Development of a wheelchair propulsion laboratory

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A review of wheelchair ergometers
Measuring handrim wheelchair propulsion in the lab: a critical analysis of stationary ergometers

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Abstract

There are many ways to simulate handrim wheelchair propulsion in the laboratory. Ideally, these would be able to — at least mechanically — simulate field conditions. This narrative review provides an overview of the lab-based equipment used in published research and critically assesses their ability to simulate and measure wheelchair propulsion performance. A close connection to the field can only be achieved if the instrument can adequately simulate frictional losses and inertia of real-life handrim wheelchair propulsion, while maintaining the ergonomic properties of the wheelchair-user interface. Lab-based testing is either performed on a treadmill or a wheelchair ergometer (WCE). For this study WCEs were divided into three categories: roller, flywheel, and integrated ergometers. In general, treadmills are mechanically realistic, but cannot simulate air drag and acceleration tasks cannot be performed; roller ergometers allow the use of the personal wheelchair, but calibration can be troublesome; flywheel ergometers can be built with commercially-available parts, but inertia is fixed and the personal wheelchair cannot be used; integrated ergometers do not employ the personal wheelchair, but are suited for the implementation of different simulation models and detailed measurements. Lab-based equipment is heterogeneous and there appears to be little consensus on how to simulate field conditions.
Introduction

To improve wheelchair design and the quality of life of handrim wheelchair users in both a daily and sports setting, reliable and valid measures of wheelchair propulsion are necessary [1]. These measurements can either be made in the field (e.g. in everyday propulsion or on the sports court) or in the laboratory on a treadmill or Wheelchair Ergometer (WCE). The equipment used by researchers to measure handrim wheelchair specific performance in the laboratory is diverse. This diversity in itself has implications for the generalizability of results and the applicability of the existing knowledge base [2], yet no critical overview currently exists.

Field-based testing present researchers with the least standardized but most externally valid conditions in which to study wheelchair propulsion [3,4]. It allows for the subject to be tested in their natural environment and personal wheelchair [5]. The latter is especially important as wheelchair settings greatly influence performance and modern wheelchair technology has become increasingly more individualized [6]. It is, however, problematic to collect physiological, kinetic, or kinematic data without changing the wheelchair in terms of mass and configuration, and it is further complicated by the non-stationary position of the wheelchair-user combination with respect to the environment. Additionally, in field testing, experimental conditions, friction or power output are difficult to control, reducing the reliability of any such measures [2].

Hence, wheeled mobility research today is still predominantly conducted inside the laboratory. Lab-based research allows detailed physiology and biomechanics studies to be conducted under controlled conditions [7], while the wheelchair-user combination is stationary on a treadmill or WCE. However, lab-based equipment is often customized and may vary in reliability and validity [2]; in fact, no commercial line-up of wheelchair ergometry, as for instance in the bicycling domain, is available for manual wheelchair testing. Moreover, while lab-based wheelchair testing protocols have been described in the literature [8,9], information on diversity and reliability details of the equipment is sparse. Certain choices during the design process might offer advantages on realism, ease of use, specific measurement capabilities, or cost. Yet, if the limitations of the equipment are not understood, interpretation errors can be made.

The choice of equipment is important as a lab-based modality should not only allow for accurate measurements but must also simulate wheelchair driving as realistically as possible in relation to the research at hand [7]. There are three main factors in wheelchair propulsion that decide the eventual behaviour: the wheelchair, the user,
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and the interaction thereof [10]. All three should be considered when assessing the validity of a lab-based testing instrument. A lab-based modality should thus not only be mechanically realistic, but also ergonomically (e.g. seat height or camber), and ecologically (e.g. visual or proprioceptive feedback). In general, to perform a valid simulation of overground manual wheelchair propulsion, the ergometer set-up used to evaluate wheelchair propulsion should thus ideally be able to:

- Simulate frictional losses, environmental conditions, and translational inertia of the wheelchair-user system;
- Facilitate valid and reliable measurements of power output on the wheels;
- Respect the ergonomic properties of the wheelchair-user interface and provide adequate sensory feedback to the user;
- Facilitate different testing protocols (i.e. submaximal, anaerobic and aerobic exercise testing and training)

