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Review

Handbike for Daily Use, Sport, and Rehabilitation Purposes: A Literature Review of Actuation and Technical Characteristics

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Abstract: With respect to alternative devices like traditional wheelchairs, handbikes can offer advantages from biomechanical and physiological perspectives, to several kinds of users. Assuring high mechanical efficiency and homogeneous force distributions along cycles, and being suitable for indoor and outdoor activities, these systems are used for rehabilitation, sports, and daily applications. From a technical perspective, their main characteristics can vary with the device final purpose and operational context. This review aims to provide an overall outline of handbikes in the literature from a general and comprehensive point of view, up until 2022. The analysis is performed (i) with a systematic approach, without a priori limitations on document type and content focus, and (ii) to identify the areas of interest for the scientific development of these systems. A systematic evaluation method for the identification and analysis of the documents was designed and implemented and the selection criteria, as well as the rationale for the procedure, are described. A specific taxonomy was defined and applied for the subsequent analysis, and each category is specifically evaluated and described, detailing the main outcomes of the literature analysis and relative discussion. Particular attention is paid to actuation strategies and propulsion efficiency. Finally, the main results of the work and future developments for handbikes are briefly synthesized.

Keywords: handbike; wheelchair; handcycling; actuation; propulsion; biomechanics; rehabilitation review

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1. Introduction

Handbikes are vehicles composed of two-rear wheels and one front wheel. The latter is connected to a handle through a roller chain, which is able to increase the mechanical efficiency, with respect to traditional wheelchairs, up to 15 [1]. Handbikes may present various architectures to adapt to the needs of different users. Figure 1 collects the most common kinds of handbikes. Besides the most traditional solutions, nowadays hybrid devices are also available, which functionally transform wheelchairs into handbikes by adding custom or off-the-shelf attachments to traditional wheelchairs. In the present work, only integrated devices, realized as a whole to enable handcycling, and often referred to as fixed-frame devices, will be properly considered as handbikes; hybrid solutions will be also partially described, but an analysis of these systems is outside the main purpose of the present work. Figure 2 presents an example of the considered handbikes, depicting the main components of this kind of devices and synthesizing the basic applied nomenclature.

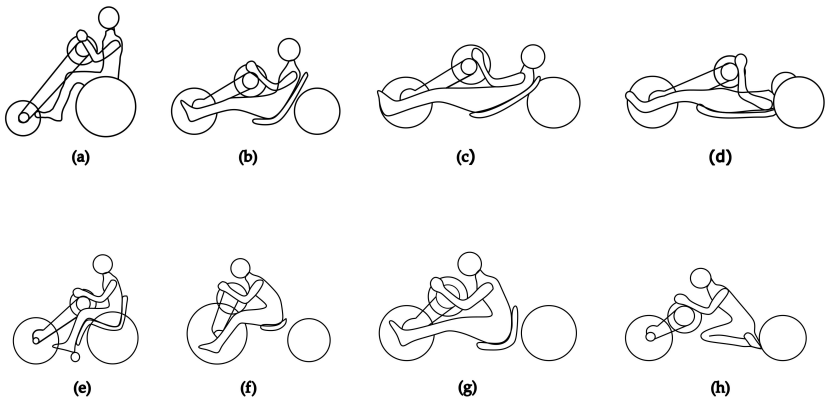


Figure 1. Schematic of the most common kinds of handbike architectures, divided into arm propulsion on the upper row, and arm trunk propulsion on the lower row, with: (**a**) attach unit handbike, (**b**) recumbent 60° rigid frame, (**c**) recumbent 30° rigid frame, (**d**) recumbent 0° rigid frame, (**e**) attach unit handbike, (**f**) car-seat, (**g**) long-seat, and (**h**) knee-seat.

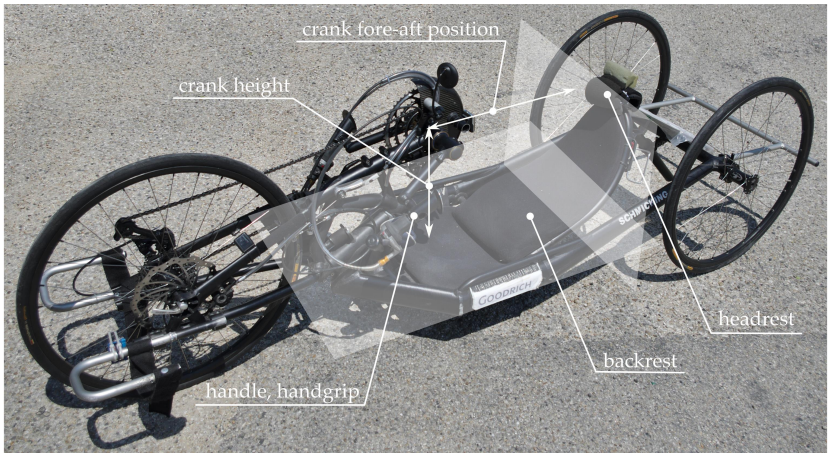


Figure 2. Example of handbike: main components and basic applied nomenclature. Modified version of the image by C. Bucco-Lechat, 2014 [2].

According to literature, using a handbike for daily life confers advantages from a biomechanical and physiological point of view with respect to traditional wheelchairs for several kinds of patients, like subjects affected by spinal cord injury (SCI) [3,4].

For instance, as observed in the work by Dallmeijer et al. of 2004 [5], the propulsion of a handbike depends on a closed-chain motion, and the force applied to the handle contributes to movement during all the 360° of the motion cycle. Furthermore, in a work of 2012, Arnet et al. [6] shows that the force distribution is more homogeneous during an entire handle rotation of the handbike, also referred to as the hand-cycle, than during an analogous wheelchair cycle. This is due to the fact that, for the handbike, an individual's hands are always in contact with the handle during the propulsion act; for the wheelchair instead, the hands have to transmit sufficient force on the wheel generating movement in a short amount of time. As a result, the force during a wheelchair cycle presents peaks three times higher than a handbike, and generates significant torques at the shoulder joints. Over time, this condition could lead to overuse injuries called repetitive strain injuries (RSI).

Another advantage of the handbike is its versatility. Handbikes can be used outdoors and indoors and for different purposes, such as for training, also attached to a traditional ergometer, or to follow rehabilitation programs. In this latter case, handbikes can be equipped with specific components, like additional gears assuring different gear ratios, as

shown in the study by Van Der Woude et al. [7], to confer fluidity to the movement and enhance mechanical efficiency.

Focusing on technical solutions, the backrest deserves particular attention. Indeed, the backrest can be reclining as well as not even present, according to the needs of the user and the severity of their impairment, or depending on the UCI (Union Cycliste Internationale) rules in the case of racing. In the first case, with backrest, according to Nevin et al. [3] we have an Arm power Propulsion (AP), propelled by paraplegic patients, and the backrest angle can range from 0° to 60°(see Figure 1a–d). In this scenario, propulsion is only given by upper limbs movements. The second case, without backrest, is called Arm Trunk Propulsion (ATP), and in these devices the trunk's flexion/extension contributes to propelling the handbike (as depicted in Figure 1e–h).

The kind of propulsion can also be classified into two types: synchronous and asynchronous. According to the works conducted by Kraaijenbrink et al. [8,9], the synchronous mode with the extra use of trunk is the more efficient way to propel a handbike in terms of power production and vehicle conduction.

Furthermore, handbikes also play an important role in rehabilitation. As exposed in the work of Nooijen et al. [10], wider physical benefits like greater power production and maximal oxygen consumption have been detected in the SCI subject when handbike training was added to the traditional rehabilitation program. In addition, a cross-sectional study by Van Der Woude et al. [11] reveals that handcycling is an effective intervention, which is able to maintain an active lifestyle and enables preventing secondary health conditions like pressure sores, urinary tract infections, osteoporosis, upper-extremity pain and cardiovascular diseases.

According to the Scopus database, the interest of the scientific community in handbikes and their features has remarkably increased since 2008, reaching a peak in 2021 and 2022 with 20 published documents every year, as Figure 3 depicts. Within all the published documents, only seven were classified as reviews according to Scopus.

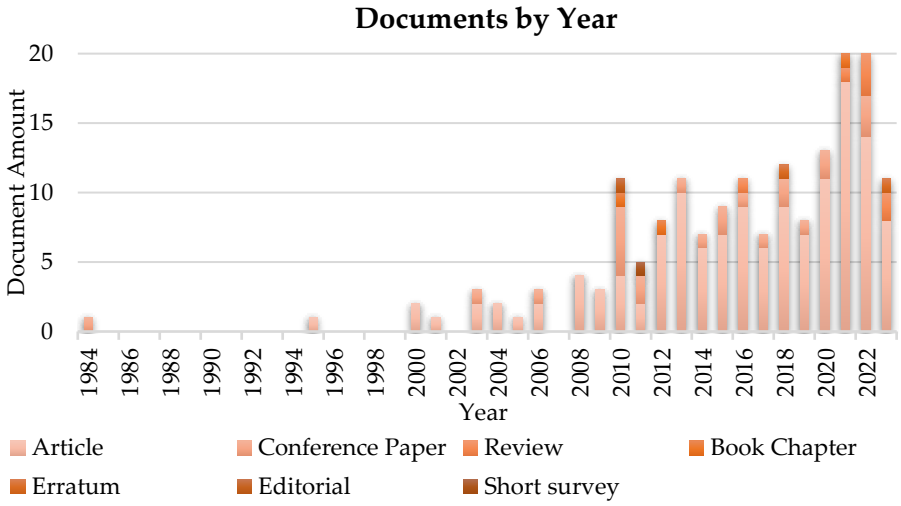


Figure 3. Documents referring to the "Handbike" topic in the Scopus database, by year.

Among the first literature reviews, there is the work published in 2016 by Rice et al. [4]. However, more than outlining an overview of the overall scientific literature from a broad perspective, the paper mainly focuses on the specific topic of the technology used in sports where a wheelchair is needed. In 2021, Flueck et al. [12] present a narrative review, but centered it on nutritional considerations for para-cycling athletes. Finally, Nevin et al. [3], Goodlin et al. [13], and Rayes et al. [14] published three additional review works in 2022. In the first one, Nevin et al. proposed a narrative review of the handbike analyzing 49 documents, focusing on biomechanics and physiology characteristics of competitive handcycling, such as seat positioning, crank height, and fore-aft position, as well as peak

aerobic power output, and relative upper body strength, suggesting practical training of the human upper body for competitive performance. The work by Goodlin et al. [13] instead depicts an overview of para-cycling, including evaluations on technological solutions from tandem cycling, to handcycling, to tricycles. Similarly, Rayes et al. [14] describe adaptive sports for the SCI subject, including the handbike, among several others, without a dedicated focus.

Since none of the previous works seem to provide an overall technical outline of handbike in literature from a general and comprehensive point of view, this review analyzes scientific literature until 2022 (i) with a systematic approach, without a priori limitations to document type or content focus, and (ii) with the main aim of depicting an overview of the areas of interest for scientific developments of these systems, giving particular attention to the actuation field.

To reach this goal, a systematic evaluation method for identification and analysis of the documents was designed and implemented. The following Section 2 describes selection criteria and rationale of this procedure, introducing the taxonomy applied for the subsequent analysis. Each category is then specifically evaluated and described in Section 3, detailing main outcomes of the literature analysis and relative evaluations. Finally, Section 4 briefly summarizes the main results and possible limitations of the work.

2. Materials and Methods

This section describes the procedure applied to select the analyzed research products, the identified taxonomy for the data evaluation, and the implemented data processing.

2.1. Data Selection

The research was performed querying the Scopus database with the string *TITLE-ABS-KEY (hand*bik* OR hand*cycl*)*. The last query was run on the 30 November 2023, providing 174 results, classified according to the Scopus database as follows: 136 articles, 24 conference papers, 7 reviews, 3 book chapters, 2 errata, 1 editorial, and 1 short survey.

Two exclusion criteria were imposed on the results of the string search: (i) documents must have been published within 2022, and (ii) the document language of the full text was required to be English. The final dataset was therefore composed of 160 documents.

Figure 4 presents a schematic of the applied data selection process, whereas Figure 5a,b depict the distribution of the results as total number of documents by type and their evolution in time, respectively.

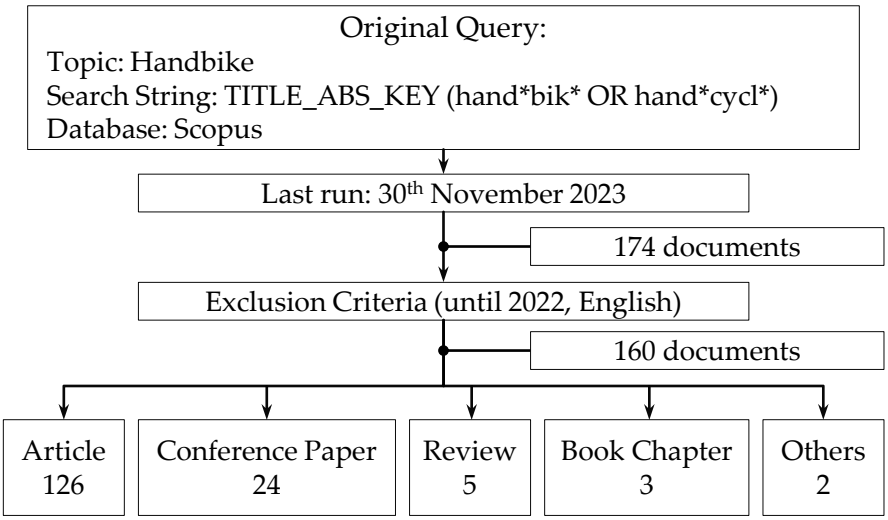


Figure 4. Flow chart of the applied documents selection process ('Others' includes editorials, short surveys, and errata).

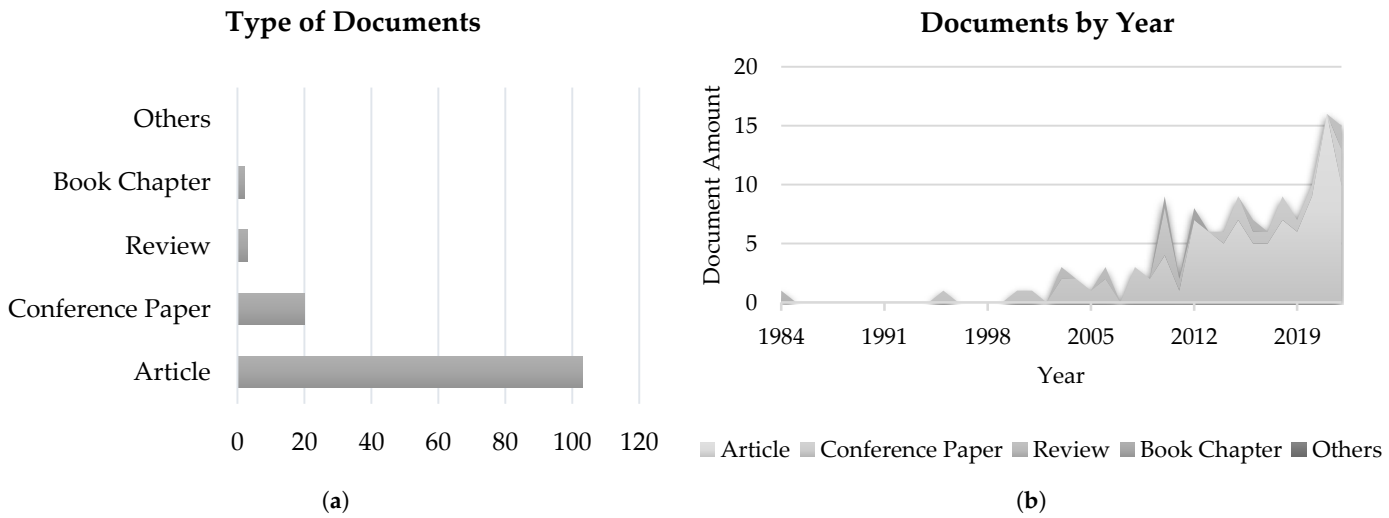


Figure 5. Literature overview. (**a**) Total number of documents divided by type; the category 'Others' includes errata, short surveys, and editorials. (**b**) Evolution in time of the total number of documents by type.

2.2. Taxonomy

To investigate and classify the main topic of the documents, a set of categories and sub-categories was initially defined based on preliminary analysis of previous works and authors' experience. The list was interactively integrated during the analysis, and the following categories were finally identified:

Clinical tests. To be included in this class, documents shall include results regarding main physiological parameters in handcycling (e.g., maximal oxygen uptake VO2, Blood lactate BLa, energy expenditure EE, and power output PO), or involve patients to produce results. Papers in this category can therefore be clinical studies, but this characteristic is not mandatory.

Device. This category collects documents focusing on the analysis of the devices for the experimental setup of handbike testing. For instance, papers describing the use of ergometers or treadmills during data acquisition, as well as focusing on the design process of the whole handbike, or the study of parts of it, are included in this class.

Forces. This section includes documents investigating the forces exerted by the user during a handcycle. The analysis can include the assessment of forces generated in the subject at different anatomical areas (like the shoulder or all the upper limb), as well as at the interface with the device (i.e., handle).

Geometry. This category collects the documents that study mechanical adjustments of the handbike that alter the biomechanics of athletes or patients. For instance, works referring to modifications at crank inclination, height, and length, as well as distance between cranks, or backrest inclination, and wheels dimensions or pressure, are classified within this class.

Sensors. This class gathers the works dealing with sensors and measurement systems used to access the performance of the subject and/or the handbike, both in laboratory and outdoor environments, for tests, sport practice, and race conditions. No distinction in the inclusion was made between papers presenting custom-made systems and works using commercial sensors.

Actuation. This category collects the documents which study the propulsion of the handbike, both in terms of biomechanical models of the handcycling and technical solutions, like different crank modes.

Other. This class gathers the studies focusing on topics not expressly falling into one or more of the previous categories, such as literature reviews.

Each document in the subset of the 160 selected products was in particular classified according to a set of sub-classes for each category. Figure 6 collects the applied taxonomy. The classification was performed assigning each paper to one or more sub-classes.

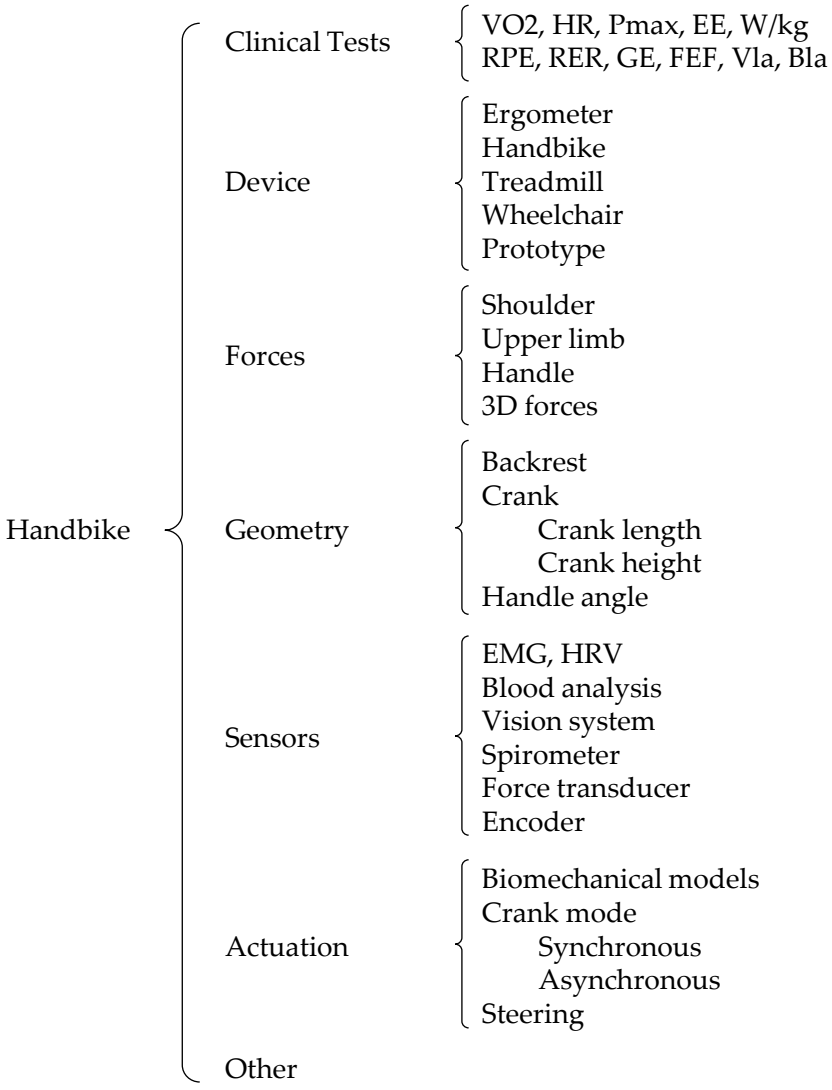


Figure 6. Applied taxonomy: classes and sub-classes adopted for the classification of the analyzed documents.

