time to exhaustion at 85% POpeak was impaired following a respiratory warm-up. Similarly, while 20 respiratory muscle training sessions improved local muscular endurance in trained handcyclists, there was no change in performance during an incremental test to exhaustion, nor a 22 km over-ground TT.³⁰ This is in contrast to what may have been expected from the AB literature, ⁷⁴ but was possibly as a result of the respiratory muscle fatigue due to the extent of the paraplegia and consequences of their limited respiratory function.

One factor that should be acknowledged, while not advocated as a pre-event intervention, is athletes’ use of “boosting.” This is an act of deliberately inducing an episode of autonomic dysreflexia in those with a SCI.⁵ Although autonomic dysreflexia may occur unintentionally as a consequence of afferent stimuli, for example a full bladder or pain, athletes have reported consciously invoking this state for performance gain.⁵ Boosting induces a sizeable sympathetic reflex, triggering peripheral vasoconstriction, hypertension, and tachycardia, all improving endurance performance.⁷⁵ This is likely more beneficial for athletes with autonomic complete cervical SCI whom face a performance disadvantage compared to autonomic incomplete athletes.⁵ However, the act is banned by the International Paralympic Committee due to the significant associated side effects and health risks including dizziness, blurred vision, and impaired cognition with potential intracranial hemorrhage, retinal detachments, seizures, cardiac arrhythmias, and even death.⁵,⁷⁵
4 | METHODOLOGICAL CONSIDERATIONS

Much of the handcycling research to date has reflected ambulatory or recreational handcycling, which differ drastically from competitive recumbent handcycling. Competitive handcycling is a unique activity, performed by a small group of individuals at an elite level, and one of the toughest challenges for all researchers in this domain is recruitment. Further, Flueck et al.37 noted a consideration in Paralympic sports, that since most athletes start their career after acquiring an injury, the Para-athlete samples tend to be older. Therefore, researchers need to critically consider the specifics of the participant group as well as the exercise protocol (eg, which physiological parameters to measure) for the purpose of sport-specific handcycling research. Moreover, it is imperative that the handbike-user interface is investigated in realistic, sport-specific conditions to enhance the transferability of the findings to the modern competition environment; this means the use of individually optimized handbike ergonomics.12

4.1 | Participant Selection

A significant amount of handcycling research has studied AB participants likely as they are more homogenous than a group with a disability, regarding their physical capabilities, and there is a greater population to recruit from. The use of AB participants may be acceptable as a starting point, but testing under the most ecologically valid conditions, that is, using participants with a disability, is recommended.77,78

Handcycling experience or skill level, regularly denoted as the number of years of participation, has been associated with higher aerobic capacity and ME.21,28 During submaximal, steady-state handcycling, ME is defined as the ratio between external PO and the total energy cost, which is calculated from the VO2, RER, and a standard conversion table.79,80 Simply, ME is the metabolic energy input to locomotion.81 While careful interpretation is needed due to the influence PO and cadence may have on ME, trained handcyclists can achieve a ME > 15%18,25,35,58,81-83 while unaccustomed handcyclists tend to attain a ME < 10% (Table 4).19,62,84-86 Within other upper body cyclic sports, such as wheelchair propulsion, differences in skill level have been attributed to changes in upper limb kinematics and push-rim kinetics; a similar finding is present when assessing handcycling.13,87-89 Furthermore, in leg cycling, skill level has been shown to affect muscle recruitment and joint range of motion.90 In leg cycling, Bini et al.80 suggested that differences in joint motion and muscle activation may be determined by long-term training adaptations as competitive and recreational cyclists configure their bikes similarly. Recent work by Fischer et al supports the importance of athletes’ skill level on ME, even to a greater extent than impairment level, as trained H1-2 handcyclists displayed no statistically significant difference to trained H3-4 athletes (~17% vs. 19%).81 Therefore, to maximize the transferability of the findings in handcycling literature, it is also critical to consider the skill level of the participant and not just their ability or disability.

Recruiting trained handcyclists with a disability would enhance the transferability of the findings to the competition environment. However, as the population of handcyclists is small, it is unlikely that the group will be homogeneous regarding disability, fitness, and handcycling experience. Participants classified in the H1 and H2 classes have lower VO2peak, POpeak, and HRpeak than H3-5 handcyclists, due to impaired cardiovascular, respiratory, and neuromuscular function.29,77 For example, impaired triceps and grip function affects cycle kinetics and potentially affects upper limb kinematics and muscle activity.91 As such, even within a handcycling cohort, athletes with full arm function (H3-5) are likely to respond more homogeneously, demonstrated by their similar cycle force profiles,91 than a group also including H1-2 athletes. Therefore, classification is a critical consideration when recruiting handcyclists for studies of athletes’ physiology and performance. However, it is apparent that the majority of research conducted with handcyclists to date has recruited those in the H3-H4 classes, likely due to a greater population available. This has resulted in significantly less attention paid to those in the H1, H2, and H5 categories where unique considerations regarding varied recruitable muscle mass and propulsion techniques exist.