The aim of this narrative review is therefore twofold. First, to create an overview of the available lab-based equipment in the research literature. Second, to assess the equipment on their ability to simulate and measure wheelchair propulsion in the laboratory based on the four indicators mentioned above. The current review starts off by providing a simple mechanical model of wheelchair propulsion as a conceptual framework for mechanically realistic wheelchair propulsion and simulation. Then the simulation and measurement capabilities of the available equipment and how researchers have approached this in international literature are discussed. Subsequently, ergonomics and sensory feedback on the equipment is examined and finally the testing capabilities are considered. The information from the current review is useful when comparing results of different studies, the standardization thereof, and could aid in the design of new (calibration procedures of) lab-based equipment.

Search strategy

For this narrative review, an overview of the existing literature was made by performing a semi-structured search using the PubMed, CINAHL, and Web of Science internet databases with the query “wheelchair AND (ergomet* OR dynamomet*)” on 2017-05-22 (n=842 results, 333 duplicates) and the consequent snowball method (11 additional papers). Thereafter, articles were first screened by one author on title, then on abstract, and then on full content (if still available/accessible). Articles were screened in chronological order. If two similar devices were found from the same research group or if a newer article referenced a previous article, they were assumed to use the same device. Like any literature study this study relies on the previously published literature and the availability thereof.
Due to the nature of this review, it often depended on relatively old literature which could not always be accessed.

**Overground vehicle mechanics**

To simulate the mechanics of handrim wheelchair propulsion in the field, a model [11–13] of wheelchair propulsion with the governing equations of motion is required (Figure 1.1). In this paper a reductionistic translational model for wheelchair propulsion is proposed which can be considered as a minimum requirement for the study of manual wheelchair propulsion and is limited to straight forward motion. The wheelchair can be modelled as a linear system, where the acceleration of the centre of mass of the wheelchair-user combination is equal to the total acting force divided by the mass:

$$F_{\text{sum}} = m_{\text{tot}} \cdot a$$  \hspace{1cm} (1)

Where $m_{\text{tot}}$ is the combined mass of the user ($m_{\text{user}}$) and wheelchair ($m_{\text{wc}}$), and the combined moments of inertia (J) of the wheels:

$$m_{\text{tot}} = m_{\text{user}} + m_{\text{wc}} + \sum_{i=1}^{\text{n.wheels}} \frac{J_i}{r_i^2}$$  \hspace{1cm} (2)

Where $F_{\text{sum}}$ includes the user generated forces ($F_s$), rolling resistance ($F_{\text{roll}}$), air drag ($F_{\text{air}}$), gravitational forces on an incline ($F_{\alpha}$), and internal friction $F_{\text{int}}$ experienced during wheelchair propulsion [7]. The forces acting on the wheelchair can then be expressed by:

$$F_{\text{sum}} = F_s - F_{\text{roll}} - F_{\text{air}} - F_{\alpha} - F_{\text{int}}$$  \hspace{1cm} (3)
The driving force in wheelchair propulsion are the forces and torques generated by the user, where the effect ($F_s$) of the tangential force on the handrim ($F_h$) and the local torque at the hand ($T_h$) can be calculated with (4):

$$F_s = \frac{F_h \cdot R_h + T_h}{R_{rw}}$$

(4)

During everyday propulsion (low to medium speeds), rolling resistance is the largest resistive force [2]. It is determined by the mass ($m_{user} + m_{wc}$), the distribution thereof on the front and rear wheels ($N_{fw} & N_{rw}$), the radius of the wheels ($R_{rw}$ and $R_{fw}$), and the characteristics of the wheels and floor surface ($\mu_{rw} & \mu_{fw}$). It can be expressed by the following equation:

$$F_{roll} = \left( \frac{\mu_{rw}}{N_{rw} \cdot R_{rw}} + \frac{\mu_{fw}}{N_{fw} \cdot R_{fw}} \right) \cdot \cos(\alpha)$$

(5)