For the category Clinical Tests, a set of sub-classes was identified, corresponding to the most common measurable quantities associated with the assessment of performance, such as biosignals, functional quantities, and performance indexes. The following sub-classes were therefore identified:

VO2, Maximal Oxygen Uptake [mL/min]: this quantity corresponds to the maximum rate of oxygen consumption measured during incremental exercise;

HR, Heart Rate [Bpm]: this parameter represents the frequency of the heartbeat measured by the number of beats of the heart per minute;

$\mathbf{P_{max}}$, Power Peak [W]: this index describes the maximal power exerted during specific tasks, like incremental, exhaustion, or sprint tests;

EE, Energy Expenditure [kcal/h]: this parameter evaluates the mean energy consumption. This value is typically evaluated according to the definition used by Abel et al. in 2006 [1,15];

W/kg, Power per Kilogram [W/kg]: this index computes the power produced by the subject, per kilogram;

RPE, Rating of Perceived Exertion: this quantity is evaluated according to the RPE Borg Scale, i.e., a clinical scale used to assess an individual's perception of their own exertion or effort during physical activity or exercise [16].

RER, Respiratory Exchange Ratio: this index measures the ratio between the produced volumes of carbon dioxide (VCO2) and oxygen (VO2);

GE, Gross Efficiency: this parameter computes the ratio between the power measured on the handbike, and the estimation of the power generated by the user;

FEF, Fraction Effective Force: this quantity accesses the component of force that actively contributes to the motion of the crank;

Vla, Lactate Production [mmol/(L·s)]: this index estimates the maximal lactate accumulation rate produced by the subject;

Bla, Blood Lactate Concentration [mmol/L]: this index assesses the lactate concentration in the subject's blood.

For the Device category, the sub-classes presented in the following were considered:

Ergometer. This sub-class gathers papers including the use of ergometers for handbike-related applications;

Handbike. This sub-category collects the works providing some technical details of the used handbike, for instance describing the device model;

Treadmill. This sub-class includes papers presenting treadmills in the experimental setup of the handbike;

Wheelchair. This sub-category collects the works that include comparisons between handbike and wheelchair perfomances;

Prototypes. This sub-class includes papers describing prototypes of innovative solutions, such as new methods of propulsion with respect to handcycling, or re-designs of classic devices.

For the Forces category, a set of sub-classes corresponding to relevant anatomical districts were identified. An additional field was considered to capture those works investigating handcycling as a three-dimensional movement. The final set of sub-classes was therefore composed of the following:

Shoulder. The shoulder sub-category includes all the papers that are related to the study of the forces and torques acting on the whole shoulder complex in general, or on parts of it, like the glenohumeral joint, when using a handbike or a wheelchair.

Upper Limb. This sub-class collects all the documents involving the investigation of forces exerted during handbike activities by muscles of the upper body.

Handle. The Handle sub-category collects all the papers that study the force exchanged between the subject and the handle grip when handcycling.

3D Forces. This sub-class includes the papers in which force is analyzed in space, therefore evaluating the three components of the force vector.

For the Geometry class, four sub-classes were investigated:

Backrest. This sub-class gathers the works dealing with the investigation of the backrest of handbikes, analyzing its effects on the handbike performance.

Crank. This sub-class includes the documents proposing and comparing different settings regarding the handbike crank, with particular attention to crank length and height.

Handle Angle. The Handle Angle sub-category collects the papers focusing on the analysis of the handle grip's angle, for instance evaluating the effect of modifications in its value.

For the Sensors category, the followings sub-classes were considered, depicting the most spread measurement systems integrated or applied to handbikes, as well as the most commonly measured quantities for both the handbike and the user:

Electromyography. This sub-class collects all the papers describing the use of electromyographic (EMG) sensors during tests performed with a handbike.

Heart Rate Variability [HRV]: This sub-category gathers the works presenting sensors of different kinds, that record heartbeats fluctuations.

Blood Analysis. This sub-class gathers the works that include sensors for the analysis of the user's blood, i.e., sensors that enable the assessment of chemical or physical properties of blood samples taken during or after a test.

Vision System. The vision system sub-class collects all the documents related to the acquisition of real-time movements of the subjects, through vision capture systems.

Spirometer. This sub-category collects the papers involving the use of systems to measure the volume of air expired or inspired by the subject's lungs, for instance to identify ventilation patterns.

Force Transducer. The force transducer sub-class collects the documents related to instruments placed on the handle that provide information about the forces exerted by subjects, for instance, in terms of amplitude and direction.

Encoder. This sub-category gathers documents in which encoders are used or investigated.

Finally, the following sub-classes were identified for the Actuation category:

Biomechanical models. This sub-class gathers all the works describing the handcycling task with biomechanical models, for instance presenting the design of new models, investigating solutions for the identification of related parameters, or optimization strategies for handbike propulsion.

Crank mode. This sub-category collects all the documents that investigate the propulsion of the device from a mechanical perspective. This includes for instance the analysis of the different crank modes, as well as the comparison of the two main types of possible propulsion, namely synchronous and asynchronous, which depict the conditions of shift-phase between left and right handles at 0° or 180°, respectively.

Steering. The steering sub-class collects those papers presenting studies in which the handbike used for tests or outdoor activities has the capacity to turn the crank around an axis in the sagittal plane of the subject in order to change the direction of motion.

Each category was then independently analyzed with respect to the following aspects:

- The distribution of the documents in time, by type;
- An analysis of the documents by sub-class;
- A discussion of main characteristics and results of the category, with particular attention to sub-classes.

In particular, the first two levels of analysis were performed through an observational approach, aiming to outline a quantitative description of the literature, whereas the final level of investigation was performed through a detailed study of the documents that aimed to provide the reader with a descriptive analysis of the most relevant findings currently available in the scientific literature.

According to these considerations, the following Section 3 presents for each subsection a first part, reporting the quantitative aspects of the analysis, and a second part, depicting

the descriptive analysis, as the main results of the defined categories with specific attention to the identified sub-classes.

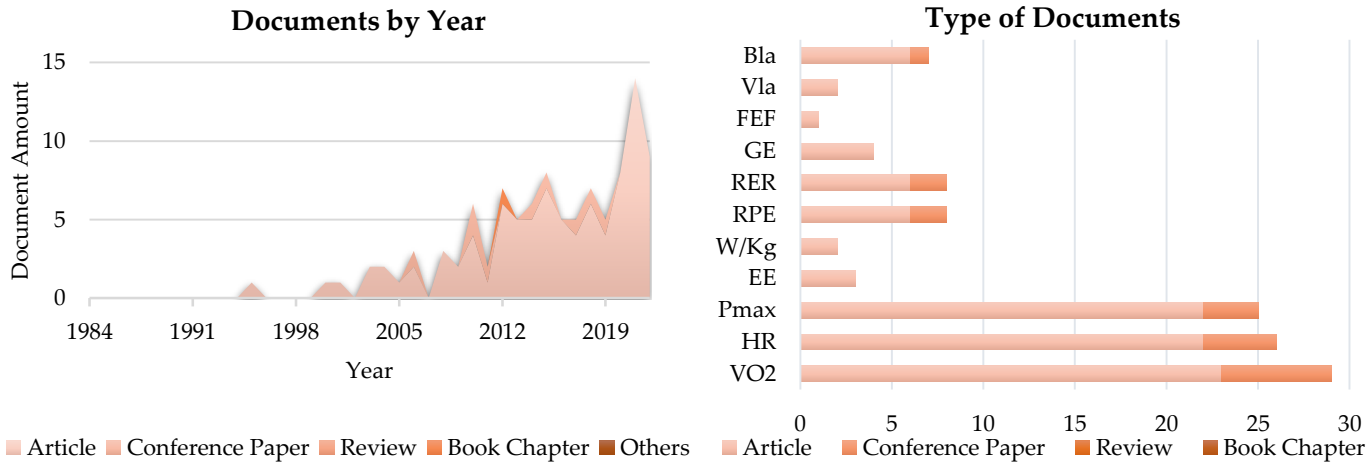
3. Results and Discussion

The set of 160 documents was analyzed by applying the proposed taxonomy, and 32 products were classified as out of topic. The final set of documents, analyzed by categories and sub-classes, was therefore composed of 128 products.

The list of the evaluated documents is reported in Table A1, with the synthesis of the classification among categories and an extract of the sub-classes. More detailed investigations by category are presented in the following.

3.1. Clinical Tests

There were 107 documents classified in the clinical test category, and these were distributed among 95 articles, 11 conference papers, and 1 book chapter, as Figure 7a shows. The number of published documents, and number of articles in particular, has especially increased in the last twenty years, with a peak of 14 articles reached in 2021.



(**a**) (**b**)

Figure 7. Clinical test category: (**a**) evolution of documents in time, and (**b**) number of documents in each sub-class for the clinical test category, divided by document type.

Clinical Test Sub-Classes

Figure 7b presents the distribution of identified documents among the sub-fields of the clinical test category: the most studied quantities are the maximal oxygen uptake (VO2), with 29 documents, then heart rate (HR) and maximum pressure (P_{max}), with 26 and 25 documents, respectively. The graph also allows capturing the distribution by type of document. In more detail, most of the products are classified as articles, followed distantly by conference papers.

While investigating the documents in this category, the opportunity of evaluating additional elements in more detail, for better understanding and comparison purposes, emerged. In particular, the documents revealed interesting analogies and differences when investigating the applied experimental setups and protocols. Table 1 presents an example of those characteristics for an illustrative subset of relevant documents.

The data reveal that 41 documents enrolled subjects without disabilities, 64 involved subjects with disabilities, such as SCI, tetraplegia, and paraplegia, and 12 documents enrolled both subjects with and without disabilities. Referring to the exploited instrumentation, 43 documents used handbikes and 3 documents used both handbike and wheelchair. In some cases, hybrid handbikes are also used for the acquisitions, especially where the use of a treadmill is required, as in the experimental setups described in Figure 8.

Table 1. Example of characteristics describing applied experimental setups and protocols for the documents classified into the clinical test category.

Document ID	Subject		Instrumentation		Experimental Conditions					Environment			
	with Disability	without Disability	HB	Wheelchair	RPE	%HRR	Fixed Power	Fixed Lactate	Exhaustion	Indoor	Race	Train	Therapy
Abel_2003 [17]	x		x						x				
Dallmeijer_2004 [5]	x	x	x				x [1]						
Lovell_2012 [18]	x		x				x [2]		x				
Verellen_2012*a* [19]		x	x			x	x [3]						
Hettinga_2013 [20]	x	x	x						x				
Abel_2015 [21]		x	x				x [4]						
Bakkum_2015 [22]													
Fischer_2015 [23]	x									x			
Hettinga_2016 [24]		x				x			x				
Schoenmakers_2016 [25]		x				x							
Hutchinson_2017 [26]	x				x					x			
Kraaijenbrink_2017 [27]		x					x [5]						
Quittmann_2018 [28]		x	x						x				
Rappelt_2022 [29]		x	x				x				x		
Kouwijzer_2022 [30]	x		x							x			
Abonie_2021 [31]		x	x			x							
Hutchinson_2021 [32]	x	x	x	x					x				
Kouwijzer_2021 [33]	x						x [6]						
Hall_2022 [34]	x		x						x				
Muchaxo_2022 [35]	x		x						x				

[1] (25–35) W. [2] (50–80) W. [3] 130 W. [4] 20 W. [5] (0–10–20) W. [6] (0–5–10–15–20) W.

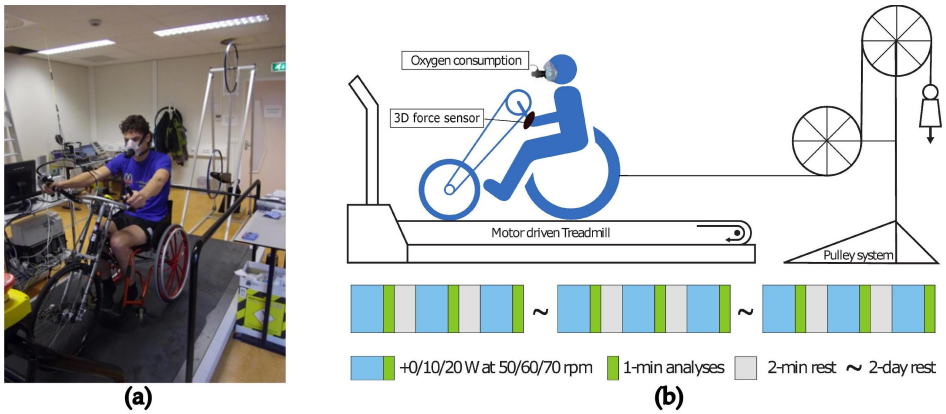


Figure 8. Examples of experimental setups for the assessment of relevant quantities in the Clinical Test category: (**a**) a spirometer is used to evalute VO2 while the subject is handcycling on a treadmill with a hybrid handbike (source: Schoenmakers et al., 2016 [25]) and (**b**) a 3D force sensor is used to compute the power production (source: Kraaijenbrink et al., 2017 [27]).

Focusing on the experimental conditions, in two cases the evaluations were performed at fixed RPE condition, and in four cases at fixed %HRR. In 12 documents, fixed power conditions were imposed, and in two cases a fixed lactate threshold was applied. In 16 cases, the test was conducted until the subject's exhaustion. Finally, considering the environment of the data acquisition, in 25 works, the tests were performed in a laboratory, in 5 documents during races, in 12 cases during training, and in 3 works during rehabilitation training sessions.

Evaluating in more detail the content of the investigated documents, several interesting aspects emerge. The assessment of oxygen uptake VO2 and peak oxygen uptake $VO2_{max}$ holds vital significance for a wide spectrum of professionals, including clinicians and athletes. Particularly in SCI individuals engaged in upper-body exercises, it not only stands out as a predictor of all-cause mortality, but also the percentage of $VO2_{max}$ is advocated for as a fundamental metric for customizing exercise intensity based on an individual's fitness level. In the work conducted by Hutchinson et al. [26], a method of evaluating $VO2_{max}$ is presented. Participants have to complete five two-minute stages at clamped RPE of respectively 11 (light), 13 (somewhat hard), 15 (hard), 17 (very hard), and 20 (maximal exertion) on Borg's RPE scale. Gas exchange variables were collected throughout the test. The authors explain that this test is a valid protocol to assess $VO2_{max}$ in novice, recreationally active, and young handbike users. According to Dallmeijer et al. [5], handcycling is less strenuous and produces a higher exercise response than the traditional wheelchair at a moderate power output level. In fact, the authors' data reveal that tests conducted at a constant power of 35 W present lower values of VO2 and HR, both for paraplegic and subjects without disabilities. Accordingly, the authors suggest handbikes as a means of transportation in daily life. Abonie et al. [31] also highlight how low-intensity upper-body handbike training (training conducted at 30% of maximal subject's heart rate) on a powered treadmill reduces VO2 and improves physical capacity and prevents premature fatigue and overuse in untrained subjects. On the other hand, Hall et al. [34] evaluate how SCI subjects reach high values of $VO2_{max}$ when they regularly use handbikes for at least 1 hour per day. According to Hall et al., handbike-trained SCI subjects have the higher aerobic capacity and, as a consequence, more tolerance to high-intensity exercise. Similarly to Hall et al., the study conducted by Lovell et al. [18] reveals, through a peak aerobic test carried out on an electromagnetically braked cycle ergometer, that handbike-trained SCI subjects had higher $VO2_{max}$ with respect to their age-matched non-trained counterparts. According to the authors, handbike training can therefore prevent cardiovascular disease, and $VO2_{max}$ can serve as a predictor for 20 km time trial performance. Rappelt et al. [29] find that lower-body low-frequency electromyostimulation (EMS) significantly increases acute oxygen uptake. In their work, 26 healthy participants completed a task of sitting,

sitting with concurrent EMS of the legs, handcycling, and handcycling with concurrent EMS of the legs. The protocol consists of four 10 min intervals interspersed with 5 min of passive rest. EMS was applied for 2–3 min. Electrodes were positioned at buttocks, with intensity 80.0 ± 22.7 mA, at thighs, with intensity 94.5 ± 20.5 mA, and at calves, with intensity 77.5 ± 19.1 mA. The average power output during handcycling was 35.9 ± 8.4 W. Participants were given instructions to maintain a target cranking cadence of 60 rpm. According to the authors, the simultaneous use of EMS on the participants' legs led to an acute increase in oxygen demand, amounting to a 39.7% rise (from 0.97 ± 0.21 L/min to 1.36 ± 0.44 L/min) when compared to handcycling without additional EMS stimulation.

Concerning heart rate, Hettinga et al. [24] find that local exercise for the upper body using a handbike could significantly improve heart rate peak (4%), peak $VO2_{peak}$ (+18.1%), and PO_{peak} (+31.9%) in females. In the works carried out by Abonie et al., Verellen et al., and Hettinga et al. [19,20,31], heart rate was used as a fixed parameter to conduct tests, and heart rate reserve (HRR) was especially considered, meant as the ratio between instant heart rate and heart rate peak (HR_{peak}). In particular, the subjects involved in the study of Abonie et al. performed tests at a fixed heart rate reserve of 30%, while participants engaged by Verellen et al. and by Hettinga et al. performed at 80% to 90% HRR.

Focusing on P_{max}, the same work of 2021 by Abonie et al. [31] also evaluated the effect of 7-week low-intensity upper-body handbike training in untrained individuals without disabilities. This kind of training increases the P_{max} by 20% with respect to the control group who receives no training. In the work by Lovell et al. [18], P_{max} for trained handcyclists would appear to be the best predictor of 20 km time trial performance. The authors clarify that the greater P_{max} is due to improved central and peripheral aerobic factors rather than muscular size.

Considering the energy expenditure, EE, the work by Abel et al. [17] reveals that using a handbike at moderate intensity allows an EE high enough to maintain a good health state in the person with disability, and to prevent cardiovascular disease. Specifically, a 60 min training session each day allows achieving the value of 350 kcal consumed which is described by Abel et al. as the greatest value to reduce the risk of myocardial infarction.

An additional parameter investigated in the literature is the relative peak functional performance (W/kg), which expresses the amount of power generated by an individual in relation to their body weight. In the study carried out by Abel et al. in 2015 [21], relative peak functional performance was adopted to study the effect on the subjects of three different handbike grip angles. No significant differences emerged among the three hand grip angles for W/kg.

Focusing then on the rating of perceived exertion, RPE, Hutchinson et al. [32] monitored exercise intensity in the patient with tetraplegia and paraplegia, comparing the values of a clinical scale, namely the Borg exertion scale, obtained from the two populations samples. In their study, 134 competitive subjects were split in three groups depending on the severity of illness: tetraplegic, paraplegic, and non-SCI. Subjects completed a first sub-maximal step test, then a graded exercise test, to exhaustion; during the second test, the intensity was gradually increased by 10–20 W/min or 0.1 $m \cdot s^{-1}$/min, until the participants reached a point of volitional exhaustion. According to the analysis performed by the authors, the data collected throughout the test were not affected by age or sex. In another study, Hutchinson et al. [26] conducted tests at specific RPE values to assess the oxygen uptake during handcycling.

As an alternative approach to the assessment of the intensity level of training, Dallmeijer et al. [5] investigate the respiratory exchange ratio (RER), calculated as the ratio between the volume of produced carbon dioxide VCO2 and the maximal oxygen uptake VO2. In fact, Dallmeijer et al. use RER as the value to determine whether the subject's exercise is conducted at a submaximal level, that is, with an RER value of less than 1.0.

Among the papers in literature, gross-efficiency (GE) is also investigated. According to Hettinga et al. [20] and Dallmeijer et al. [5], this quantity is computed as the percentage ratio between power output (PO) and the power value associated with a basal metabolism

condition P_{met}. This value P_{met} was in particular calculated from the previously identified quantities VO2 and RER, as Pmet = VO2 · [(4940 · RER + 16,040)/60)]. In this work by Hettinga et al. [20], seven physically able male participants underwent an incremental peak exercise handcycling test on a treadmill. Furthermore, two indoor treadmill sessions were conducted at speeds of 1.3 m/s with a slope of 0.7%, and 1.0 m/s with a slope of 4.8%. Additionally, three outdoor over-ground exercise sessions were completed at speeds of 1.7, 3.3, and 5.0 m/s. One of the participants also engaged in an 8-kilometer handcycling session outdoors, representing a typically covered distance. The results indicate that GE increases as the intensity of the test arises, probably because the relative fraction of basal metabolism contributing to energy expenditure decreases with intensity.