4.2 | Exercise Methodologies

The exercise protocol used to investigate the physiology of elite handcycling is another critical methodological consideration, and it is imperative that the exercise protocol replicates sport-specific intensities. In recumbent handcycling, these conditions should be propulsion at training or competition intensity and, to a less extent, sprint performance. Past studies have adopted a range of approaches, including maximal exercise tests to determine VO2peak and POpeak (Table 2), sprint protocols to determine maximal PO (Table 3), and steady-state submaximal intensities to measure economy or ME (Table 4). An emerging area of interest in handcycling is the utilization of the critical power/speed model. Knowledge of the hyperbolic power/speed-duration relationship is not new,92 and it has been applied extensively in AB cycling.93 However, preliminary evidence, albeit from unpublished work, suggests this concept can be equally implemented in handcycling as critical speed has been shown to correspond to the second ventilatory threshold in eight trained handcyclists.94 Nonetheless, future work is needed in this promising area.
It is apparent that handcycling TTs or road races are completed at sustained high relative intensities. Yet, steady-state exercise protocols have ranged 3–6 minutes in duration at ambulatory or submaximal exercise intensities, at constant modest POs (8–90 W) and cadences (24–70 rev min⁻¹) (Table 4). Selecting an appropriate PO and cadence is essential to maximize transferability into the elite sport domain. Furthermore, most studies investigating the physiological responses to handcycling have used exercise intensities that were not selected relative to metabolic (ventilatory or lactate thresholds) or maximal (VO₂peak and POpeak) measures, but selected arbitrarily. An arbitrarily selected submaximal PO will cause a heterogeneous relative exercise intensity across a group, although individualizing ME measurements from ramp tests may not ensure a steady state is attained so should be cautioned against.

In handcycling, [BLA⁻] > 4.0 mmol L⁻¹ and RER > 1.00 are common, indicating the contribution of anaerobic metabolism to meet the energy demands for propulsion via active musculature of the upper limbs, which are significantly smaller than the active musculature during leg cycling. As such, ME is often systematically overestimated. Furthermore, caution is required when utilizing ME to assess handcycling performance as ME has a curvilinear relationship with PO and cadence. Therefore, an improvement in ME could be due to an increase in PO or a more optimal cadence selection, as opposed to a reduction in VO₂ or RER. As a result, handcycling economy has frequently been reported to establish the physiological demand of a task. Economy is calculated independent of the energy cost, whereby the submaximal VO₂ at a given PO, can be used to define efficient performance. Nonetheless, ME and economy are appropriate measures for within-subject experimental designs, if PO and cadence are controlled.

4.3 Simulating Performance

Stationary ergometers have been favored by researchers to simulate handcycling propulsion in the laboratory. Modern ergometers, such as the commonly used Cyclus II, allow PO, cadence, and gearing to be controlled, measured accurately and reliably and also allow several exercise protocols, such as incremental exercise tests, TTs, and sprints, to be conducted in the users’ own handbike. However, as the ergometers are fixed, factors such as rolling resistance and air resistance are estimated and the steering/stabilization mechanisms of handcycling are removed. A smaller number of studies have utilized treadmills to assess the physiology of handcycling. During treadmill protocols, cycling intensity may be regulated via pulley systems whereby PO can be calculated using drag tests. Alternatively, the incline and/or velocity of a treadmill belt can be manipulated although the ecological validity of protocols utilizing gradient changes may be questioned. No differences in cycle kinetics have been observed between treadmill and ergometer handcycling, which is attributed to the fixed position that handcyclists ride in thus comparisons may be made between tests at similar POs. However, when treadmill tests are used, handcycling PO is either estimated or measured via power meters unlike during ergometer tests where direct measurement is common. The diversity in PO measurements between ergometers and power meters must be considered. To our knowledge, there is no published research concerning the reliability and validity of PO measures in handcycling; this is highly disparate from AB cycling where power meters and ergometers have commonly been assessed. Thus, it is unknown how synchronous pedaling and altered torque production across the pedal revolution compared to leg cycling may affect the efficacy of adapted power meters. Furthermore, it is pertinent to understand power meters’ validity and reliability at the lower absolute workloads common during handcycling.