Where $\alpha$ is the angle of inclination and $N_{fw}$ and $N_{rw}$ dynamically change during propulsion and are dependent on the length of the wheelbase ($L_{wb}$) and the distance of the center of mass from the rear wheels ($R_{cg}$):

$$N_{fw} = \frac{R_{cg} \cdot m \cdot g}{L_{wb}}$$

(6)

$$N_{rw} = m \cdot g - N_{fw}$$

(7)

At high speeds the air drag becomes an important source of friction [14]. It is a velocity dependent friction ($v^2$) that is influenced by the velocity of the wheelchair ($V_{wc}$) and wind ($V_w$), the frontal plane area of the wheelchair user combination ($A$), the air density ($D$), and the aerodynamic drag coefficient ($C_d$) [15]. The frontal plane area is dependent on the posture of the wheelchair user. Moreover, the drag coefficient can also be influenced by the characteristics of the wheelchair user combination:

$$F_{air} = 0.5 \cdot D(V_{wc} - V_w)^2 A C_d$$

(8)

When the wheelchair is going up or down a slope ($\alpha$) there will be a force acting on the system as a result of gravity:

$$F_a = m \cdot g \cdot \sin(\alpha)$$

(9)

The internal friction as a result of the bending of and localized deflections in the bearing rings is defined as a function of the velocity in Cooper’s model [13]. The internal friction is therefore equal to the constant $K$ multiplied by the velocity:
The contribution hereof is not entirely clear. The hubs typically have annular sealed bearings and the friction coefficient will not exceed 0.001 if the bearings are properly maintained and lubricated [16,17].

Simulations & Measurements: Treadmills

Simulation

Extra-wide treadmills have been used in wheelchair research as early as 1969 [18,19] and allow wheelchair propulsion at various speeds and/or slopes accommodating both every day and sports wheelchairs. They provide a realistic, safe, and stationary environment to measure wheelchair propulsion during a range of constant velocities and loads. Propulsion on a treadmill provides a mechanically accurate simulation of straight-line regular wheelchair wheeling [20,21]. Small steering corrections are necessary, while rolling friction and inertia are realistic due to Galilean invariance [20]. Moreover, the contribution of trunk movement to the wheelchair dynamics is also realistic. However, air drag is not simulated in treadmill propulsion (which only becomes an issue at high speeds [15,22]), turning is not possible, there is different/limited feedback on speed, and due to practical and safety concerns acceleration tasks cannot easily be performed. Many treadmills are fitted with safety systems like sliders or rubber bands [23] which could influence the wheelchair user, but limited information is available on their effect [24]. However, such systems could limit the steering requirements of treadmill propulsion and reduce the required power output, which would hurt the validity.

Few studies have compared overground wheelchair propulsion with propulsion on treadmills. A recent study demonstrated that, similar to gait, self-selected speed on a treadmill is lower in experienced wheelchair users [25]. The authors attributed this to differences in feedback and the higher cadence needed for treadmill propulsion as participants feel a sense of urgency to control the wheelchair. At matched speed conditions and similar power output they still found that spatiotemporal variables were different from overground propulsion [25]. Stephens and Ensberg [26] showed that hand trajectories for overground and treadmill propulsion were significantly different. However, in later studies Kwarciak et al. [21] and Mason et al. [27] found correlations for physiological and biomechanical parameters in treadmill propulsion and over ground propulsion at specific treadmill settings.

Measurements

Mean power output (11) during steady-state wheelchair propulsion can be relatively accurately determined by performing a drag test [10,19]. The treadmill allows for
power output to be varied through belt inclination or the application of resistance to the back of the wheelchair via a pulley system (12, Figure 1.2). The importance of determining power output before testing is highlighted by the findings of De Groot et al. [28]. Treadmill speed was often inaccurate and that power output could differ even among identical treadmill models. The source of the difference in power output between institutes in their study was not due to calibration, the wheelchair occupant, or experimenter errors but rather related to small manufacture-based differences in treadmill characteristics. As in any measurement device, regular calibration (of speed and inclination) is crucial in using a treadmill [28]. In a study of Vegter and colleagues [29] the drag test slightly underestimated the required power output. This could be because during the drag test the user assumes a constant immobile upright position and a perfectly straight heading, while in reality the rolling resistance fluctuates and small steering corrections are necessary.