The fraction effective force parameter, FEF, expresses a force effective index, as it evaluates the contribution of the tangential force component F_{tan} to the forward propulsion, and is calculated as the ratio between F_{tan} and the total force F_{tot} acting on the handle during handcycling. In the study conducted by Kraaijenbrink et al. [27], twelve capable men used an instrumented add-on handcycle on a motorized level treadmill, riding at a speed of 1.94 m/s. They underwent three sessions, each comprising three four-minute blocks of steady-state exercise. Between the blocks, they changed gears (70, 60, and 52 rpm) and adjusted resistance levels (+0 W, +10 W, +20 W) in a counterbalanced order across sessions. FEF was used as the main outcome to evaluate that a cadence of 52 rpm against a higher resistance of about 35 W leads to a more optimal direction of forces.

Finally, Vla and Bla evaluate lactate production and its concentration in the subject's blood, respectively. In the study by Quittmann et al. [28], Vla is evaluated for twelve able-bodied nationally competitive triathletes that underwent a series of tests, including a familiarization session, a sprint test, an incremental step test, and a continuous load trial at a fixed lactate concentration of 4 mmol/L. These trials were performed on a racing handcycle, which was mounted on an ergometer. The 15 s All-Out sprint test was performed to assess the participants' anaerobic performance and lactic power, and Vla_{max} was calculated as the difference between maximal post-exercise lactate and resting lactate. To evaluate this quantity, a normalization was performed, dividing the maximal post-exercise lactate by the difference between the test's duration, and the initial exercise phase during which no lactate formation was assumed. The participants' mean values for la_{max} and Vla_{max} were 6.64 ± 1.32 mmol/L, and 0.45 ± 0.11 mmol/(L·s), respectively. The incremental step tests started with an initial load of 20 W and increased every 5 min by 20 W until volitional exhaustion. In this case, la and HR were collected within the last 30 s of every power level, and the mean la at volitional exhaustion was 9.64 ± 2.24 mmol/L. For the continuous load trial, the mean Vla at the end of the tests was 5.36 ± 1.85 mmol/L. In their work, Quittmann et al. reveal that Vla_{max} can be considered a promising parameter for exercise testing in handcycling, since it shows a positive correlation with anaerobic performance and a negative correlation with aerobic performance measures, and moreover, parameters related to post-exercise lactate kinetics and Vla_{max} are interconnected and provide valuable insights into the athlete's physiology. Therefore, it is advisable to utilize both approaches in tandem for a comprehensive assessment.

Focusing on Bla, Hall et al. [34] found that individuals with spinal cord injury who were trained in handcycling had higher Bla (9.9 ± 3.7) than able-bodied males who were trained in power lifting (9.2 ± 1.7) and than the control group of fourteen subjects (9.8 ± 1.2 mmlol/L). According to the authors' findings, this suggests that these athletes likely have a higher aerobic capacity, which is most likely a result of more extensive training.

Besides the set of works described so far, which mainly emphasize specific details primarily on individual parameters that identify sub-classes, several papers also investigate more parameters or cross-cutting aspects. For instance, in the work by Fischer et al. [23] an additional division between tetraplegic and paraplegic patients is made. In tests conducted at sub-maximal speed, the authors find that the tetraplegic patient has a lower aerobic speed (4.7 ± 0.6 m/s vs. 7.1 ± 0.9 m/s) and mechanical power (54 ± 15 W vs. 111 ± 25 W) with respect to the paraplegic patient at equal metabolic cost. Schoenmakers et al. [25]

studied the difference between moderate-intensity continuous training (MICT) and high-intensity interval training (HIIT). Despite training 22% less time for HITT than MICT, a higher improvement is obtained in the patient trained with HIIT. Power output peak values represent a 47.1 $\pm$ 20.7% increase for HIIT and 32.2 $\pm$ 8.1% increase for MICT.

Instead, Kouwijzer et al. [33] analyzed the physical capacity of 33 subjects comparing at 1-year follow-up with the physical capacity assessed before and after the training period for the HandbikeBattle event. Data showed an increase in the capacity during the training period, which remained stable after the follow-up. The authors therefore suggest that keeping committed to a challenge may ease long-term exercise maintenance.

Finally, additional considerations, at a more general level, can be retrieved by the works of de Groot et al. [36] and Nooijen et al. [37]; in the former, data revealed that the SCI level of the subject is not significantly associated with racing performance, assessed as race time. In the latter, the authors compared the performance of 168 athletes racing in elite para-cycling events with different devices, i.e., bicycles, tricycles, recumbent handbikes, and kneeling handbikes. According to the data, bike type and impairment type were not effect modifiers in the studied relation between road time trial performance and sprint power.

Table 2 synthesizes the main highlights that emerged from the analysis of the Clinical Tests category and its sub-classes.

Table 2. Clinical Tests: highlights for the category and sub-classes.

Clinical Tests: Highlights
General remarks
• Handbikes could be used as means of transportation in everyday life: handcycling is less strenuous and produces higher exercise response than the traditional wheelchair at a moderate power output level [5].
• Low-intensity upper-body handbike training reduces VO2, improves physical capacity, and prevents premature fatigue and overuse in untrained subjects [31]. Handbike training can prevent cardiovascular disease [18].
• The SCI level of a subject is not significantly associated with racing performance, as racing time [36].
• Bike type and impairment type may not be effect modifiers in the relation between road time trial performance and sprint power [37].
VO2
• $VO2_{max}$ can be used as predictor of all-cause mortality in SCI patients engaged in upper-body exercises, and as a basis for customizing exercise intensity [26].
• Lower-body low-frequency EMS significantly increases the acute oxygen uptake [29].
Peak functional performance (W/kg)
• Different hand grip angles on the handbike do not significantly affect the amount of power generated by the subject in relation to their body weight [21].
RER
• RER can be used as parameter to discriminate whether an exercise is performed at a submaximal level [5].
FEF
• Lower velocity at a higher resistance level offers better direction forces [27].
Vla
• Vla is a promising parameter for exercise testing in handcycling: it presents positive and negative correlation with anaerobic and aerobic performance measures, respectively [28].

3.2. Device

The documents for the Device category were distributed as follows: 85 articles, 15 conference papers, and 1 book chapter, as shown in Figure 9a. The increase in publications became relevant from 2012, although a peak in 2010 with four articles and four conference papers emerged.

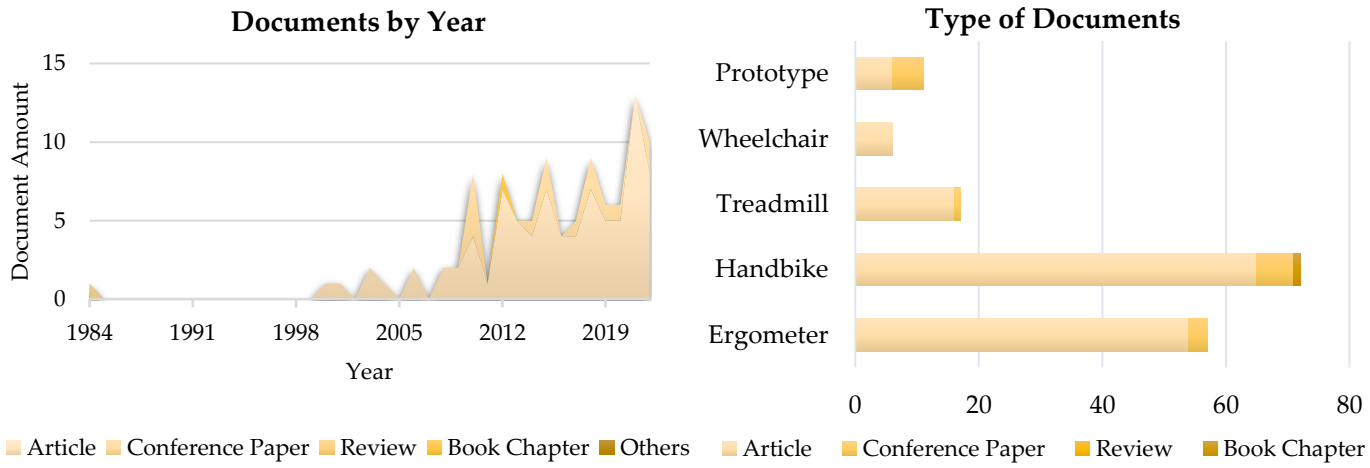


Figure 9. Device category: (**a**) evolution of documents in time, and (**b**) number of documents in each sub-class for the device category, divided by document type.

Device Sub-Classes

The device category was subdivided into sub-classes, each related to different methods for analyzing hand propulsion in subjects, as indicated in Figure 9b. In the same figure, the distribution of documents reveals that articles are the predominant form of publication in each sub-class.

Focusing on the content of the documents, different aspects that affect the device are collected in this class; Figure 10 presents some examples of these elements, whereas Figure 11 collects illustrative examples of handbike prototypes at a glance.

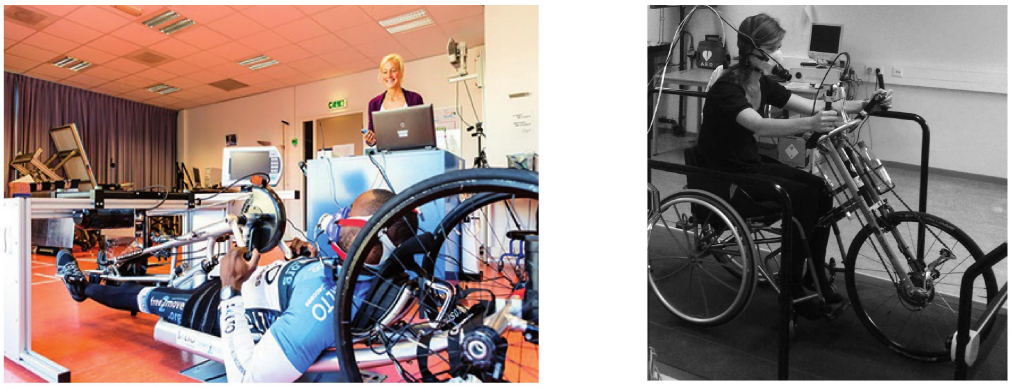


Figure 10. Examples of elements considered in the Devices category: from the left, (**a**) an ergometer used for indoor activities (source: de Groot et al., 2018 [38]), and (**b**) a handbike attach-unit mounted on a treadmill (source: Hettinga et al., 2013 [20]).

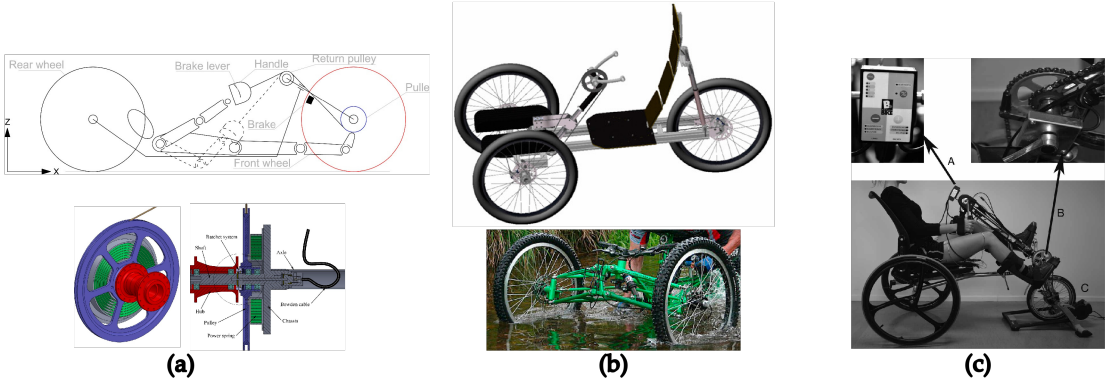


Figure 11. Examples of prototypes: from the left, (**a**) an innovative propulsion system applied to a recumbent handbike (source: Quaglia et al., 2019 [39]), (**b**) a multi-adjustable handbike chassis for off-road use (source: Siebert, 2010 [40]), and (**c**) a hybrid cycle showing the detail of the mounted stimulator (source: Bakkum et al., 2014 [41]).

Ergometer

In 57 cases, an ergometer was used to perform handbike tests. The most used ergometer is the Cyclus II (RBM elektronik-automation GmbH, Leipzig, Germany), which was utilized 29 times, followed by Tacx Flow (Technische Industries, Waibstadt, Germany) in 6 studies, and CycleOps Fluid 2 (Saris, Medison, WI, USA), which was used once.

Handbike

According to data, handbikes were utilized 72 times; 5 of those instances involved outdoor activities or races, and in 17 studies the handbike was mounted on a treadmill, to simulate road conditions or control handle velocity in comparative studies with wheelchair users. Among the most frequently used handbikes Shark RS, Spirit 468, Spirit 469, and Spirit 470 (Sopur, Sunrise Medical, Malsch, Germany) have been identified. These devices were used in experiments 16 times. The Tracker Tour (Double Performance, Gouda, The Netherlands), a wheelchair attach-unit, was mentioned seven times. Finally, the BerkelBike Pro (BerkelBike B.V., St Michielsgestel, The Netherlands) was used in three experiments; this device is defined as a hybrid-bike, as it combines synchronous handcycling with asynchronous Functional Electrical Stimulation-induced leg cycling.

Treadmill

In the study conducted by Abel et al. [1], a motor-driven treadmill was employed to elicit the subject's physiological responses at maximum load one week before the race. The treadmill velocity was set at 12 km/h, with a progressive increase of 2 km/h every 3 min. Abonie et al. [31], on the other hand, utilized a motor-driven treadmill with a constant power output to achieve 30% of the participant's Heart Rate Reserve (HRR).

Arnet et al. and Hettinga et al. [20,42] employed a motor-driven treadmill to simulate different velocities and slopes. The treadmills used in these studies were the Mill (Forcelink, Culemborg, The Netherlands) and the Mill-track (Enraf Nonius, The Netherlands).

Arnet et al., Kraaijenbrink et al., and Schoenmakers et al. [25,27,42] incorporated a pulley system in conjunction with a motor-driven treadmill to maintain an external power output. For Kraaijenbrink and Schoenmakers, the treadmills used were the Motek force Link b.v. (Motek Medical B.V., Houten, The Netherlands) and Mill-track (Enraf Nonius, The Netherlands), respectively.

Wheelchair

The documents classified in the Wheelchair sub-category allow the investigation of analogies and differences between handbike and wheelchair use. Wheelchair propulsion is used in some cases as a baseline for comparison, given the higher popularity of this topic in the scientific literature, which makes it a de facto gold standard [5,32,43].

In other cases, like in the work by Nooien et al. of 2015 [10], the handbike is used as an experimental setup tool, to enable the acquisition of the relevant data in the defined protocol. In fact, unlike what happens in wheelchair propulsion, during handcycling, user and device create a closed kinematic chain: this makes subsequent cycles and repetitions more standardized and comparable, reducing the potential variability of the task across sessions and across subjects [44].

Prototype

Regarding prototypes, several of the analyzed papers focus on wheelchairs more than handbikes mockups. For instance, Chong et al. [45] introduce a new type of wheelchair, aiming to catalyze the development of such devices for children with cerebral palsy. This wheelchair meets the 3As criteria, focusing on availability, accessibility, and affordability. It is equipped with a heartbeat monitoring system, training programs, and a user interface, making it a promising tool in this domain.

In the work conducted by Quaglia et al. [39], an innovative propulsion system is proposed, named Handwheelchair. In this case, the mechanism works as an attachment that functionally transforms a wheelchair into a handbike.

Instead, Siebert et al. [40] addressed two primary challenges associated with handbikes: traction optimization, as most of the weight rests on the two non-driven rear wheels, and the inability to simultaneously pedal and steer in off-road handbiking. To address these issues, a new prototype was developed featuring two steerable front wheels, one of which is powered, allowing users to pedal and control the device with both arms simultaneously. Additionally, a multi-adjustable backrest was incorporated to accommodate the specific requirements of individual users.

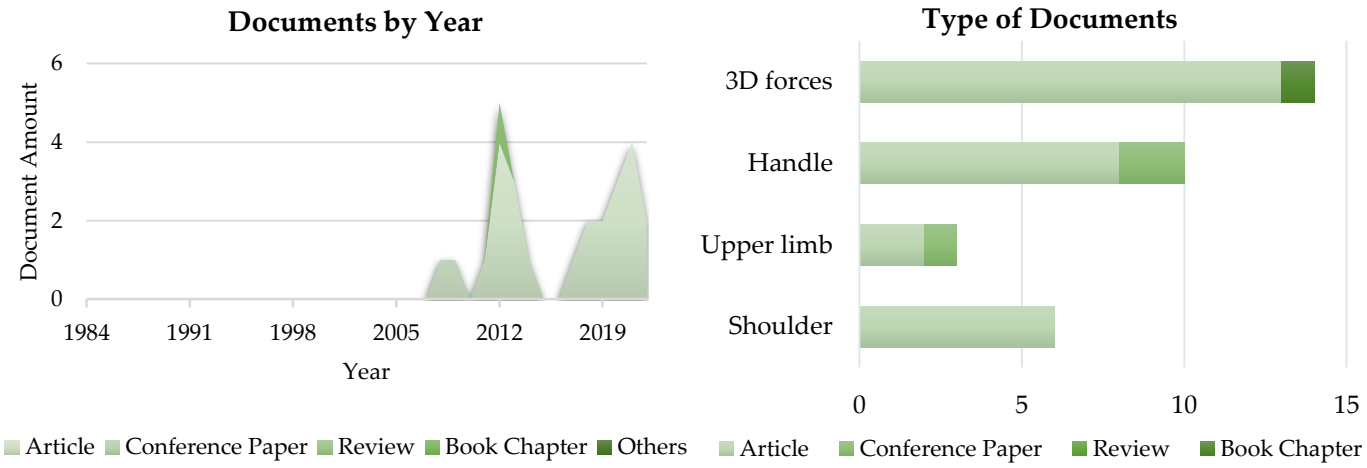
The main highlights that emerged from the analysis of the Device category and its sub-classes are collected in Table 3.

Table 3. Device: highlights for the category and sub-classes.

Device: Highlights
General remarks
• Ergometers are often used in handbike tests, as well as treadmills, to simulate different velocities and slopes. • Wheelchair propulsion can be used as a baseline for comparison [5,32,43]. • Handbikes can be also used as experimental setup tool [10].
Prototype
• Wheelchair prototypes are more common in the literature than handbike prototypes. • Prototypes often focus on the optimization or the design of innovative solutions for components [39], and more rarely of devices [40].

3.3. Forces

The Forces category collects a total of 25 articles, 4 conference papers, and 1 book chapter, as indicated in Figure 12a. The distribution of documents dealing with the forces exerted during handcycling reveals a first peak of interest in 2012, with the publication of five documents, and another peak in 2021, with four published articles.



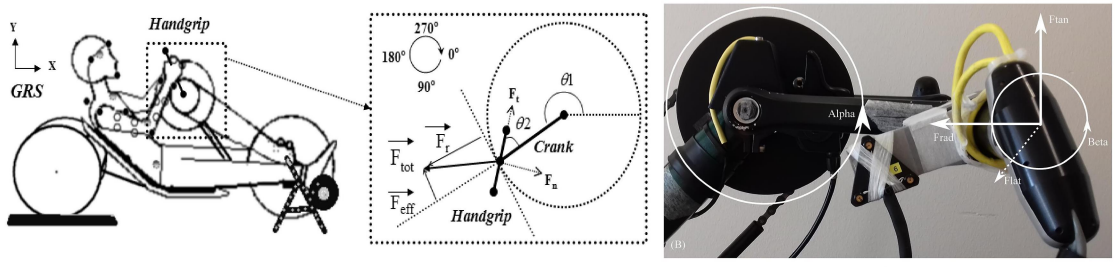
(**a**) (**b**)

Figure 12. Forces category: (**a**) evolution of documents in time, and (**b**) number of documents in each sub-class for the forces category, divided by document type.

Forces Sub-Classes

Within the sub-classes, 10 documents investigated the forces at the handle, 6 at the shoulder, and 3 performed the analysis considering the whole upper limb. Notably, 14 papers explored forces in a 3D context, moving beyond the sagittal plane to offer a comprehensive view of the results (see Figure 12b). Articles represent the predominant type of publication in the Forces class. Most of the documents address the study of 3D forces, with 13 articles and 1 book chapter, representing 56% of the overall production. The peak of works on this aspect was in 2012.