Field-based methodologies, although more ecologically valid, are less frequent and more challenging to standardize. In these studies, variables such as HR, [BLA⁻], and VO₂ have been measured during simulated TTs and during competitive races. This approach maximizes external validity as factors such as rider skill (steering/braking), rolling resistance, and aerodynamics have an effect, but additional confounding factors, such as the climatic conditions, also need to be considered. It is also more challenging to collect variables such as [BLA⁻], VO₂, PO, and cadence in the field. Most of the aforementioned studies were unable to record PO or cadence during their field testing, which was a considerable limitation. However, the emergence of mobile power meters, devices that can be attached to a handbike to measure variables such as PO, cadence, torque, speed, and distance, can be used either in the laboratory or field, albeit with a significant financial cost and, as yet, little validation. Although measuring performance in the field is more externally valid, the methodology adds several experimental challenges and confounding variables that researchers should seek to control.

A number of studies in the broader literature have examined ACE, particularly with respect to movement efficiency. During ACE, the participants sit in an upright posture, like the configuration of an attachable-unit handbike, and tend to use asynchronous propulsion mode, making much of the earlier studies less transferrable to the elite handcyclist in terms of performance diagnosis. For example, in asynchronous propulsion, the arms move out of phase, as in leg cycling, while in synchronous propulsion, both arms move in phase in the same angular pattern. The handbikes used today typically adopt a synchronous propulsion mode as it has been found to be more efficient and result in higher POpeak when compared to asynchronous propulsion. The lower ME, lower POpeak, and higher submaximal VO₂ in asynchronous
propulsion have been explained by increased co-contraction of the upper limb and trunk musculature to combine both power production and steering. During ACE, where no steering is required, contradicting results have been found. These findings suggest that significant differences in physiological outcome parameters are present between synchronous and asynchronous propulsion. Therefore, it is critical that a synchronous propulsion mode is used to investigate handcycling performance.

5 | SUMMARY

The physiology of handcycling has been studied regularly over the last 20 years; however, it is only recently that protocols applicable to recumbent handcycling have been undertaken. Notably, these cycling positions differ dramatically from handbikes used recreationally or during rehabilitation making the transferability to sports performance fairly limited. That said, many studies have reported the aerobic capacity of handcyclists of varying impairments (albeit mainly those in the H3-4 categories) and training histories, although a wide variety of test protocols have been used. Less attention has been paid to the anaerobic capabilities of handcyclists with most studies utilizing AB athletes to examine sprint performance. Nonetheless, research is emerging which details the physiological correlates to handcycling TT performance over distances representative of international events. Like AB cycling, it appears that in trained populations, athletes’ fractional utilization of $\text{VO}_{2\text{peak}}$ and measures of $\text{PO}_{\text{peak}}$ best relate to performance. Research is scarce regarding the training habits, nutritional strategies, and pre-event interventions of elite handcyclists and should be an area for future work. However, it appears that while handcyclists may be adopting the training practices recommended for AB endurance athletes, physical impairment must be considered when determining the risk of thermoregulatory strain or responses to acute interventions, including medical contraindications. Further, it is apparent that the role of ergonomic optimization and bespoke configuration and maintenance of bike position is key for handcyclists to maximize their mechanical efficiency.

6 | PERSPECTIVES

It is evident that many experimental protocols have been employed across a wide range of participant impairments (Tables 2-4). Here, we provide some considerations when interpreting the findings of previous research and applying it to the sport domain. Even in studies which have recruited handcyclists rather than AB athletes, caution should be applied with the level of the athletes’ impairment as well as their training history, physical fitness, and skill level all considered. Further, studies have used exercise protocols that are not representative of competitive handcycling and may have used workloads that lead to errors in the calculation of variables such as ME. Lastly, the physiological responses to handcycling have been assessed over a range of ergometers—including the use of asynchronous ACE—as well as during over-ground propulsion which brings many confounding factors. It is therefore increasingly clear that international scientific collaboration is needed to provide consistency across protocols and consensus on how best to measure parameters such as $\text{VO}_{2\text{peak}}$, $\text{PO}_{\text{peak}}$, ME, ventilatory/lactate thresholds, and anaerobic capacity, all deemed important for handcycling performance. Such collaboration could also permit multi-centre studies and greater recruitment of athletes.

Future research should look to move beyond the detailing of male handcyclists’ aerobic capacity in a laboratory scenario and continue the current trends in handcycling research, building our knowledge of competitive handcycling. Researchers should consider the anaerobic capacities of truly elite handcyclists—especially understudied H1, H2, and H5 athletes—their training habits and nutritional strategies while using protocols that are ecologically valid and representative of the physiological strain imposed by real-world competition.

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