\[ P_{ext} = F_{drag} \times v_{belt} \]  

(11)

\[ P_{ext} = (F_{roll \_int} + m_{pulley} \times g) \times v_{belt} \]  

(12)

Detailed kinetics
More detailed kinetic information can be obtained with the use of measurement wheels (e.g. [30–37]) of which two systems have been commercially available [37,38], but today are no longer available on the market. Most measurement wheels acquire 3D forces and torques around the handrim (though some 2D systems also exist [33]). This is valuable data which, when combined with 3D kinematics, can be used for inverse dynamics [39]. Moreover, information from these systems can be used to assess wheelchair propulsion technique by calculating spatio-temporal variables such as contact angle or push time, and kinetic variables such as peak torques or
fraction of effective force. Measurement wheels can be used on treadmills, but can also be used overground and on WCEs and have even been used to control WCEs [40]. Alternatively, ground reaction forces from an instrumented dual-belt treadmill can be used to estimate kinetic measures [41]. This will not result in 3D kinetics, but it does give more detailed kinetic and temporal information than a simple drag test alone.

**Simulation & Measurements: Wheelchair ergometers (WCEs)**

WCEs provide the most constrained wheelchair testing environment as the wheelchair is fixed and no steering is required to keep the wheelchair on the WCE. They offer some noticeable advantages over treadmills as power output can be easily adjusted, simulated turning is often possible, and acceleration tasks (e.g. a Wingate) can be safely performed. The importance of acceleration tasks is apparent considering that most motor activities of daily living that are practiced in the everyday life of wheelchair users are usually of short duration and of relatively high intensity [42,43], thus taxing the anaerobic energy system.

However, in contrast to treadmills, WCEs are mechanically heterogeneous and there are various different approaches to designing WCEs. The first WCE found was the device of Brouha and Krobath in 1967 [44], with 50 unique WCEs found in the literature in 2017. They can roughly be grouped into three categories: roller ergometers, flywheel ergometers, and integrated ergometers (Figure 1.3). Some hybrid designs (roller attached to flywheel) were also found. An overview of the ergometers found in the literature and their specifications is presented in Table I. In general, WCEs use a simplified model of wheelchair propulsion close to the one in this paper. It should be noted that (most of) these ergometers make some additional assumptions about wheelchair propulsion which could hurt the relation with the field [45]:

- The wheelchair is propelled on a strictly straight line;
- The movements of the subject on the wheelchair do not contribute to the dynamics;
- The rolling resistance force is constant;
- The wheels do not slip on the floor;
- The castors do not contribute to the dynamics of the wheelchair.

**Roller ergometers**

The majority of WCEs found in literature could be categorized as roller ergometers (Table 1.1). To be considered a roller ergometer, the WCE had to have at least one roller on which a wheelchair could be fixated. Similar to the TM, the advantage of roller ergometer is that they can be used with the personal wheelchair of the user.
This typically allows for fast testing as no provisions have to be made to match the ergonomics of the WCE with the regular wheelchair of the user. Roller ergometers range from fully passive rollers to highly advanced computer-controlled systems with electronic brakes or motors for the individual rear wheels.

In their most basic form, roller ergometers consist of one or more rollers that have a moment of inertia that is (or should be) similar to the translational inertia of a wheelchair-user system and which provides passive friction. The most straightforward and common method of simulating wheelchair propulsion on a WCE is to use a static friction and an inertia that is matched to the participant or a 50th percentile equivalent mass. The inertial properties of the roller can be calculated, obtained from CAD-models, or determined with an acceleration or trifilar pendulum test [46].

If the inertia is too low the wheel speed at the start of the push cycle will be low and it is easy to accelerate the wheel. On the other hand, if the inertia is too high it will resist changes to speed more and it will be very difficult to accelerate or decelerate the wheelchair. Two different approaches to simulate the translational inertia of wheelchair propulsion on a roller ergometer have been found:

- Mechanical: choosing a roller with a rotational inertia that matches with the translational inertia of the wheelchair and the subject combined; attach the roller to a flywheel; use weighted disks to adjust the rotational inertia of the roller; change the moment of inertia by adjusting the inner diameter of the roller, thereby changing the inertia experienced by the user [47].
• Electronic: using an electronically controlled motor or brake.