Figure 13 presents some examples of schematics for the evaluation of 3D forces on the handle depicted in the analyzed literature.



(**a**) (**b**)

Figure 13. Examples of schematics for the evaluation of the forces exchanged between subject and handbike at the handle level: from the left, an example of (**a**) model (source: Faupin et al., 2010 [46]) and (**b**) real setup (source: Kraaijenbrink et al., 2017 [27]) of 3D force measurement on the handle during handcycling.

Shoulder

The shoulder is among the anatomical areas that are more involved in handcycling. Among the six documents classified within this category, Arnet et al. proposed a comparison between handbike and wheelchair performance [6,43]. In the first study conducted by Arnet et al. [6], eight subjects with paraplegia underwent testing while propelling both a handbike and a wheelchair at different power output levels (25, 35, 45, and 55 W). The treadmill speed was adjusted to 1.6 m/s for the handbike and 1.11 m/s for the wheelchair, aiming to simulate everyday propulsion conditions. The estimated force exerted on the rotator cuff during handbiking was approximately 268 N, marking a 29% reduction compared

to the force generated when using a wheelchair at a constant power output of 25 W. This discrepancy grew at a constant power output of 55 W, with the handbike recording a force of 345 N, representing a 70% decrease compared to the wheelchair. During handcycling, glenohumeral contact forces were distributed across the entire cycle, reaching their peak at the end of the cycle. In contrast, wheelchair propulsion exhibited a force peak in the middle of the push phase, with smaller peaks at the beginning and end of the recovery phase. Regarding muscle activation, the supraspinatus and infraspinatus muscles were most engaged during handcycling. Arnet et al. [6] reported that their percentage of activation during handcycling was less than 5%, reducing the risk of overuse injuries compared to traditional wheelchair use and making the handbike a suitable device for daily use.

In the second study, Arnet et al. [43] focused on the impact on the shoulder joint caused by external force production during an entire handbike cycle or in the push phase of the wheelchair on different slopes. Across all slope variations, the force acting on the handle (Total Force and Mean Force calculated over the last 30 s of each repetition) was approximately three times lower during handcycling compared to wheelchair propulsion. Additionally, F_{peak} was about 60 N for the handbike and 160 N for the wheelchair during the push phase, resulting in lower torque on the glenohumeral joint and reducing the risk of shoulder injuries.

The position of the backrest and the crank position were also found to influence shoulder load. Arnet et al. [47] demonstrated that an upright backrest position led to lower shoulder load and reduced muscle activation (specifically the supraspinatus and infraspinatus), while mechanical efficiency, calculated, according to the definition proposed by Kraaijenbrink in 2017 [27], as the percentage of Power Output PO over Energy Expenditure EE, remained constant. However, no significant differences were observed when changing the crank position.

Upper Limb

For the analyzed data, three documents were classified in the Upper Limb category [48–50]. Among their findings, Nevin et al., in a work of 2021 [48], state that there is a strong correlation between strength tests and handcycling performance. The authors conducted tests on 13 UCI male handcyclists belonging to H3/H4 categories, which included a graded exercise test, a 15 s all-out sprint, and a 15 km Individual Time Trial, and the study revealed a significant relationship between upper body strength and handcycling performance. Specifically, improvements in maximal upper body strength led to enhanced gross mechanical efficiency in handbiking. This allowed cyclists to generate the same power output while minimizing the workload required to produce it. Higher mechanical efficiency can also extend the endurance of type I muscle fibers, delaying the activation of less efficient type II fibers. Additionally, there was an observed improvement in strength stiffness, resulting in a better mechanical transmission of force to the handle.

Handle

In works dealing with the handbike handles, particular attention is paid to the interaction with the user in terms of force exchange and propulsion optimization. For instance, in the case of van Drongelen et al. [51], force measurements were taken by replacing the handle's stud with a force transducer, providing three voltage outputs related to the three force components. Encoders were positioned between the handgrip and the handle, and between the handle and the crank, to express forces in the global coordinate system of the bike. According to the authors, the force characteristics can be influenced by several parameters, including crank speed, crank height, and power output.

Arnet et al. [42] studied the correlation between handle speed and force characteristics. They found that, at a constant power output (PO) and gear setting, an increase in crank speed led to a decrease in both total force (F_{tot}) and tangential force (F_{tan}), from 24.2 N to 18.2 N and 20.0 N to 13.5 N, respectively. However, at higher speeds, F_{tot} and F_{tan} did not decrease uniformly across all sectors of the cycling motion, resulting in the Force

Effectiveness Fraction (FEF) not decreasing in every sector. FEF decreased in the sector where gravity acted against the crank's movement but increased in other sectors. Due to the complex nature of the upper limb joint framework, applying force becomes less efficient at higher velocities. Therefore, selecting a lower gear ratio is advisable to maintain a sufficient FEF. The analysis of the relative work produced in each sector revealed that, in sectors where less work was generated (e.g., "lift up" against gravity), work decreased with greater speed, possibly due to inertia. However, in areas where the highest amount of relative work was produced (e.g., "pull down" and "press down", following gravity), the relative work increased with increasing speed. This was because, due to inertia, the crank rotated evenly without the need for high force application.

Kramer et al. [52] also demonstrated an increment in work production during the pull-down phase, suggesting an improved efficiency. Modifying handle angles, particularly a pronated 30° angle, has been shown to enhance the work generation and increase the efficiency of handcycling.

Jacquier-Bret et al. [53] introduced a new index called the Postural Force Production Index (PFPI) to evaluate force production in handcycling. This index considers both the rotation of the handgrips and the patient's ability to generate force from their current posture. The fore-aft position, i.e., the longitudinal position of the crank with respect to the subject's shoulder, also affects the force application and the distribution of relative work.

Vegter et al. [54] tested participants without disabilities on a recumbent handbike at different crank-fore-aft positions (103%, 100%, 97%, 94% of arm length), at two different power outputs (30 W and 60 W). Increasing the crank distance correlated with a decrease in elbow flexion and an increase in shoulder protraction, shifting work production to the pull phase, where the highest torque was recorded. For a more consistent power output, which is useful in daily life, a shorter crank-fore-aft position is recommended to evenly distribute work production throughout the entire cycle, maintaining handle velocity as consistently as possible.

Table 4 depicts the main highlights that emerged from the analysis of the Forces category and its sub-classes.

Table 4. Forces: highlights for the category and sub-classes.

Forces: Highlights
General remarks
• The force characteristics can be affected by several parameters, such as crank speed, crank height, and power output [51].
Shoulder
• Handcycling reduces the risk of overuse injuries compared to the wheelchair: glenohumeral contact forces are distributed across the cycle [6] and lower torques act on the glenohumeral joint [43]. • The backrest position influences the shoulder load: an upright backrest position produces a lower shoulder load and muscle activation [47]. Mechanical efficiency remains constant [27].
Upper Limb
• Improvements in upper body strength enhance gross mechanical efficiency in handbiking [48]. An improved strength stiffness provides better mechanical transmission of forces to the handle [48].
Handle
• At high velocity, selecting a lower gear ratio is advisable to maintain a sufficient force effectiveness fraction: applying force becomes less efficient at high velocities [42]. • A pronated 30° handle angle enhances work generation and increases the efficiency of handcycling [52]. • A short crank-fore-aft position is recommended in daily life: it maintains handle velocity as constant as possible and allows for an even distribution of the work production throughout the cycle [54].

3.4. Geometry

According to the literature, 22 documents have been published for the Geometry category: in particular, 16 articles, 5 conference papers, and 1 book chapter. Figure 14a

describes the evolution of scientific production over time, identifying three peaks, in 2015, 2019, and 2021, with three documents each.

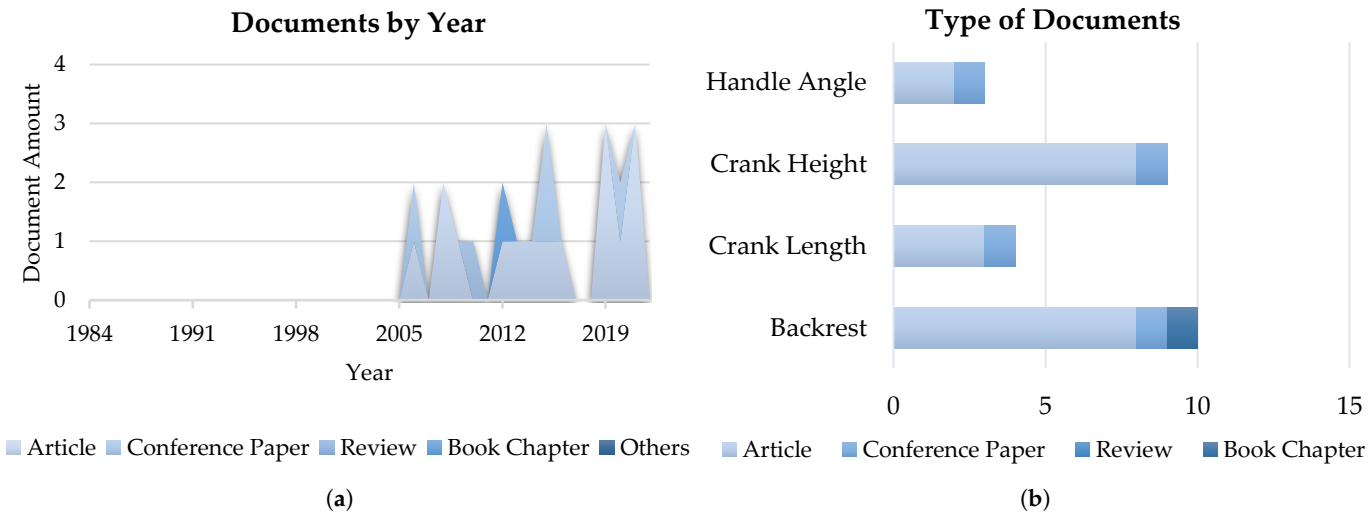


Figure 14. Geometry category: (**a**) evolution of documents in time, and (**b**) number of documents in each sub-class for the geometry category, divided by document type.

Geometry Sub-Classes

Regarding the sub-classes, most of the studies investigate changes in the crank height and backrest. Backrest has been analyzed in 10 documents, of which 8 are articles, 1 is a conference paper, and 1 a book chapter, whereas crank height has been studied in 8 articles and 1 conference paper. The distribution of sub-classes publications is represented in Figure 14b. Paper production is concentrated in three specific time windows: between 2006 and 2010, 2012 and 2017, and from 2018 to 2022. A higher level of production was reached in the second period, with a focus on crank and backrest. Most of the production is represented by articles for all sub-classes.

Some examples of the different aspects that could be evaluated in the documents included in the Geometry class are illustrated in Figure 15.

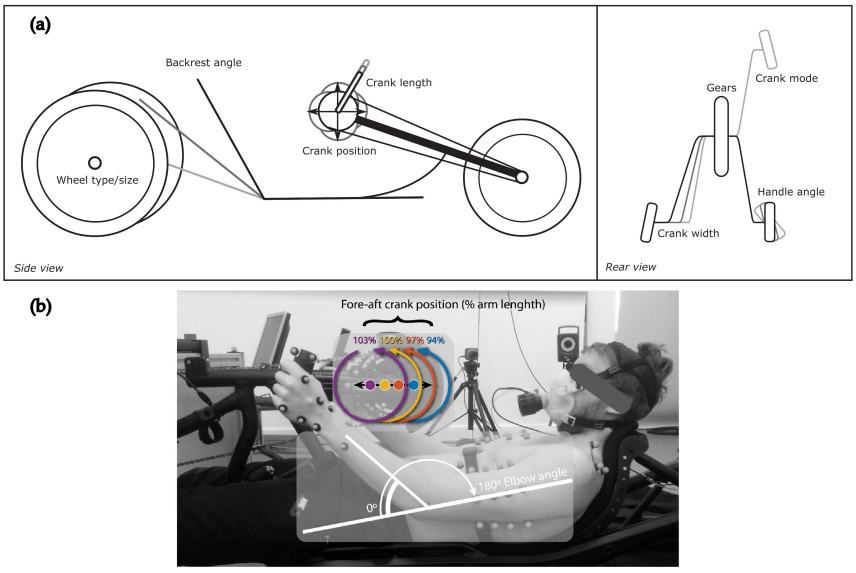


Figure 15. Examples of variabilities evaluated in the documents of the Geometry class: (**a**) different types of handbike settings (source: Kraaijenbrink et al., 2021 [55]), and (**b**) models of different configurations for the crank-fore aft position (source: Vegter et al., 2019 [54]).

Backrest

Among the analyzed data, the first document exploring the effect of backrests on handcycling performance is a work of 2008 by Faupin et al. [56]. In this paper, the authors investigated the impact of backrest position on subjects without disabilities during an 8-second sprint test at different gear ratios. They found that the absence of a backrest improved movement efficiency, especially at higher gear ratios. These results hold significance for patients with trunk mobility issues, suggesting potential benefits and considerations for optimizing backrest positions to enhance performance and reduce risks of injury.

In 2014, Arnet et al. [47] demonstrated that altering the backrest inclination affects the glenohumeral contact force and the forces exerted by the supraspinatus and infraspinatus muscles but does not affect mechanical efficiency. Decreasing the backrest inclination led to an increase in mean and high peak glenohumeral contact force; this phenomenon is particularly noticeable in the lying position, which is common in handbike cycling. Consequently, the lying configuration presents a higher risk of overuse injuries compared to other backrest conditions. Their findings suggest that the most optimal inclination stands at 60°, resulting in the lowest shoulder load. Litzenberger et al. [57] corroborate this outcome by testing a world-class male handbiker across various parameters. They found that a lower backrest position increased the elbow range of motion (ROM), while the opposite was true for higher backrest positions.

The effect of backrest inclination on handcycling performance is so relevant that handbikes can be classified as Arm-Powered or Arm Trunk-Powered depending on this value. The inclination can assume a fixed value, as 90° in the attach-unit handbike, which often presents a motor drive system, or may range from 0° to 60°, depending on factors such as: kind of use (e.g., race or mobility), severity of impairment, or UCI categories (e.g., H1, H2, H3, H4, and H5). In fact, backrest inclination affects several biomechanical factors, such as the trunk flexion/extension, the power production, the crank velocity, and the muscles recruitment.

Crank

Crank position and crank length are fundamental parameters for what concernes handbike daily use. In fact, crank geometry is strongly related to ROM of the upper limb, muscle activation, and force expressed on the crank itself or in shoulder joints. Faupin et al. [58] described a kinematic model with seven degrees of freedom, presenting as input quantities the lengths of the patient's arm segments, the shoulder position, and the size of the crank; the output of the model was the joints kinematics. To achieve an optimal position, i.e., one that reduces the risk of repetitive strain injuries (RSI), by moving the crank axis or modifying the distance between cranks, the following indications were identified:

1. The distance between left and right extremes of the crank is to be set equal to the distance between the shoulders;
2. The crank height should remain below the axis passing through the acromions;
3. The crank should be positioned so as to avoid complete elbow extension.

In the study conducted by Vegter et al. [54], untrained subjects with disabilities were examined on a recumbent handbike at a consistent power output of 60 W. They found that increasing the distance between the acromial angle and the handle's center, specifically at 94%, 97%, 100%, and 103% of the arm's length, resulted in decreased elbow flexion (from 42° to 29°) and a more pronounced shoulder protraction (from 29° to 36°). This alteration shifted the distribution of work during the pull phase, with 69% of the work being produced at the 103% arm length position. However, since handbike races and daily activities benefit from a more equal distribution of work and fatigue among muscle groups, a shorter crank-fore-aft position is favored. This not only aids in reducing speed fluctuations but also helps evenly distribute fatigue. Interestingly, there were no observed effects on VO2, mechanical efficiency, or heart rate when choosing the most extended crank fore-aft position.

The work by Stone et al. [59] was conducted under similar conditions, with a horizontal crank positioned at 97% of the arm length, and with this configuration the authors found more favorable handcycling conditions. This positioning improved the musculature surrounding the joints, enabling more economical force production. Stone et al. discovered that, at 70% of athletes' peak power output, the 97% position was 4% more economical than the 94% and 103% positions. Such data hold significance in endurance competitions or longer activities, where energy-saving measures can influence final results. While the crank length in normal handbikes during professional competitions can vary from 150 mm to 180 mm, the physiological economy remains unaffected by changes in crank length. However, shorter crank lengths are favored during races due to the reduced frontal areas that they offer, which become especially smaller when the crank is at the top dead center, subsequently decreasing air resistance and creating more advantageous conditions. Litzenberger et al. [60] reported that shorter cranks led to higher electromyography (EMG) values for the upper limb muscles throughout the cycle. Moreover, the crank length is related to the number of revolutions per minute (rpm) that the subject can comfortably express. A 190 mm crank length suits a cadence of 180 rpm, while a length of 139 mm is favorable for 125 rpm. Thus, depending on the conditions, crank length can remarkably influence handbike performance.

Handle angle

During handcycling, force is transmitted to the crank through the handle grip. Abel et al. [21] tested participants without disabilities, with incremental tests to exhaustion performed with the three different hand grip angles presented in Figure 16: 0° for a horizontal configuration, 90° for a vertical configuration, and 10° for a diagonal configuration. For each angle, four parameters were evaluated, i.e., peak functional performance (W/kg), peak heart rate (bpm), associated lactate concentrations (mmol/l), and peak oxygen uptake per kilogram of body weight (Ml/min·kg). No significant differences emerged among the three hand grip angles for any parameter, but the vertical position seems to be less efficient than the horizontal and diagonal in the analysis of the lactate concentration. Kramer et al. [52] focus on the correlation between handle angle and work distribution. The effect of the angle on the work distribution is relevant in the pull-down and lift-up phase. In these phases, a higher work production was achieved with angles of −15° and 30°, but the phenomenon of premature fatigue related to these configurations should be further studied, since these results were obtained with a 30 s test.

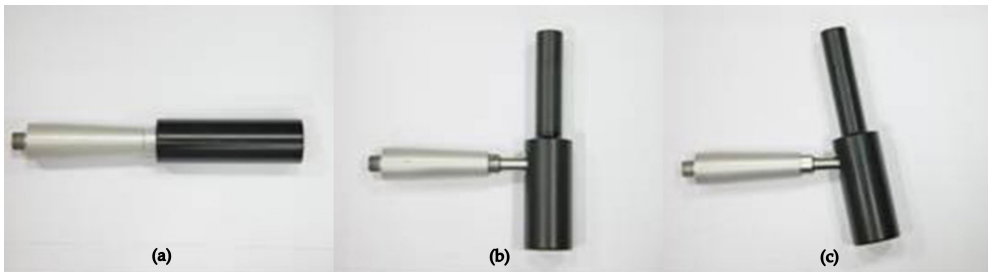


Figure 16. Handle angle configurations analyzed by Abel et al. [21]: from the left, (**a**) horizontal (0°), (**b**) vertical (90°), and (**c**) diagonal (10°) configuration. Source: Abel et al., 2015 [21].

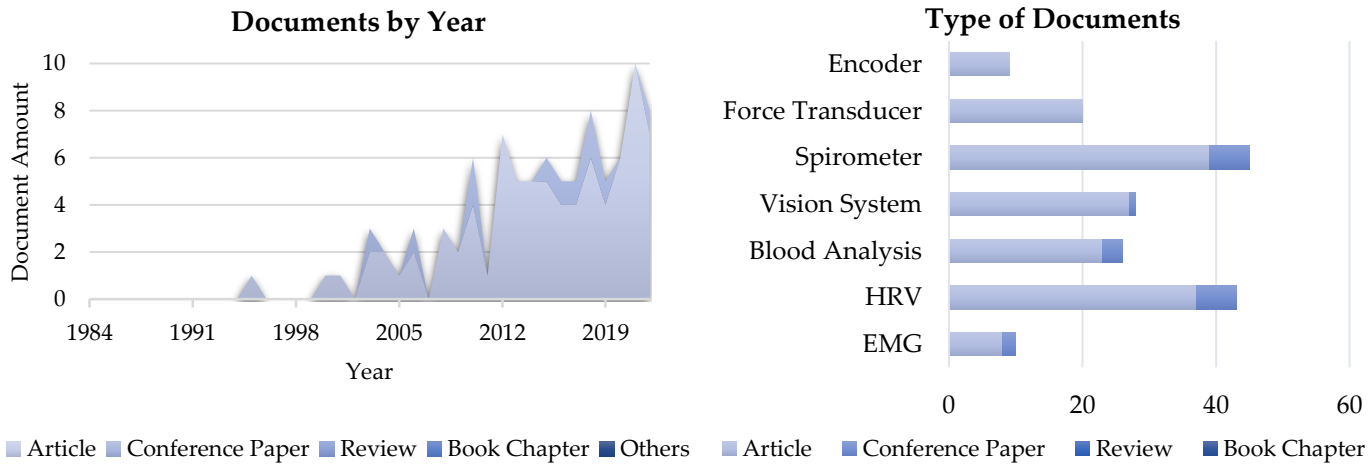
The main highlights that emerged from the analysis of the Geometry category and its sub-classes are synthesized in Table 5.