The change in velocity of the wheels ($\alpha_{rw}$) is dictated by the torque applied by the user ($T_s$), inertia, the frictional torque in the bearings of the ergometer and wheelchair ($T_{int}$), and the contact friction ($T_{fr}$) of the wheel on the roller (13). These frictional characteristics are influenced by the weight pressing down on the wheelchair and roller.

$$\alpha_{rw} = \frac{T_s - T_{int} - T_{fr}}{J_{roller} \times \left(\frac{r_{rw}}{r_{roller}}\right)^2 + J_{rw}}$$  \hspace{1cm} (13)

The power output required for propulsion on these ergometers can be determined using the Theisen et al. method [48] when the inertia is known. The total internal torque ($T_{tot,int}$), which consists of $T_{int}$ and $T_{fr}$, can be determined by performing a coast-down test. The deceleration test provides data of time and velocity. The calculation of a linear regression line on values that lie within the range of the velocities performed represents the linear acceleration from which the angular acceleration of the roller can be derived. The external torque delivered to the wheels during this period is zero therefore; a reflection of the total resistive forces of the specific wheelchair ergometer can be calculated.

$$T_{tot,int} = \frac{J_{roller} \times \left(\frac{r_{rw}}{r_{roller}}\right)^2 + J_{rw}}{\alpha_{rw}}$$ \hspace{1cm} (14)

Assuming a constant frictional torque, the work output at a constant velocity can then be determined by multiplying the total internal torque with the distance travelled.

$$W_s = T_{tot,int} \times s$$ \hspace{1cm} (15)

The first problem encountered with roller ergometers is that the coast-down test assumes a constant total internal torque. However, during actual overground wheelchair propulsion the weight on the rear wheels shifts. At the end of the push phase the weight is shifted to the castor wheels of the wheelchair, which would increase the rolling friction in regular overground propulsion [49,50]. However, on roller ergometers the opposite happens, the total internal torque is reduced when the weight is shifted to the castor wheels. No information on the impact of this discrepancy between overground propulsion and WCE propulsion is available at this time.

Another problem encountered with roller systems is that the base resistance of the system can be too high for some individuals as rolling friction on a roller system is considerably higher than overground. If this friction is too high for the participant
there is little that can be done as friction can usually only be increased (e.g. with a brake). Aissaoui et al. [51] solved this by reducing the weight on the rollers, thereby also increasing the risk of slipping. High base resistance becomes even more problematic considering the effect of camber on roller ergometers [52], which could further increase the base friction of the WCE. This effect is likely bigger than during overground propulsion, especially on two-roller systems as camber might lead to a misalignment on one of the rollers [53]. Consequently, the ergometer presented by Faupin et al. [52] can be adjusted to rear wheel camber to reduce camber induced friction. Use of low-friction bearings, adaptable camber [52], using a different tie-down system, or reducing the weight on the rollers [51] could reduce internal friction. Similar to the friction on treadmills, the friction in roller ergometers is not constant, even within the same model [54]. Between models there can be even larger differences as the wheelchair setup or method of fixation differs.

The frictional torque on the roller can also be increased with an external mechanism such as a brake or a motor. Equation 13 can be adjusted to account for this friction (16). The Theisen et al. method [48] can then be used to determine the braking torque of the braking mechanism. With multiple tests the characteristics of the brake can be identified.

\[
\alpha_{rw} = \frac{T_s - T_{int} - T_r - T_{brake}}{I_{roller} \left( \frac{r_{rw}}{r_{roller}} \right)^2 + I_{rw}}
\] (16)

However, even if adjustments are made for assumed constant forces like rolling resistance and slope, a variable external torque is still required to simulate air resistance [13]. This requires the use of an electronically controlled braking system. Another advantage of such a system is the increased flexibility for simulations or adjusting workload during a test. For example, it can be used to simulate transitions...
A review of wheelchair ergometers

between surfaces [55]. An example of a WCE with an advanced braking system are the ergometers described by Theisen et al. [48], Wu et al. [55] or the VP100H [56]. Roller ergometers with an electronic control system offer more flexibility to mechanically emulate wheelchair propulsion, but they still have to adjust for system friction.