Table 5. Geometry: highlights for the category and sub-classes.

Geometry: Highlights
Backrest
• The backrest inclination affects several biomechanical factors, such as trunk flexion/extension, power production, crank velocity, and muscles recruitment.
• The absence of a backrest improves movement efficiency in individuals without disabilities, especially at high gear ratios [56].
• The backrest inclination affects glenohumeral contact forces and forces generated by supra/infraspinatus muscles; it does not affect mechanical efficiency [47]. The lying configuration presents a higher risk of overuse injuries [47]. The optimal backrest inclination for the lowest shoulder load is at 60° [47].
• A lower backrest position increases the elbow ROM [57].
Crank
• To minimize the risk of repetitive strain injuries, (i) the distance between cranks must be equal to the distance between shoulders, (ii) the crank height must be below the axis of acromions, and (iii) the crank should avoid complete elbow extension [58].
• Increasing the crank-fore-aft decreases the elbow flexion and increases the shoulder protraction [54]. A short crank-fore-aft is favored for handbike races and daily use: it aids in evenly distributing fatigue and reducing velocity fluctuations [54]. Shorter crank lengths are favored during races, as they offer reduced frontal areas and resistance [59].
• A horizontal crank at 97% of the arm length offers optimal economical force production [59].
Handle
• Modifications to the alignment of the handles do not seem to generate significant differences in W/kg (peak functional performance), HR_{peak}, Bla, and VO2 [21]. Vertical alignment seems to be less efficient than the others for Bla [21].
• The angle of the handles affects the work distribution in the pull-down and lift-up phases [52].

3.5. Sensors

The Sensor category comprises 94 documents, divided into 83 articles and 11 conference papers. The presence of sensors within the set of analyzed documents has almost constantly increased since the beginning of the millennium, reaching a peak in 2021 with 15 published papers (see Figure 17a).



(**a**) (**b**)

Figure 17. Sensors category: (**a**) evolution of documents in time, and (**b**) number of documents in each sub-class for the sensors category, divided by document type.

Sensors Sub-Classes

The sensors most commonly used for handbike measurements are synthesized in Figure 17b. The most applied devices are spirometers, with 45 publications. HRV sensors are also remarkably present, with 43 documents.

The analysis of the used sensors in time reveals a globally increasing trend in the last years. Often, documents state names and models of commercial devices, revealing that in scientific literature the most used sensors are generally produced by few companies, that are often key players in their market. Regardless of the various brands, the works involving EMG and optical cameras often provide the gathered data to biomechanical models, like in the cases of Litzenberger et al. [60], Quittmann et al. [61], or Mason et al. [62]. Similarly, the use of sensors for the assessment of physiological parameters is particularly common in the case of studies with a clinical focus, as in the works by Antunes et al. [63] or Stone et al. [64].

The analysis of Table A1 also allows appreciating the almost complete overlapping between documents classified in the Sensors category and in the Clinical Tests class, highlighting the strong relation between these aspects. Some examples of the sensors and devices described in the documents included in the sensors class are presented in Figure 18.



Figure 18. Examples of sensors used in the experimental setup of documents in the sensors category: from the left, (**a**) a spirometer used in V02 measurements (source: Abel et al., 2006 [1]), (**b**) a bike computer, a cadence sensor, and an HR sensor (source: Koontz et al., 2021 [65]), and (**c**) an encoder mounted on a handbike (source: Bakkum et al., 2014 [41]).

Table 6 presents the main highlights that emerged from the analysis of the Sensors category and its sub-classes.

Table 6. Sensors: highlights for the category and sub-classes.

Sensors: Highlights
General remarks
• The number of sensors used by experimental setup seems to follow an increasing trend. • The data for biomechanical models are often collected with EMG sensors and optical cameras. In documents with a clinical focus, sensors for the assessment of physiological parameters are typically used.

3.6. Actuation

According to the data, for the Actuation category 61 documents have been published; 46 works are classified as articles in the Scopus database, 14 as conference papers, and 1 as a book chapter (see Figure 19a). Also for this class, the analysis of the number of papers published in time reveals an increasing trend, with a peak in 2021 of eight documents.

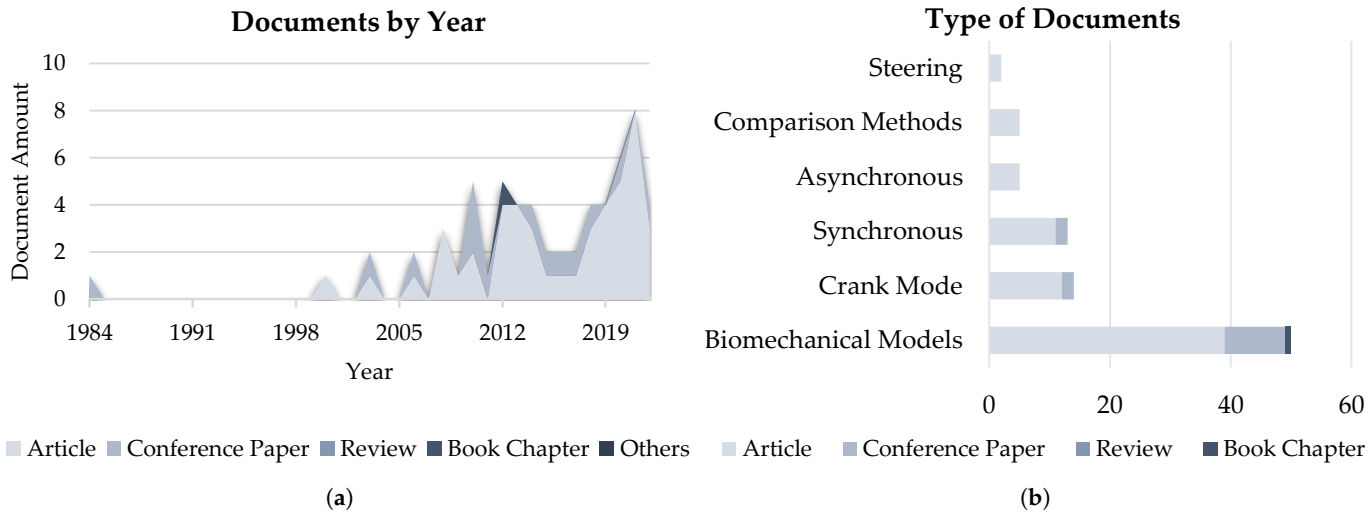


Figure 19. From the left: (**a**) evolution of documents in time, and (**b**) number of documents in each sub-class for the Actuation category, divided by document type.

Actuation Sub-Classes

The distribution of documents by sub-class presented in Figure 19b reveals that most of the documents focus on biomechanical models, particularly articles (39 articles, making up 78% of the documents in the sub-class). The crank mode is investigated in 15 documents, mainly devoted to the study of the synchronous configuration (14 documents). Steering is especially evaluated in only three documents.

Figure 20 collects some illustrative examples of models applied to the investigation of the actuation propulsion included in the Actuation class.

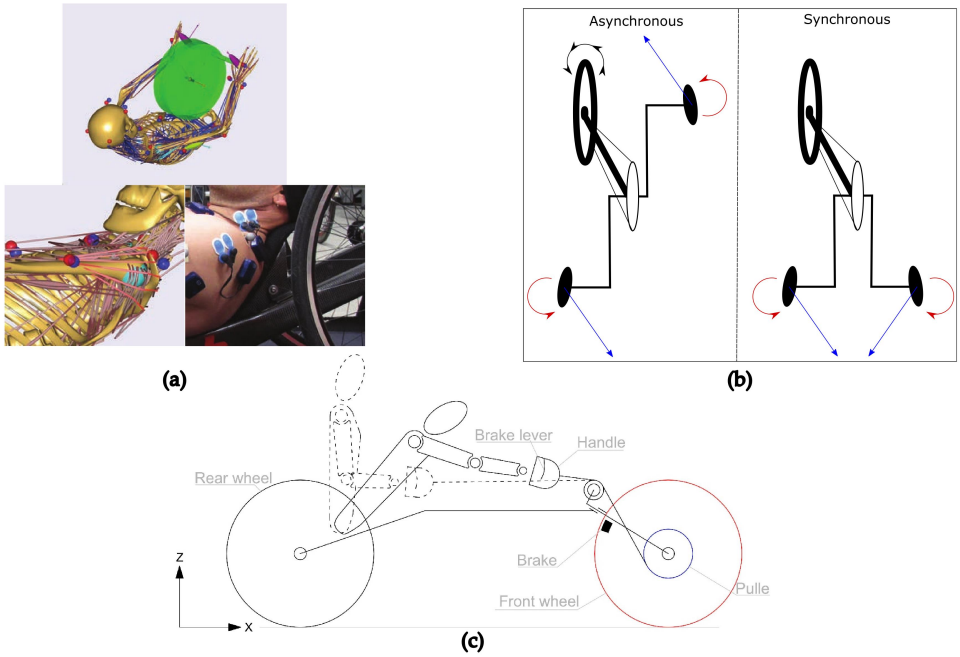


Figure 20. Examples of actuation propulsion models: (**a**) details of a biomechanical model of the handcycling (source: Felsner et al., 2016 [66]), (**b**) schematic of synchronous and asynchronous handbike propulsion (source: Kraaijenbrink et al., 2020 [8]), and (**c**) a new type of handbike propulsion (source: Quaglia et al., 2019 [39]).

Biomechanical Models

Among the analyzed data, 51 documents investigated the propulsion task with biomechanical models. For instance, in the study conducted by Felsner et al. [66], a musculoskeletal model of a handcyclist was developed. The model was realized using the software AnyBody 6.0.5 (AnyBody Technology, Aalborg, DE). To validate the model, the muscle activity of the pectoralis major, deltoid, biceps brachii, and triceps brachii (TRIC), on both sides, was examined and compared to the recorded activity from a previous study, in which one male elite handbiker was tested. For the validation, different settings were considered (power level, crank height, crank length, and height of the backrest) and different muscles thresholds were applied, i.e., 10%, 20%, 25%, and 30% of the maximum muscular activity. To quantitatively assess the results, the mean overlap duration between the simulated and measured muscle activation phases was calculated. The overlap of muscle activation times ranged between 64% and 75%, satisfying the model validation. The most promising results were achieved using thresholds of 10% and 20% of the maximum muscular activity.

In the work by Mazzola et al. [67], a model was developed to describe the ergonomic behavior of a handbike to be assessed for elite competition. Information about the aerodynamic performance of the device was collected through an experimental campaign in wind tunnel. In the study, the results of ergonomic and aerodynamic tests are conflicting. The ergonomic analysis showed two key findings: increasing the length of the handlebar levers negatively affects ergonomic scores in all riding positions, and a more upright riding position is associated with lower perceived ergonomic discomfort. On the other hand, the vertical position of the torso has a negative impact on the aerodynamic drag coefficient, consistent with the observation that increasing the wind-exposed surface area leads to higher drag values. The results on handlebar lever length are also in contrast with the ergonomic analysis: longer levers seem to be more aerodynamically efficient.

Several papers then focus on specific aspects of the propulsion, like muscular activity [57,60] and activation patterns [61,68], techniques for the EMG signal processing [66,69], or shoulder loads, also assessed applying dedicated models such as Delft Shoulder or Elbow Model [70,71]. In 2010, Groen et al. [72,73] proposed a power balance model to describe the handcycling task, that enables the estimation of realistic values for power losses and power output, evaluating the physiological responses of subjects under given conditions (e.g., a range of regular velocities, on a treadmill or track). The model is expected to be a useful tool in the study of elite performance.

A different kind of approach is proposed in works with clinical purposes: in these cases, more than depicting new models that describe the handcycling task, models that combine physiological parameters are evaluated. In these works, predictive models are implemented, and ANOVA tests [8,27] or regression models, from linear, to hyperbolic and multilevel models [35,37,64,74–76], are generally applied to elaborate the data.

Finally, two additional works make use of models to evaluate the performance predictors: by Hettinga et al. [20] and de Groot et al. [36]. In particular, the first paper evaluates the physical stress and strain of handcycling by applying a set of training guidelines proposed by the American College of Sports Medicine; the latter analyzes a mountain time trial in handcycling in terms of exercise intensity in order to determine predictors of race time.

Crank mode

Since the handbike originally derives from traditional bikes, the handcycling crank was initially asynchronous, i.e., the cranks were mounted with a phase shift of 180 degrees. Over the years, handcycling has become more popular, and the crank mode has changed from asynchronous to synchronous, setting the cranks parallel.

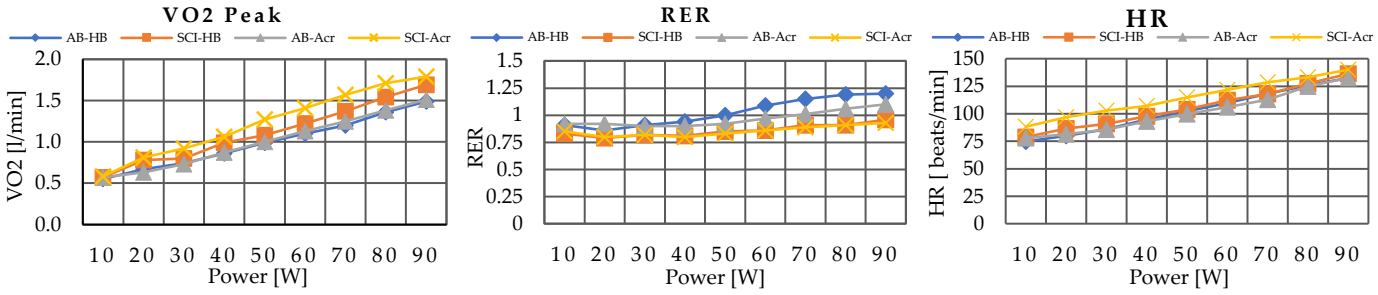
In the work conducted by Kraaijenbrink et al. [8], twelve men without disabilities performed tests on handbikes, in both asynchronous and synchronous modes. The tests were performed by placing the handbike on a treadmill, which was set at a speed of 1.94 m/s; the resistance during the analysis was 15 W, and the crank length was 0.17 m. According to the authors' data, in the synchronous mode the tangential force is maximum

in the lift-push up phase, when the crank moves from the horizontal position towards the subject, with a module of 10 N. In the asynchronous configuration, the force is the highest during press-down phase (∼16 N). The radial force, i.e., the force that produces a torque around the steering axle, had a significant excursion in the asynchronous mode, ranging between its higher peak (20 N) and lower peak (−10 N). This variation causes high levels of muscles activation in order to stabilize the crank. An excursion is also seen in the synchronous mode, but presenting lower values (from 10 N to −10 N); nonetheless, the average radial force in this propulsion mode is equal to zero. The Force Effectiveness Fraction, FEF, was significantly higher during synchronous propulsion (50%) than asynchronous (25%); however, the synchronous mode was less efficient in the lift-pull up phases (from 0° to 90°), where the FEF is almost zero. The power production was more constant during asynchronous cycling throughout the cycle (∼12 W); in the synchronous mode, a lower power production is generated in the push phases (almost 0 W), and a higher power production (40 W) in the pull phases. The difference between push and pull phases during the synchronous cranking causes an acceleration and subsequent deceleration of the angular crank velocity. From a metabolic point of view, the same energy expenditure (EE) was consumed in the performed tests for both methods (3.5 W/kg); therefore, the synchronous mode was revealed to be more efficient, generating more power at the same cost. The mechanical efficiency (ME) was higher in the synchronous mode (6.5%) than in the asynchronous configuration (5%), while the heart rate (HR) was the same for both the modes (86 bpm). Table 7 synthesizes the described data in a schematic form.

Table 7. Synchronous and asynchronous handcycling: schematic comparison by parameter according to the data described by Kraaijenbrink et al. [8].

Parameter	Synchronous		Asynchronous	
Tangential forces	↑	(10 N)	↑↑	(16 N)
	max in lift-push up phase		max in press-down phase	
Radial forces	↑	([−10 N; 10 N])	↑↑	([−10 N; 20 N])
FEF	↑↑	(50%)	↑	(25%)
	less efficient in lift-pull up phase			
Power Production	variable	([∼0 W; 40 W])	∼constant	(12 W)
	push phase–pull phase			
EE	=		=	
ME	↑↑	(6.5%)	↑	(5%)
HR	=		=	

Oviedo et al. [77] focused on physiological differences in SCI patients and subjects without disabilities, comparing asynchronous cranking on an ergometer versus the recumbent synchronous handcycling. For the initial set-up, the ergometer was set at 10 W. This value was incremented by 10 W each minute, until reaching the maximum value of 90 W. Significant differences were found by the authors, and the main numerical values detected during the tests are synthesized in graphical format in Figure 21. For the peak of the volume of oxygen uptake VO2 (see Figure 21a), significant differences were found between subjects without disabilities and SCI patients at all the workloads. In particular, ranging from 30 W to 90 W, the handbike seems to be more efficient than the ergometer for SCI subjects. The maximum difference is reached at 60 W. As Figure 21b depicts, the respiratory exchange ratio RER was lower for the SCI patients, in both the conditions of handcycling with handbike and ergometer, and a maximal difference of 0.28 was found at the workload of 80 W. Analyzing the heart rates synthesized in Figure 21c, SCI patients with asynchronous cranking depicted high values of HR for each workload, reaching a peak of 140 bpm at 90 W, and confirming that handcycling in the configuration of asynchronous crank ergometer is a mode of propulsion that requires a high activation of muscles.



(**a**) (**b**) (**c**)

Figure 21. From the left: (**a**) peaks of volume of oxygen uptake (VO2), (**b**) respiratory exchange ratio (RER), and (**c**) heart rate (HR), as detected by Oviedo et al. [77] with respect to power output. Data are compared for the different combinations of SCI patients (SCI) and subjects without disabilities (AB), and with traditional handbike (HB) and asynchronous crank ergometer (Acr).

Steering

Steering is the capacity to rotate the crank in order to change direction. In the work conducted by Kraaijenbrink et al. [9], sixteen subjects without disabilities were tested with both synchronous and asynchronous crank modes, with an ergometer also able to simulate steering effects. The resistance of the ergometer was set at 35 W, while the crank velocity was set at 3.3 m/s (60 rpm). In the study, the steering was revealed to have a significant effect on both the crank modes from a physiological point of view. From a kinetic point of view, the synchronous crank mode was more efficient than the asynchronous mode. In fact, in synchronous configuration, the FEF increased from 56%, when the fork axle is fixed, to 59% in steering condition. In asynchronous mode, the FEF decreased from 22% to 19%. The reason, as explained by Kraaijenbrink et al. [8], is that in synchronous handcycling the moments produced with respect to the steering axle are opposite, so the total moment is almost null throughout the cycle. In asynchronous handcycling, the moments produced are the same, causing a rotation of the front wheel, so more control and consequently more muscle activation is needed.

The main highlights that emerged from the analysis of the Actuation category and its sub-classes are depicted in Table 8.

Table 8. Actuation: highlights for the category and sub-classes.

Actuation: Highlights
Biomechanical Models
• Biomechanical models of the propulsion task have been developed, which analyze the subject (e.g., musculoskeletal model of the handcyclist [66]) and the device (ergonomic behavior of a handbike [67]).
• Models often focus on specific aspects of the propulsion, such as muscular activity or shoulder loads.
• Biomechanical models for clinical purposes often combine physiological parameters: predictive and regression models are often used.
Crank mode
• The handcycling crank was originally asynchronous and has changed to synchronous over time.
• Handcycling in the configuration of asynchronous crank ergometer requires a high activation of muscles [77].
Steering
• Steering requires more control and muscle activation in asynchronous handcycling: steering produces moments, that are internally balanced in the case of synchronous cycling, but cause a rotation of the front wheel in the case of an asynchronous configuration [8].

3.7. Final Remarks

In the analysis, a set of categories and sub-classes was identified and examined. Besides the information extracted by the application of the proposed taxonomy, additional

interesting aspects emerged. For instance, a hint of the historical evolution of the handbike can be outlined, as synthesized in graphical form in Figure 22.

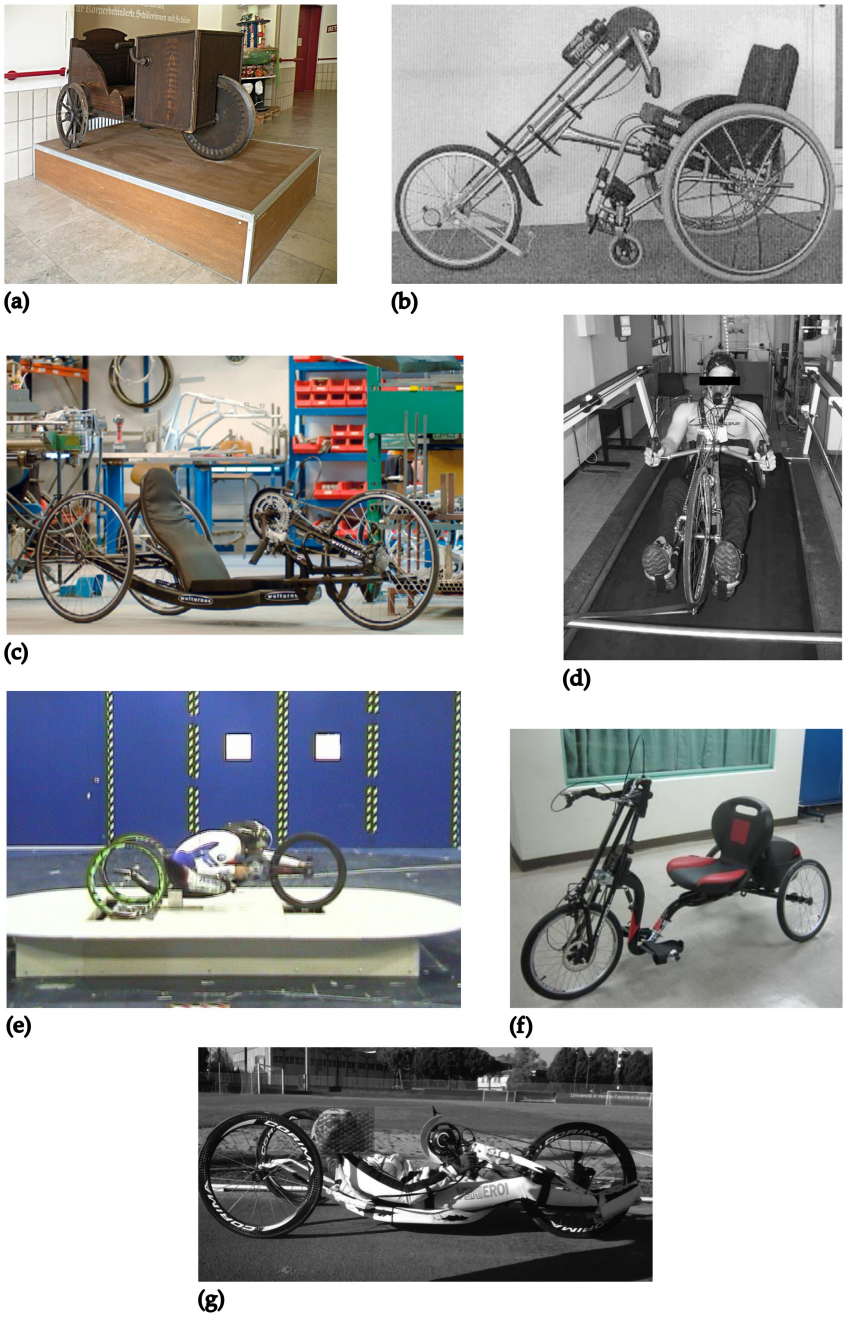


Figure 22. Handbike evolution: (**a**) the first handbike prototype made by Stephan Farffler in 1655 (image by V. Muratov, 2011 [78]), (**b**) a handbike with attach-unit (source: Dellmeijer et al., 2004 [5]), (**c**) a recumbent arm-powered road handbike (source: Siebert, 2010 [40]), (**d**) a touring handbike (source: Abel et al., 2006 [1]), (**e**) a race kneeling handbike (source: Belloli et al., 2014 [79]), (**f**) the "electric-assisted handcycle" by Jeang et al. (source: Jeang et al., 2015 [80]), and (**g**) a race recumbent handbike (source: Fischer et al., 2020 [81]).

An additional element is the relevance given in the scientific literature to the topics of comfort and discomfort of the handbike for the user. Attention is often afforded to the optimization of device configuration for performance improvement [58,73], but the sensibility of researchers is also towards ergonomics and usability of the system for the subject [59,67].

Literature also describes comparisons between handcycling and other tasks, especially hybrid-cycling [11,22,41,82–84]: these works generally present a clinical approach, and evaluate the comparison in terms of physiological parameters for the analyzed conditions.

Focusing on the design of new devices, besides the description of new handbike prototypes, some works depict innovative solutions for parts of the handbike: examples of these studies are the new transmission presented by Cavallone et al. [85], the new ergometer proposed by Verellen et al. [86], the new wheel rotation monitor by Hiremath et al. [87], or the new fork by Solazzi et al. [88]. These kinds of innovations may be difficult to capture with focused reviews, since the proposed systems can often be applied to different types of devices, like handbikes and wheelchairs. In this sense, interesting hints for the design of handbikes could also be extracted from the analysis of papers focusing on collateral topics. For instance, Florio et al. [89] investigated the unmet needs, use, and provision of assistive devices: handbikes are listed among the less frequently used devices, but are considered together with adapted cars and manual wheelchairs.

Interdisciplinary contamination among application fields is also at the basis of additional solutions, like the tandem bicycle proposed by Schwandt et al. [90], or the watercraft designed by Fuglsang et al. [91] by combining parts of a handbike and a waterbike.

As the relation between wheelchair and handbike is particularly close, literature also presents examples of attachments that enable the functional transformation of a wheelchair into a handbike. This is for instance the case for the studies proposed by Janssen et al. [92] and Dallmeijer et al. [5]. Moreno et al. identify an alternative solution, presenting the adaptation of an electric scooter to propel a conventional wheelchair [93], whereas Quaglia et al. design an innovative system of manual propulsion, defined as Handwheelchair.q [39].

Finally, few works deal with assistive or externally provided propulsion in handbikes. Siebert et al. [40] propose a powered rear wheel that can be mounted on the device instead of the traditional wheel, and nowadays some examples of analogous systems are also currently available on the market. The only case of an electric-assisted handcycle is presented by Jeang et al. [80]: the paper describes the design and development process of the device, from the concept definition to the release and testing of the first-generation prototype. For the actuation, few details are provided, but that the system incorporates a hub brushless motor which was tested for applicability and functionality by the various manufacturers that provided it. The lack of works on power-assisted solutions for handbikes in literature may be partially expected considering that handbikes are mostly used as a tool to improve mobility or to exercise in subjects with disabilities. Nonetheless, since the comfort of the user seems to be a particularly relevant element in the scientific literature on this topic, such a limited number of works still seems partially surprising. This is especially true when considering that few examples of power-assisted handbikes seem to be already available on the market (see Table 9). Given these considerations, a research focus also on this topic and on the development of handbikes equipped with external motors can be reasonably expected in the next future.

Finally, the world of handbikes represents a peculiar market sector, characterized by relatively small market shares and many professionals as final users. Perhaps also for this reason, commercial devices are rapidly evolving and developers keep implementing innovative technological solutions. According to this consideration, a market analysis investigating the main technical characteristics of off-the-shelf devices, as well as a thorough patent review, could provide valuable hints about possible trends and evolutions in the design of handbikes. Integrating the current work with this kind of analyses may de facto provide a comprehensive overview of the state of the technique on handbikes.

Table 9. Technical characteristics of three examples of electric handbike: Scrambler RS (by Handbike Garage, I), #Elba4All (by CGDE, I), and E-Handbike (by Custom Regeneration and G5Mobility, I).

Parameter	Scrambler RS	#Elba4All	E-Handbike *
Motor & Transmission			
Motor	OliEds Sport 85 Nm 250 W	Polini E-P3 70 Nm 250 W	by G5Mobility
Max Velocity	25 km/h		
Battery	single (540 W), double (2· 540 W)	single (500 W), double (2·500 W)	
Roundtrip (km)		220 (single battery)	>100
Wheels & Brakes			
Front wheel	27.5″ boost 148″	27.5″	
Rear wheel	27.5″ boost 110/15″	27.5″	
Brakes	anterior hydraulic 203 mm, posterior hydraulic 180 mm mono-pump		
Frame & Measures			
Frame	alluminium		
Width (cm)	80	80	
Length With wheels (cm)	220	220	
Length without wheels (cm)	180		
Span from the ground (cm)	20		
Maximum high with wheels (cm)	60	80	
Maximum load (kg)	100	110	
Pilot height (cm)	160–210		

* The company produces handbikes by reconditioning sports products.

4. Conclusions

In this work, a study of the scientific literature on handbikes was proposed, organizing the results with both a quantitative and a qualitative analyses. The analysis was performed with a systematic approach, and with the main purpose of depicting a comprehensive overview of the topic, with particular attention paid to actuation solutions and propulsion strategies.

Although the current literature review provides a general overview of technical characteristics of handbikes, the applied method may represent a limitation, as the proposed categories and sub-classes were identified and optimized in order to capture at best the peculiarities of the current dataset of documents. In this sense, analyzing the same dataset with different purposes may suggest modifications to the taxonomy, in order to elicit different characteristics of the works in literature.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AP	Arm propulsion
ATP	Arm trunk propulsion
Bla	Blood lactate concentration
EE	Energy expenditure
EMG	Electromyography
EMS	Electromyostimulation
FEF	Fraction effective force
FES	Functional electrical stimulation
GE	Gross efficiency
HITT	High intensity interval training
HR	Heart rate
HRR	Heart rate reserve
HRV	Heart rate variability
ME	Mechanical efficiency
MICT	Moderate intensity continuous training
P_{max}	Power peak
PO	Power output
RER	Respiratory exchange ratio
ROM	Range of motion
RPE	Rating of perceived exertion
RSI	Repetitive strain injuries
SCI	Spinal cord injury
UCI	Union Cycliste Internationale
VCO2	Volume of produced carbon dioxide
Vla	Lactate production
VO2	Maximal oxygen uptake
W/kg	Power per kilogram

Appendix A

In the following, an extract of the tables obtained from the classification procedure applied to the data is presented as Table A1.

Table A1. Main categories and some example of sub-classes classifications. Marks between brackets describe the absence of data required to populate technical details in sub-classes. From the left, document identification code, document type (Ar = article, CP = conference paper, Re = review, BC = book chapter), and if the publication is open access. For each category, the first column collects the general classification and possible additional sub-columns describe additional details. For the Actuation category, BioM describes the Biomechanical Models sub-class, Sync and Async are the crank modes synchronous and asynchronous, respectively, and CM is the presence of comparison methods.

Document ID	Type	OA	Clinical Tests	Subjects	Device	Prototype	Forces	3D	Sensors	Geometry	Actuation	BioM	Crank Mode	Sync	Async	CM	Steering	Other
Schwandt 1984 * [90]	CP				x	x					x						(x)	
Maki 1995 [94]	Ar		x	x					x									x
Van Der Woude 2000 [7]	Ar		x	x	x				x		x		x	x	x	x		
Janssen 2001 [92]	Ar		x	x	x				x									
Abel 2003 [17]	Ar		x	x	x				x		x		x	x	x	x		
Abel 2003a [95]	Ar		x	x	x				x									
Faupin 2003 [96]	CP								x		x	x						
Dallmeijer 2004 [5]	Ar	x	x		x				x									
Knechtle 2004 [97]	Ar	x	x	x					x									
Postma 2005 [98]	Ar	x	x	x					(x)									x
Abel 2006 [1]	Ar	x	x	x	x				x									
Faupin 2006 [99]	Ar		x	x	x				x	(x)	x	x						
Faupin 2006a [100]	CP		x	x					(x)	x	x	x						
Faupin 2008 [58]	Ar	x	x	x	x				x	x	x	x						
Faupin 2008a [56]	Ar		x	x	x		x	x	x	x	x	x	x	x				
Verellen 2008 [101]	Ar		x	x					x		x	x						x
Krämer 2009 [52]	Ar		x	x	x		x	x	x	x	x	x						
Meyer 2009 [102]	Ar		x	x	x				(x)									x
Abel 2010 [103]	Ar	x	x	x	x				x									x
Bollini 2010 [104]	CP				x	x					x							
Faupin 2010 [46]	Ar	x	x	x	x				x		x	x						
Goosey-Tolfrey 2010 [105]	Ar	x	x	x	x				x									
Groen 2010 * [72]	Ar		x	x	x				x		x	x						
Groen 2010a [73]	CP		x	x	x				x		x	x						
Rice 2010 [106]	BC																	x
Siebert 2010 [40]	CP	x			x	x				(x)								
Van Drongelen 2010 [107]	CP		x	x	x		x		x		x		x	x				

Table A1. *Cont.*

Document ID	Type	OA	Clinical Tests		Device		Forces		Sensors	Geometry	Actuation		Crank Mode				Steering	Other
			Subjects		Prototype		3D				BioM		Sync		Async	CM		
Hettinga 2011 [108]	CP		x	x							x	x						
Van Drongelen 2011 [51]	Ar		x	x	x	(x)	x	x	x									
Allgrove 2012 [109]	Ar	x	x	x	x				x									
Arnet 2012 [6]	Ar		x	x	x		x		x	(x)	x	x	x	x				
Arnet 2012a [42]	Ar	x	x	x	x		x	x	x		x	x	x	x				
Arnet 2012b [70]	Ar	x	x	x	x		x		x		x	x						
Lovell 2012 [18]	Ar	x	x	x	x				x									
Mazzola 2012 [67]	BC		x	x	x		x	x		x	x	x						x
Verellen 2012 [86]	Ar				x	x	x	x	x		x	x						
Verellen 2012a [19]	Ar		x	x	x				x									
Arnet 2013 [43]	Ar		x	x	x		x	x	x		x	x						
Hettinga 2013 [20]	Ar	x	x	x	x				x		x	x						x
Jacquier-Bret 2013 [53]	Ar				x		x		x	x	x	x						
Koopman 2013 [110]	Ar	x	x	x	x				x									
Van Der Woude 2013 [11]	Ar		x	x														x
Van Drongelen 2013 [71]	Ar		x	x	x		x	x	x		x	x	x	x				x
Arnet 2014 [47]	Ar	x	x	x	x		x		x	x	x	x						
Bakkum 2014 [41]	Ar	x	x	x	x	x			x									
Belloli 2014 [79]	CP	x	x	x	x						x	x						x
de Groot 2014 [36]	Ar	x	x	x	x				x		x	x						
Fischer 2014 [111]	Ar		x	x					x									x
Meyns 2014 [82]	Ar	x	x	x	x				x		x		(x)					x
Abel 2015 [21]	Ar	x	x	x	x				x	x	x	x						
Bakkum 2015 [22]	Ar	x	x		x	x			x									
Bakkum 2015a * [83]	Ar	x	x		x	x												
Fischer 2015 [23]	Ar		x	x	x				x									x
Jeang 2015 [80]	CP				x	(x)				(x)								x
Litzenberger 2015 [60]	CP	x	x	x	x				x	x	x	x						
Nooijen 2015 [10]	Ar	x	x	x	x				x									x
Nooijen 2015a [112]	Ar		x	x	x													
Simmelink 2015 [113]	Ar	x	x	x	x				x									

Table A1. *Cont.*

Document ID	Type	OA	Clinical Tests		Device		Forces		Sensors	Geometry	Actuation		Crank Mode			Steering	Other
				Subjects		Prototype		3D				BioM		Sync	Async	CM	
Abreu 2016 [114]	Ar	x	x	x					x								x
Arnet 2016 [115]	Ar		x	x	x												x
Felsner 2016 [66]	CP	x		x					(x)		x	x					
Hettinga 2016 [24]	Ar	x	x	x	x				x								
Litzenberger 2016 [57]	Ar		x	x	x				x	x	x	x					
Rice 2016 [4]	Re																x
Schoenmakers 2016 [25]	Ar	x	x	x	x				x								
Azizpour 2017 [116]	CP		x	x	x		(x)		x		x	x					
Fuglsang 2017 [91]	Ar	x															x
Hoekstra 2017 * [117]	Ar		x	x	x				x								
Hutchinson 2017 [26]	Ar	x	x	x	x				x								
Kraaijenbrink 2017 [27]	Ar	x	x		x		x	x	x		x	x	x	x			x
Zeller 2017 [118]	Ar		x		x				x								
Azizpour 2018 [119]	Ar		(x)	x	x	x	x		x		x	x					
Chong 2018 [45]	CP				x	x			(x)								x
de Groot 2018 [38]	Ar	x	x	x	x												x
de Groot 2018a [38]	Ar	x	x	x	x				x								
Kouwijzer 2018 [120]	Ar	x	x	x	x				x		x	x					
Legnani 2018 [121]	CP		x	x	x		x		x		x	x					
Morse 2018 [122]	Ar	x	x	x	x				x								x
Quittmann 2018 [28]	Ar		x	x	x		(x)	(x)	x		x	x					
Quittmann 2018a [123]	Ar		x	x	x				x								
Cudicio 2019 [124]	CP		x	x	x				x								x
Quaglia 2019 [39]	Ar	x			x	x					x	x					
Stangier 2019 [125]	Ar	x	x		x				x								
Stone 2019 [126]	Ar	x	x	x	x		(x)		x	x	x	x					
Stone 2019a [59]	Ar	x								x							x
Stone 2019b [127]	Ar	x	x	x	x				x		x	x					x
Vegter 2019 [54]	Ar	x	x	x	x		x		x	x	x	x	x	x			
Chaikhot 2020 [128]	Ar	x	x	x													
Fischer 2020 [81]	Ar	x	x	x					x								x

Table A1. *Cont.*

Document ID	Type	OA	Clinical Tests		Device		Forces		Sensors	Geometry	Actuation		Crank Mode				Steering	Other
			Subjects		Prototype		3D				BioM		Sync		Async	CM		
Himarosa 2020 [129]	CP	x			x	x				(x)	x		x	x				
Kouwijzer 2020 [130]	Ar	x	x	x														
Kouwijzer 2020a [74]	Ar	x	x	x	x				x		x	x						
Kraaijenbrink 2020 [8]	Ar	x	x	x	x		x	x	x	(x)	x	x	x	x	x	x	x	
Quittmann 2020 [61]	Ar		x	x	x		x	x	x		x	x						
Quittmann 2020a [69]	Ar		x	x	x		(x)		x		x	x						x
Stone 2020 [64]	Ar	x	x	x	x				x		x	x						x
Turoń-Skrzypińska 2020 [131]	Ar	x																x
Abonie 2021 [31]	Ar	x	x	x	x				x		x		x	x				
Hutchinson 2021 [32]	Ar	x	x	x	x				x							(x)		
Koontz 2021 [65]	Ar	x	x	x	x				x									
Kouwijzer 2021 [33]	Ar	x	x	x														
Kraaijenbrink 2021 [55]	Ar	x	x	x	x		x	x	x		x	x	x	x	x	x	x	
Kraaijenbrink 2021a [9]	Ar	x																x
Mason 2021 [62]	Ar	x	x	x	x				x	x	x	x						
Muchaxo 2021 [76]	Ar	x	x	x	x				x	x	x	x						
Nevin 2021 [132]	Ar	x	x	x	x		(x)		x									
Nevin 2021a [48]	Ar		x	x	x		x											
Nevin 2021b [49]	Ar	x	x	x	x		x		x									
Nooijen 2021 [37]	Ar	x	x	x	x						x	x						
Oviedo 2021 [77]	Ar		x	x	x				x	x	x		x	x	x	x		
Quittmann 2021 [133]	Ar		x	x	x													
Quittmann 2021a [68]	Ar		x	x	x				x		x	x						x
Stephenson 2021 [134]	Ar	x																x
Abonie 2022 [135]	Ar	x	x	x	x				x									
Antunes 2022 [63]	Ar		x	x	x				x									
Antunes 2022a [75]	Ar		(x)	(x)	(x)						x	(x)						
Digo 2022 [50]	CP		x	(x)	(x)		x		x		x	x						
Hall 2022 [34]	Ar	x	x	x	x				x									
Hutchinson 2022 [136]	Ar	x	x	x	x				x									
Kouwijzer 2022 [30]	Ar	x	x	x	x													

Table A1. *Cont.*

Document ID	Type	OA	Clinical Tests		Device		Forces		Sensors	Geometry	Actuation		Crank Mode			Steering	Other
				Subjects		Prototype		3D				BioM	Sync	Async	CM		
Muchaxo 2022 [35]	Ar	x	x	x	x		x	x	x		x	x					x
Nevin 2022 [3]	Re	x															x
Pasko 2022 [137]	CP		(x)	(x)													x
Quittmann 2022 [138]	Ar		x	x	x		x	x	x		x	x					
Rappelt 2022 [29]	Ar	x	x	x					x								
Rayes 2022 [14]	Re	x															x
Solazzi 2022 [88]	CP	x			x	(x)											
Soo Hoo 2022 [139]	Ar	x	x	x													x

* Full text not available. Data were retrieved from title and abstract only.

References

1. Abel, T.; Schneider, S.; Platen, P.; Strüder, H. Performance diagnostics in handbiking during competition. *Spinal Cord* **2006**, *44*, 211–216. [CrossRef] [PubMed]
2. Bucco-Lechat, C. Wikimedia Commons. 2014. Available online: https://commons.wikimedia.org/wiki/File:Salon_de_l%27auto_de_Gen%C3%A8ve_2014_-_20140305_-_Skoda_Vision_C.jpg (accessed on 15 January 2024)
3. Nevin, J.; Kouwijzer, I.; Stone, B.; Quittmann, O.; Hettinga, F.; Abel, T.; Smith, P. The Science of Handcycling: A Narrative Review. *Int. J. Sport. Physiol. Perform.* **2022**, *17*, 335–342. [CrossRef] [PubMed]
4. Rice, I. Recent Salient Literature Pertaining to the Use of Technology in Wheelchair Sports. *Curr. Phys. Med. Rehabil. Rep.* **2016**, *4*, 329–335. [CrossRef]
5. Dallmeijer, A.; Zentgraaff, I.; Zijp, N.; Van Der Woude, L. Submaximal physical strain and peak performance in handcycling versus handrim wheelchair propulsion. *Spinal Cord* **2004**, *42*, 91–98. [CrossRef]
6. Arnet, U.; Van Drongelen, S.; Scheel-Sailer, A.; Van Der Woude, L.; Veeger, D. Shoulder load during synchronous handcycling and handrim wheelchair propulsion in persons with paraplegia. *J. Rehabil. Med.* **2012**, *44*, 222–228. [CrossRef] [PubMed]
7. Van Der Woude, L.; Bosmans, I.; Bervoets, B.; Veeger, H. Handcycling: Different modes and gear ratios. *J. Med. Eng. Technol.* **2000**, *24*, 242–249. [CrossRef] [PubMed]
8. Kraaijenbrink, C.; Vegter, R.; Hensen, A.; Wagner, H.; Van Der Woude, L. Biomechanical and physiological differences between synchronous and asynchronous low intensity handcycling during practice-based learning in able-bodied men. *J. NeuroEng. Rehabil.* **2020**, *17*, 29 . [CrossRef]
9. Kraaijenbrink, C.; Vegter, R.; Ostertag, N.; Janssens, L.; Vanlandewijck, Y.; van der Woude, L.; Wagner, H. Steering Does Affect Biophysical Responses in Asynchronous, but Not Synchronous Submaximal Handcycle Ergometry in Able-Bodied Men. *Front. Sport. Act. Living* **2021**, *3*, 741258. [CrossRef]
10. Nooijen, C.; Van Den Brand, I.; Ter Horst, P.; Wynants, M.; Valent, L.; Stam, H.; Van Den Berg-Emons, R. Feasibility of Handcycle Training during Inpatient Rehabilitation in Persons with Spinal Cord Injury. *Arch. Phys. Med. Rehabil.* **2015**, *96*, 1654–1657. [CrossRef]
11. Van Der Woude, L.; de Groot, S.; Postema, K.; Bussmann, J.; Janssen, T.; Post, M. Active LifestyLe Rehabilitation Interventions in aging Spinal Cord injury (ALLRISC): A multicentre research program. *Disabil. Rehabil.* **2013**, *35*, 1097–1103. [CrossRef]
12. Flueck, J. Nutritional considerations for para-cycling athletes: A narrative review. *Sports* **2021**, *9*, 154. [CrossRef] [PubMed]
13. Goodlin, G.; Steinbeck, L.; Bergfeld, D.; Haselhorst, A. Adaptive Cycling: Classification, Adaptations, and Biomechanics. *Phys. Med. Rehabil. Clin. N. Am.* **2022**, *33*, 31–43. [CrossRef] [PubMed]
14. Rayes, R.; Ball, C.; Lee, K.; White, C. Adaptive Sports in Spinal Cord Injury: A Systematic Review. *Curr. Phys. Med. Rehabil. Rep.* **2022**, *10*, 145–153. [CrossRef] [PubMed]
15. Heymsfield, S. *Human Body Composition*; Human kinetics: Champaign, IL, USA, 2005; Volume 918.
16. Borg, G. *Borg's Perceived Exertion and Pain Scales*; Human Kinetics: Champaign, IL, USA, 1998.
17. Abel, T.; Kröner, M.; Rojas, V.; Peters, C.; Klose, C.; Platen, P. Energy expenditure in wheelchair racing and handbiking —A basis for prevention of cardiovascular diseases in those with disabilities. *Eur. J. Prev. Cardiol.* **2003**, *10*, 371–376. [CrossRef] [PubMed]
18. Lovell, D.; Shields, D.; Beck, B.; Cuneo, R.; McLellan, C. The aerobic performance of trained and untrained handcyclists with spinal cord injury. *Eur. J. Appl. Physiol.* **2012**, *112*, 3431–3437. [CrossRef] [PubMed]
19. Verellen, J.; Meyer, C.; Janssens, L.; Vanlandewijck, Y.; Lacour, J.R. Peak and submaximal steady-state metabolic and cardiorespiratory responses during arm-powered and arm-trunk-powered handbike ergometry in able-bodied participants. *Eur. J. Appl. Physiol.* **2012**, *112*, 983–989. [CrossRef] [PubMed]
20. Hettinga, F.; de Groot, S.; Van Dijk, F.; Kerkhof, F.; Woldring, F.; Van Der Woude, L. Physical strain of handcycling: An evaluation using training guidelines for a healthy lifestyle as defined by the American College of Sports Medicine. *J. Spinal Cord Med.* **2013**, *36*, 376–382. [CrossRef]
21. Abel, T.; Burkett, B.; Thees, B.; Schneider, S.; Askew, C.; Strüder, H. Effect of three different grip angles on physiological parameters during laboratory handcycling test in able-bodied participants. *Front. Physiol.* **2015**, *6*, 331. [CrossRef]
22. Bakkum, A.; de Groot, S.; Stolwijk-Swüste, J.; Van Kuppevelt, D.; Van Der Woude, L.; Janssen, T. Effects of hybrid cycling versus handcycling on wheelchair-specific fitness and physical activity in people with long-term spinal cord injury: A 16-week randomized controlled trial. *Spinal Cord* **2015**, *53*, 395–401. [CrossRef]
23. Fischer, G.; Figueiredo, P.; Ardigò, L. Physiological performance determinants of a 22-km handbiking time trial. *Int. J. Sport. Physiol. Perform.* **2015**, *10*, 965–971. [CrossRef]
24. Hettinga, F.; Hoogwerf, M.; van der Woude, L. Handcycling: Training effects of a specific dose of upper body endurance training in females. *Eur. J. Appl. Physiol.* **2016**, *116*, 1387–1394. [CrossRef] [PubMed]
25. Schoenmakers, P.; Reed, K.; Woude, V.; Hettinga, F. High intensity interval training in handcycling: The effects of a 7 week training intervention in able-bodied men. *Front. Physiol.* **2016**, *7*, 638. [CrossRef] [PubMed]
26. Hutchinson, M.; Paulson, T.; Eston, R.; Tolfrey, V. Assessment of peak oxygen uptake during handcycling: Test-retest reliability and comparison of a ramp-incremented and perceptually-regulated exercise test. *PLoS ONE* **2017**, *12*, e0181008. [CrossRef] [PubMed]

27. Kraaijenbrink, C.; Vegter, R.; Hensen, A.; Wagner, H.; Van Der Woude, L. Different cadences and resistances in submaximal synchronous handcycling in able-bodied men: Effects on efficiency and force application. *PLoS ONE* **2017**, *12*, e0183502. [CrossRef] [PubMed]
28. Quittmann, O.; Abel, T.; Zeller, S.; Foitschik, T.; Strüder, H. Lactate kinetics in handcycling under various exercise modalities and their relationship to performance measures in able-bodied participants. *Eur. J. Appl. Physiol.* **2018**, *118*, 1493–1505. [CrossRef] [PubMed]
29. Rappelt, L.; Held, S.; Donath, L. Handcycling with concurrent lower body low-frequency electromyostimulation significantly increases acute oxygen uptake: Implications for rehabilitation and prevention. *PeerJ* **2022**, *10*, e13333. [CrossRef] [PubMed]
30. Kouwijzer, I.; Valent, L.; van Bennekom, C.; Post, M.; van der Woude, L.; de Groot, S. Training for the HandbikeBattle: An explorative analysis of training load and handcycling physical capacity in recreationally active wheelchair users. *Disabil. Rehabil.* **2022**, *44*, 2723–2732. [CrossRef]
31. Abonie, U.; Monden, P.; van der Woude, L.; Hettinga, F. Effect of a 7-week low intensity synchronous handcycling training programme on physical capacity in abled-bodied women. *J. Sport. Sci.* **2021**, *39*, 1472–1480. [CrossRef]
32. Hutchinson, M.; Kouwijzer, I.; de Groot, S.; Goosey-Tolfrey, V. Comparison of two Borg exertion scales for monitoring exercise intensity in able-bodied participants, and those with paraplegia and tetraplegia. *Spinal Cord* **2021**, *59*, 1162–1169. [CrossRef]
33. Kouwijzer, I.; Valent, L.; Post, M.; Wilders, L.; Grootoonk, A.; Van Der Woude, L.; de Groot, S. The Course of Physical Capacity in Wheelchair Users during Training for the HandbikeBattle and at 1-Yr Follow-up. *Am. J. Phys. Med. Rehabil.* **2021**, *100*, 858–865. [CrossRef]
34. Hall, B.; Sikora, M.; Jonas, D.; Matthews, E.; Zebrowska, A. Handcycling Training in Men with Spinal Cord Injury Increases Tolerance to High Intensity Exercise. *J. Hum. Kinet.* **2022**, *82*, 233–241. [CrossRef] [PubMed]
35. Muchaxo, R.; de Groot, S.; Kouwijzer, I.; van der Woude, L.; Nooijen, C.; Janssen, T. Association between upper-limb isometric strength and handcycling performance in elite athletes. *Sport. Biomech.* 2022, *Online ahead of print*. [CrossRef] [PubMed]
36. de Groot, S.; Postma, K.; Van Vliet, L.; Timmermans, R.; Valent, L. Mountain time trial in handcycling: Exercise intensity and predictors of race time in people with spinal cord injury. *Spinal Cord* **2014**, *52*, 455–461. [CrossRef] [PubMed]
37. Nooijen, C.; Muchaxo, R.; Liljedahl, J.; Bjerkefors, A.; Janssen, T.; van der Woude, L.; Arndt, A.; de Groot, S. The relation between sprint power and road time trial performance in elite para-cyclists. *J. Sci. Med. Sport* **2021**, *24*, 1193–1198. [CrossRef]
38. de Groot, S.; Kouwijzer, I.; Baauw, M.; Broeksteeg, R.; Valent, L. Effect of self-guided training for the HandbikeBattle on body composition in people with spinal cord injury. *Spinal Cord Ser. Cases* **2018**, *4*, 79. [CrossRef] [PubMed]
39. Quaglia, G.; Bonisoli, E.; Cavallone, P. The design of a new manual wheelchair for sport. *Machines* **2019**, *7*, 31. [CrossRef]
40. Siebert, M. Adjustable handbike-chassis for offroad-use ("mountain handbike"). *Procedia Eng.* **2010**, *2*, 3157–3162. [CrossRef]
41. Bakkum, A.; de Groot, S.; Onderwater, M.; De Jong, J.; Janssen, T. Metabolic rate and cardiorespiratory response during hybrid cycling versus handcycling at equal subjective exercise intensity levels in people with spinal cord injury. *J. Spinal Cord Med.* **2014**, *37*, 758–764. [CrossRef]
42. Arnet, U.; Van Drongelen, S.; Van Der Woude, L.; Veeger, D. Shoulder load during handcycling at different incline and speed conditions. *Clin. Biomech.* **2012**, *27*, 1–6. [CrossRef]
43. Arnet, U.; Van Drongelen, S.; Veeger, D.; Van Der Woude, L. Force application during handcycling and handrim wheelchair propulsion: An initial comparison. *J. Appl. Biomech.* **2013**, *29*, 687–695. [CrossRef]
44. Amici, C.; Ragni, F.; Ghidoni, M.; Fausti, D.; Bissolotti, L.; Tiboni, M. Multi-Sensor Validation Approach of an End-Effector-Based Robot for the Rehabilitation of the Upper and Lower Limb. *Electronics* **2020**, *9*, 1751. [CrossRef]
45. Chong, Y.; Yang, T. Development of portable hand cycle for children with cerebral palsy—The Malaysian scenario: Wheelchair propulsion motion. In Proceedings of the 5th IEEE Region 10 Humanitarian Technology Conference 2017, R10-HTC, Dhaka, Bangladesh, 21–23 December 2017; Volume 2018, pp. 873–877. [CrossRef]
46. Faupin, A.; Gorce, P.; Watelain, E.; Meyer, C.; Thevenon, A. A biomechanical analysis of handcycling: A case study. *J. Appl. Biomech.* **2010**, *26*, 240–245. [CrossRef]
47. Arnet, U.; van Drongelen, S.; Schlüssel, M.; Lay, V.; van der Woude, L.; Veeger, H. The effect of crank position and backrest inclination on shoulder load and mechanical efficiency during handcycling. *Scand. J. Med. Sci. Sport.* **2014**, *24*, 386–394. [CrossRef] [PubMed]
48. Nevin, J.; Smith, P. The Relationship between Absolute and Relative Upper-Body Strength and Handcycling Performance Capabilities. *Int. J. Sport. Physiol. Perform.* **2021**, *16*, 1311–1318. [CrossRef] [PubMed]
49. Nevin, J.; Smith, P. The anthropometric, physiological, and strength-related determinants of handcycling 15-km time-trial performance. *Int. J. Sport. Physiol. Perform.* **2021**, *16*, 259–266. [CrossRef] [PubMed]
50. Digo, E.; Gastaldi, L.; Antonelli, M.; Cornagliotto, V.; Pastorelli, S. Estimation of Force Effectiveness and Symmetry During Kranking Training. In *Proceedings of the I4SDG Workshop 2021. I4SDG 2021. Mechanisms and Machine Science, Online, 25–26 November 2021*; Quaglia, G., Gasparetto, A., Petuya, V., Carbone, G., Eds.; Springer: Berlin, Germany, 2022; Volume 108, pp. 201–208. [CrossRef]
51. Van Drongelen, S.; van den Berg, J.; Arnet, U.; Veeger, D.; van der Woude, L. Development and validity of an instrumented handbike: Initial results of propulsion kinetics. *Med. Eng. Phys.* **2011**, *33*, 1167–1173. [CrossRef] [PubMed]
52. Krämer, C.; Schneider, G.; Böhm, H.; Klöpfer-Krämer, I.; Senner, V. Effect of different handgrip angles on work distribution during hand cycling at submaximal power levels. *Ergonomics* **2009**, *52*, 1276–1286. [CrossRef] [PubMed]

53. Jacquier-Bret, J.; Faupin, A.; Rezzoug, N.; Gorce, P. A new postural force production index to assess propulsion effectiveness during handcycling. *J. Appl. Biomech.* **2013**, *29*, 798–803. [CrossRef] [PubMed]
54. Vegter, R.; Mason, B.; Sporrel, B.; Stone, B.; van der Woude, L.; Goosey-Tolfrey, V. Crank fore-aft position alters the distribution of work over the push and pull phase during synchronous recumbent handcycling of able-bodied participants. *PLoS ONE* **2019**, *14*, e0220943. [CrossRef] [PubMed]
55. Kraaijenbrink, C.; Vegter, R.; de Groot, S.; Arnet, U.; Valent, L.; Verellen, J.; van Breukelen, K.; Hettinga, F.; Perret, C.; Abel, T.; et al. Biophysical aspects of handcycling performance in rehabilitation, daily life and recreational sports; a narrative review. *Disabil. Rehabil.* **2021**, *43*, 3461–3475. [CrossRef]
56. Faupin, A.; Gorce, P.; Meyer, C.; Thevenon, A. Effects of backrest positioning and gear ratio on nondisabled subjects' handcycling sprinting performance and kinematics. *J. Rehabil. Res. Dev.* **2008**, *45*, 109–116. [CrossRef] [PubMed]
57. Litzenberger, S.; Mally, F.; Sabo, A. Biomechanics of elite recumbent handcycling: A case study: Influence of backrest position, crank length and crank height on muscular activity and upper body kinematics. *Sport. Eng.* **2016**, *19*, 201–211. [CrossRef]
58. Faupin, A.; Gorce, P. The effects of crank adjustments on handbike propulsion: A kinematic model approach. *Int. J. Ind. Ergon.* **2008**, *38*, 577–583. [CrossRef]
59. Stone, B.; Mason, B.; Warner, M.; Goosey-Tolfrey, V. Horizontal Crank Position Affects Economy and Upper Limb Kinematics of Recumbent Handcyclists. *Med. Sci. Sport. Exerc.* **2019**, *51*, 2265–2273. [CrossRef]
60. Litzenberger, S.; Mally, F.; Sabo, A. Influence of different seating and crank positions on muscular activity in elite handcycling—A case study. *Procedia Eng.* **2015**, *112*, 355–360. [CrossRef]
61. Quittmann, O.; Abel, T.; Albracht, K.; Meskemper, J.; Foitschik, T.; Strüder, H. Biomechanics of handcycling propulsion in a 30-min continuous load test at lactate threshold: Kinetics, kinematics, and muscular activity in able-bodied participants. *Eur. J. Appl. Physiol.* **2020**, *120*, 1403–1415. [CrossRef] [PubMed]
62. Mason, B.; Stone, B.; Warner, M.; Goosey-Tolfrey, V. Crank length alters kinematics and kinetics, yet not the economy of recumbent handcyclists at constant handgrip speeds. *Scand. J. Med. Sci. Sport.* **2021**, *31*, 388–397. [CrossRef]
63. Antunes, D.; Borszcz, F.; Nascimento, E.; Cavalheiro, G.; Fischer, G.; Brickley, G.; De Lucas, R. Physiological and Perceptual Responses in Spinal Cord Injury Handcyclists during an Endurance Interval Training: The Role of Critical Speed. *Am. J. Phys. Med. Rehabil.* **2022**, *101*, 977–982. [CrossRef]
64. Stone, B.; Mason, B.; Stephenson, B.; Goosey-Tolfrey, V. Physiological responses during simulated 16 km recumbent handcycling time trial and determinants of performance in trained handcyclists. *Eur. J. Appl. Physiol.* **2020**, *120*, 1621–1628. [CrossRef]
65. Koontz, A.; Garfunkel, C.; Crytzer, T.; Anthony, S.; Nindl, B. Feasibility, acceptability, and preliminary efficacy of a handcycling high-intensity interval training program for individuals with spinal cord injury. *Spinal Cord* **2021**, *59*, 34–43. [CrossRef]
66. Felsner, E.M.; Litzenberger, S.; Mally, F.; Sabo, A. Musculoskeletal Modelling of Elite Handcycling Motion: Evaluation of Muscular On-and Offset. *Procedia Eng.* **2016**, *147*, 168–174. [CrossRef]
67. Mazzola, M.; Andreoni, G.; Campanardi, G.; Costa, F.; Gibertini, G.; Grassi, D.; Romero, M. *Effects of Seat and Handgrips Adjustments on a Hand Bike Vehicle. An Ergonomic and Aerodynamic Study for a Quantitative Assessment of Paralympics Athlete's Performance*; CRC Press: Boca Raton, FL, USA, 2012; pp. 569–576.
68. Quittmann, O.; Abel, T.; Vafa, R.; Mester, J.; Schwarz, Y.; Strüder, H. Maximal lactate accumulation rate and post-exercise lactate kinetics in handcycling and cycling. *Eur. J. Sport Sci.* **2021**, *21*, 539–551. [CrossRef] [PubMed]
69. Quittmann, O.; Meskemper, J.; Albracht, K.; Abel, T.; Foitschik, T.; Strüder, H. Normalising surface EMG of ten upper-extremity muscles in handcycling: Manual resistance vs. sport-specific MVICs. *J. Electromyogr. Kinesiol.* **2020**, *51*, 102402. [CrossRef] [PubMed]
70. Arnet, U.; van Drongelen, S.; Veeger, D.; van der Woude, L. Are the force characteristics of synchronous handcycling affected by speed and the method to impose power? *Med. Eng. Phys.* **2012**, *34*, 78–84. [CrossRef] [PubMed]
71. Van Drongelen, S.; Schlüssel, M.; Arnet, U.; Veeger, D. The influence of simulated rotator cuff tears on the risk for impingement in handbike and handrim wheelchair propulsion. *Clin. Biomech.* **2013**, *28*, 495–501. [CrossRef] [PubMed]
72. Groen, W.; Van Der Woude, L.; De Koning, J. A power balance model for handcycling. *Disabil. Rehabil.* **2010**, *32*, 2165–2171. [CrossRef]
73. Groen, W.; Van Der Woude, L.; De Koning, J. *The Power Balance Model: Useful in the Study of Elite Handcycling Performance*; IOS Press: Amsterdam, The Netherlands, 2010; Volume 26, pp. 85–87. [CrossRef]
74. Kouwijzer, I.; Valent, L.; Osterthun, R.; van der Woude, L.; de Groot, S. Peak power output in handcycling of individuals with a chronic spinal cord injury: Predictive modeling, validation and reference values. *Disabil. Rehabil.* **2020**, *42*, 400–409. [CrossRef]
75. Antunes, D.; Nascimento, E.; Brickley, G.; Fischer, G.; de Lucas, R. Determination of the speed-time relationship during handcycling in spinal cord injured athletes. *Res. Sport. Med.* **2022**, *30*, 256–263. [CrossRef]
76. Muchaxo, R.; de Groot, S.; Kouwijzer, I.; Van Der Woude, L.; Janssen, T.; Nooijen, C. A Role for Trunk Function in Elite Recumbent Handcycling Performance? *J. Sport. Sci.* **2021**, *39*, 2312–2321. [CrossRef]
77. Oviedo, G.; Alamo, J.; Niño-Mendez, O.; Travier, N.; Ventura, J.; Soto-Montañez, C.; Vidal, J.; Medina, J.; Javierre, C. Physiological responses in males with and without spinal cord injury to recumbent synchronous versus seated asynchronous arm crank stress tests | Respuestas fisiológicas en hombres con y sin lesión medular al realizar pruebas de esfuerzo con ergómetros de. *Retos* **2021**, 39, 565–571. [CrossRef]

78. Muratov, V. Wikimedia Commons. 2011. Available online: https://commons.wikimedia.org/wiki/File:Faffler_carriage.jpg (accessed on 15 January 2024).
79. Belloli, M.; Cheli, F.; Bayati, I.; Giappino, S.; Robustelli, F. Handbike aerodynamics: Wind tunnel versus track tests. *Procedia Eng.* **2014**, *72*, 750–755. [CrossRef]
80. Jeang, A.; Liang, F.; Huang, H. Handcycle design & development process for the disabled. In Proceedings of the 2015 IFToMM World Congress Proceedings, Taipei, Taiwan, 25–30 October 2015. [CrossRef]
81. Fischer, G.; Figueiredo, P.; Ardigò, L. Bioenergetics and Biomechanics of Handcycling at Submaximal Speeds in Athletes with a Spinal Cord Injury. *Sports* **2020**, *8*, 16. [CrossRef] [PubMed]
82. Meyns, P.; Van De Walle, P.; Hoogkamer, W.; Kiekens, C.; Desloovere, K.; Duysens, J. Coordinating arms and legs on a hybrid rehabilitation tricycle: The metabolic benefit of asymmetrical compared to symmetrical arm movements. *Eur. J. Appl. Physiol.* **2014**, *114*, 743–750. [CrossRef] [PubMed]
83. Bakkum, A.; Paulson, T.; Bishop, N.; Goosey-Tolfrey, V.; Stolwijk-Swüste, J.; Van Kuppevelt, D.; de Groot, S.; Janssen, T. Effects of hybrid cycle and handcycle exercise on cardiovascular disease risk factors in people with spinal cord injury: A randomized controlled trial. *J. Rehabil. Med.* **2015**, *47*, 523–530. [CrossRef] [PubMed]
84. Jansen, E.; de Groot, S.; Smit, C.; Thijssen, D.; TE Hopman, M.; Janssen, T. Vascular adaptations in nonstimulated areas during hybrid cycling or handcycling in people with a spinal cord injury: A pilot study of 10 cases. *Spinal Cord Ser. Cases* **2021**, *7*, 54. [CrossRef]
85. Cavallone, P.; Vieira, T.; Quaglia, G.; Gazzoni, M. Electomyographic activities of shoulder muscles during Handwheelchair.Q vs pushrim wheelchair propulsion. *Med. Eng. Phys.* **2022**, *106*, 103833. [CrossRef]
86. Verellen, J.; Janssens, L.; Meyer, C.; Vanlandewijck, Y. Development and application of a handbike ergometer to measure the 3D force generation pattern during arm crank propulsion in realistic handcycling conditions. *Sport. Technol.* **2012**, *5*, 65–73. [CrossRef]
87. Hiremath, S.; Ding, D.; Cooper, R. Development and evaluation of a gyroscopebased wheel rotation monitor for manual wheelchair users. *J. Spinal Cord Med.* **2013**, *36*, 347–356. [CrossRef]
88. Solazzi, L.; Schinetti, G.; Adamini, R. *Developed an Innovative Handbike Fork Made of Composite Material*; IOS Press: Amsterdam, The Netherlands , 2022; Volume 297, pp. 359–366. [CrossRef]
89. Florio, J.; Arnet, U.; Gemperli, A.; Hinrichs, T. Need and use of assistive devices for personal mobility by individuals with spinal cord injury. *J. Spinal Cord Med.* **2016**, *39*, 461–470. [CrossRef]
90. Schwandt, D. *Design Development of a Tandem Bicycle for Individuals with and without Lower Limb Disability*; SAE International: Troy, MI, USA, 1984; pp. 213–214.
91. Fuglsang, T.; Padulo, J.; Spoladore, M.; Dalla Piazza, M.; Ardigò, L. Development and testing of a novel arm cranking-powered watercraft. *Front. Physiol.* **2017**, *8*, 635. [CrossRef]
92. Janssen, T.; Dallmeijer, A.; Van Der Woude, L. Physical capacity and race performance of handcycle users. *J. Rehabil. Res. Dev.* **2001**, *38*, 33–40.
93. Moreno, B.; Peris-Fajarnés, G.; Lengua, I.; Moncho-Santonja, M. *Wheelchair Mobility Aid Through the Adaptation of Electric Scooters*; Springer: Berlin, Germany, 2020; pp. 184–190. [CrossRef]
94. Maki, K.; Langbein, W.; Reid-Lokos, C. Energy cost and locomotive economy of handbike and rowcycle propulsion by persons with spinal cord injury. *J. Rehabil. Res. Dev.* **1995**, *32*, 170–178. [PubMed]
95. Abel, T.; Vega, S.; Bleicher, I.; Platen, P. Handbiking: Physiological responses to synchronous and asynchronous crank montage. *Eur. J. Sport Sci.* **2003**, *3*, 1–9. [CrossRef]
96. Faupin, A.; Campillo, P.; Rémy-Néris, O.; Bouilland, S.; Thevenon, A.; Gorce, P. A kinematic study of the upper-limb motion of handcycle propulsion. *Arch. Physiol. Biochem.* **2003**, *111*, 38.
97. Knechtle, B.; Mülle, G.; Knech, H. Optimal exercise intensities for fat metabolism in handbike cycling and cycling. *Spinal Cord* **2004**, *42*, 564–572. [CrossRef] [PubMed]
98. Postma, K.; Berg-Emons Van Den, H.; Bussmann, J.; Sluis, T.; Bergen, M.; Stam, H. Validity of the detection of wheelchair propulsion as measured with an Activity Monitor in patients with spinal cord injury. *Spinal Cord* **2005**, *43*, 550–557. [CrossRef] [PubMed]
99. Faupin, A.; Gorce, P.; Campillo, P.; Thevenon, A.; Rémy-Néris, O. Kinematic analysis of handbike propulsion in various gear ratios: Implications for joint pain. *Clin. Biomech.* **2006**, *21*, 560–566. [CrossRef] [PubMed]
100. Faupin, A.; Gorce, P.; Rémy-Néris, O.; Thevenon, A. Ergonomie assessment of the handcycling propulsion. *Model. Meas. Control. C* **2006**, 146–155.
101. Verellen, J.; Meyer, C.; Reynders, S.; Van Biesen, D.; Vanlandewijck, Y. Consistency of within-cycle torque distribution pattern in hand cycling. *J. Rehabil. Res. Dev.* **2008**, *45*, 1295–1302. [CrossRef]
102. Meyer, C.; Weissland, T.; Watelain, E.; Ribadeau Dumas, S.; Baudinet, M.C.; Faupin, A. Physiological responses in handcycling. Preliminary study. *Ann. Phys. Rehabil. Med.* **2009**, *52*, 311–318. [CrossRef]
103. Abel, T.; Burkett, B.; Schneider, S.; Lindschulten, R.; Strüder, H. The exercise profile of an ultra-long handcycling race: The Styrkeprøven experience. *Spinal Cord* **2010**, *48*, 894–898. [CrossRef] [PubMed]
104. Bollini, M. *The Figure Eight Drive: A Two-Speed Drivetrain for Handcycles in the Developing World*; IOS Press: Amsterdam, The Netherlands, 2010; Volume 26, pp. 91–93. [CrossRef]

105. Goosey-Tolfrey, V.; Lenton, J.; Goddard, J.; Oldfield, V.; Tolfrey, K.; Eston, R. Regulating intensity using perceived exertion in spinal cord-injured participants. *Med. Sci. Sport. Exerc.* **2010**, *42*, 608–613. [CrossRef] [PubMed]
106. Rice, I.; Hettinga, F.; Laferrier, J.; Sporner, M.; Heiner, C.; Burkett, B.; Cooper, R. *Biomechanics*; Wiley: Hoboken, NJ, USA, 2010; pp. 31–50. [CrossRef]
107. Van Drongelen, S.; Arnet, U.; Van Der Woude, L.; Veeger, H. *Propulsion Effectiveness of Synchronous Handcycling* ; IOS Press: Amsterdam, The Netherlands, 2010; Volume 26, pp. 82–84. [CrossRef]
108. Hettinga, F.; Valent, L.; Van Der Woude, L. *Optimal Upper Body Exercise Training: Handcycling* ; IOS Press: Amsterdam, The Netherlands, 2011; Volume 29, pp. 751–757. [CrossRef]
109. Allgrove, J.; Chapman, M.; Christides, T.; Smith, P. Immunoendocrine responses of male spinal cord injured athletes to 1-h self-paced exercise: Pilot study. *J. Rehabil. Res. Dev.* **2012**, *49*, 925–934. [CrossRef] [PubMed]
110. Koopman, A.; Eken, M.; Van Bezeij, T.; Valent, L.; Houdijk, H. Does clinical rehabilitation impose sufficient cardiorespiratory strain to improve aerobic fitness. *J. Rehabil. Med.* **2013**, *45*, 92–98. [CrossRef] [PubMed]
111. Fischer, G.; Tarperi, C.; George, K.; Ardigò, L. An exploratory study of respiratory muscle endurance training in high lesion level paraplegic handbike athletes. *Clin. J. Sport Med.* **2014**, *24*, 69–75. [CrossRef] [PubMed]
112. Nooijen, C.; Vogels, S.; Bongers-Janssen, H.; Bergen, M.; Stam, H.; Van Den Berg-Emons, H. Fatigue in persons with subacute spinal cord injury who are dependent on a manual wheelchair. *Spinal Cord* **2015**, *53*, 758–762. [CrossRef]
113. Simmelink, E.; Borgesius, E.; Hettinga, F.; Geertzen, J.; Dekker, R.; Van Der Woude, L. Gross mechanical efficiency of the combined armleg (Cruiser) ergometer: A comparison with the bicycle ergometer and handbike. *Int. J. Rehabil. Res.* **2015**, *38*, 61–67. [CrossRef]
114. Abreu, E.; Alves, R.; Borges, A.; Lima, F.; de Paula Júnior, A.; Lima, M. Autonomic cardiovascular control recovery in quadriplegics after handcycle training. *J. Phys. Ther. Sci.* **2016**, *28*, 2063–2068. [CrossRef]
115. Arnet, U.; Hinrichs, T.; Lay, V.; Bertschy, S.; Frei, H.; Brinkhof, M. Determinants of handbike use in persons with spinal cord injury: Results of a community survey in Switzerland. *Disabil. Rehabil.* **2016**, *38*, 81–86. [CrossRef]
116. Azizpour, G.; Ousdad, A.; Legnani, G.; Incerti, G.; Lancini, M.; Gaffurini, P. *Dynamic Analysis of Handcycling: Mathematical Modelling and Experimental Tests*; Springer: Berlin, Germany, 2017; Volume 47, pp. 33–40. [CrossRef]
117. Hoekstra, S.; Valent, L.; Gobets, D.; van der Woude, L.; de Groot, S. Effects of four-month handbike training under free-living conditions on physical fitness and health in wheelchair users. *Disabil. Rehabil.* **2017**, *39*, 1581–1588. [CrossRef]
118. Zeller, S.; Abel, T.; Strueder, H. Monitoring training load in handcycling: A case study. *J. Strength Cond. Res.* **2017**, *31*, 3094–3100. [CrossRef] [PubMed]
119. Azizpour, G.; Lancini, M.; Incerti, G.; Gaffurini, P.; Legnani, G. An experimental method to estimate upper limbs inertial parameters during handcycling. *J. Appl. Biomech.* **2018**, *34*, 175–183. [CrossRef] [PubMed]
120. Kouwijzer, I.; Nooijen, C.; Van Breukelen, K.; Janssen, T.; de Groot, S. Effects of push-off ability and handcycle type on handcycling performance in able-bodied participants. *J. Rehabil. Med.* **2018**, *50*, 563–568. [CrossRef] [PubMed]
121. Legnani, G.; Incerti, G.; Lancini, M.; Azizpour, G. An identification procedure for evaluating the dynamic parameters of the upper limbs during handcycling. In Proceedings of the ASME Design Engineering Technical Conference, Quebec City, QU, Canada, 26–29 August 2018; Volume 5A. [CrossRef]
122. Morse, C.; Bostock, E.; Twiss, H.; Kapp, L.; Orme, P.; Jacques, M. The cardiorespiratory response and physiological determinants of the assisted 6-minute handbike cycle test in adult males with muscular dystrophy. *Muscle Nerve* **2018**, *58*, 427–433. [CrossRef] [PubMed]
123. Quittmann, O.; Meskemper, J.; Abel, T.; Albracht, K.; Foitschik, T.; Rojas-Vega, S.; Strüder, H. Kinematics and kinetics of handcycling propulsion at increasing workloads in able-bodied subjects. *Sport. Eng.* **2018**, *21*, 283–294. [CrossRef]
124. Cudicio, A.; Girardello, A.; Negro, F.; Orizio, C.; Arenghi, A.; Legnani, G.; Serpelloni, M. Topographical and physiological data collection for urban handbike tracks design. In Proceedings of the Pedestrians, Urban Spaces and Health—Proccedings of the 24th International Conference on Living and Walking in Cities, LWC 2019, Brescia, Italy, 12–13 September 2019; pp. 225–229.
125. Stangier, C.; Abel, T.; Zeller, S.; Quittmann, O.; Perret, C.; Strüder, H. Comparison of different blood lactate threshold concepts for constant load performance prediction in spinal cord injured handcyclists. *Front. Physiol.* **2019**, *10*, 1054. [CrossRef]
126. Stone, B.; Mason, B.; Bundon, A.; Goosey-Tolfrey, V. Elite handcycling: A qualitative analysis of recumbent handbike configuration for optimal sports performance. *Ergonomics* **2019**, *62*, 449–458. [CrossRef]
127. Stone, B.; Mason, B.; Warner, M.; Goosey-Tolfrey, V. Shoulder and thorax kinematics contribute to increased power output of competitive handcyclists. *Scand. J. Med. Sci. Sport.* **2019**, *29*, 843–853. [CrossRef]
128. Chaikhot, D.; Reed, K.; Petroongrad, W.; Athanasiou, F.; Van Kooten, D.; Hettinga, F. Effects of an Upper-Body Training Program Involving Resistance Exercise and High-Intensity Arm Cranking on Peak Handcycling Performance and Wheelchair Propulsion Efficiency in Able-Bodied Men. *J. Strength Cond. Res.* **2020**, *34*, 2267–2275. [CrossRef]
129. Himarosa, R.; Sunardi. Design, Frame Analysis and Manufacture of Handcycle Prototype. *J. Phys. Conf. Ser.* 2020, *1471*, 012058. [CrossRef]
130. Kouwijzer, I.; de Groot, S.; van Leeuwen, C.; Valent, L.; van Koppenhagen, C.; Grandjean Perrenod Comtesse, P.; Helmantel, E.; Dekker, M.; Zwinkels, M.; Metsaars, M.; et al. Changes in Quality of Life During Training for the HandbikeBattle and Associations With Cardiorespiratory Fitness. *Arch. Phys. Med. Rehabil.* **2020**, *101*, 1017–1024. [CrossRef]

131. Turoń-Skrzypińska, A.; Pawlukowska, W.; Szylińska, A.; Tomska, N.; Mikołajczyk-Kocięcka, A.; Ptak, M.; Dutkiewicz, G.; Rotter, I. Assessment of the relationship between selected factors and stress-coping strategies in handcyclists—A preliminary study. *Medicina* **2020**, *56*, 211. [CrossRef]
132. Nevin, J.; Smith, P. The Effectiveness of a 30-Week Concurrent Strength and Endurance Training Program in Preparation for an Ultra-Endurance Handcycling Challenge: A Case Study. *Int. J. Sport. Physiol. Perform.* **2021**, *16*, 1712–1718. [CrossRef] [PubMed]
133. Quittmann, O.; Abel, T.; Albracht, K.; Strüder, H. Reliability of muscular activation patterns and their alterations during incremental handcycling in able-bodied participants. *Sport. Biomech.* **2021**, *20*, 603–618. [CrossRef] [PubMed]
134. Stephenson, B.; Stone, B.; Mason, B.; Goosey-Tolfrey, V. Physiology of handcycling: A current sports perspective. *Scand. J. Med. Sci. Sport.* **2021**, *31*, 4–20. [CrossRef] [PubMed]
135. Abonie, U.; Albada, T.; Morrien, F.; Van Der Woude, L.; Hettinga, F. Effects of 7-week Resistance Training on Handcycle Performance in Able-bodied Males. *Int. J. Sport. Med.* **2022**, *43*, 46–54. [CrossRef] [PubMed]
136. Hutchinson, M.; Goosey-Tolfrey, V. Rethinking aerobic exercise intensity prescription in adults with spinal cord injury: Time to end the use of "moderate to vigorous" intensity? *Spinal Cord* **2022**, *60*, 484–490. [CrossRef] [PubMed]
137. Pasko, W.; Dydek, J.; Zielinski, J.; Hulewicz, T.; Sliz, M.; Dziadek, B.; Przednowek, K. Assessing Psychomotor Abilities in Handcyclists using Computerized Tests: An Initial Study. In Proceedings of the International Conference on Sport Sciences Research and Technology Support, icSPORTS—Proceedings, Valletta, Malta, 27–28 October 2022; Volume 2022, pp. 137–142.
138. Quittmann, O.; Abel, T.; Albracht, K.; Strüder, H. Biomechanics of all-out handcycling exercise: Kinetics, kinematics and muscular activity of a 15-s sprint test in able-bodied participants. *Sport. Biomech.* **2022**, *21*, 1200–1223. [CrossRef] [PubMed]
139. Soo Hoo, J.; Kim, H.; Fram, J.; Lin, Y.S.; Page, C.; Easthausen, I.; Jayabalan, P. Shoulder pain and ultrasound findings: A comparison study of wheelchair athletes, nonathletic wheelchair users, and nonwheelchair users. *PM R* **2022**, *14*, 551–560. [CrossRef]

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