Finally, some roller ergometers use a motor to simulate overground propulsion. The advantage of using a motor is that it cannot only generate braking torques, but it can also generate assistive torques. It allows for, but also requires, more advanced calibration methods [57]. The ergometer can be modelled as a haptic feedback system [40], in which it uses the torque applied on the rollers and an internal model of a wheelchair to simulate propulsion. Moreover, slopes can be more accurately simulated as the rollers can roll back or accelerate on their own, though this was only found in the ergometer described by Brauer [58]. Examples of motorized ergometers are the Ergotronic 9000 [59], and the ergometers presented by Devillard et al. [56], Harrison et al. [60], and Klaesner et al. [61].

The only roller ergometer that does not have to adjust for system friction is the ergometer presented by Chenier et al. [40]. It uses admittance-control and uses force obtained from a measurement wheel (SMARTwheel, Three Rivers Holding, USA) as input. This is fed into a simulation model and a motor with a controller is used to set the roller speed. This method avoids the calibration problem of other roller ergometers, but it sacrifices the flexibility of being able to use the personal wheelchair (or at least the wheels) of the user. Though, for all motorized ergometers the aforementioned additional assumptions for roller ergometers still apply.

Flywheel ergometers

Ten different flywheel ergometers were found in the older (1960-1990) literature. In flywheel ergometers a chair or wheelchair is mounted on a frame. The wheels of the wheelchair are coupled to a flywheel assembly through a chain and sprocket system. The main advantage of this approach is that a commercially available bicycle ergometer can be used. Moreover, frictional torques as a result of the rear wheel pressing down on a roller is not a problem. The flywheel ergometer design was first implemented by Brattgard in 1970 and was later adopted by researchers at various other universities (Table 1.1).

Flywheel ergometers are dependent on the properties of the chosen bicycle ergometer. Friction is simulated by a standard friction belt or other braking system. This setup can only simulate a constant friction which is sufficient for simulating rolling resistance, but usually not for velocity-dependent friction such as air drag. Additionally, the inertia of the flywheel cannot be easily adjusted for participants of
different body mass without making adjustments to the original bicycle ergometer. As a result, flywheel ergometers can generally only use basic simulation models of wheelchair propulsion. The acceleration of the rear wheels is dependent on the braking torque and the inertia of the flywheel ($J_{flywheel}$) (gear ratio of 1:1):

$$\alpha_{rw} = \frac{T_s - T_{int} - T_{brake}}{J_{flywheel} * \left( \frac{r_{rw}}{r_{flywheel}} \right)^2 + J_{rw}}$$

(17)

Some researchers have chosen for an ergometer that has a work rate which is independent of the turning frequency. The flywheel ergometer at Lavel University [62] uses a bicycle ergometer with these properties. Work rate can be very tightly controlled with such an ergometer, but it could be less realistic than the other approaches.

Integrated ergometers (simulators)

In integrated ergometers or simulators, the simulation and measurement capabilities of an ergometer are integrated in a wheelchair-like device. The first integrated ergometer found in the literature was described by Dreisinger in 1978 and was patented by Cardrei Corporation [63]. The advantage of this approach, over roller ergometers, is that the system friction and inertia are almost negligible. More importantly, they do not change between users or when a user shifts their weight.

One decade later, Niesing et al. [7] presented a more advanced integrated ergometer. An electronic control system simulates frictional losses on the basis of feedback with software based on the power balance [10]. A force measuring system allows for the measurement of forces applied to the handrim for each individual wheel. The design
of this ergometer ensures provision of an accurate simulation of frictional losses and the ability to simulate slopes. In addition to this, the translational inertia of the wheelchair-user system is simulated. The force transducers in both the seat and the wheels allow for biomechanical analysis of wheelchair configuration and wheelchair propulsion. Finally, it allowed for wheelchair adjustments to be tested.

The final integrated ergometer that was found was presented by Samuelsson et al. [64] and used an isokinetic dynamometer on a wheelchair attached to a frame. The use of an isokinetic dynamometer can provide insight in the torque-velocity relation of the propulsion movement during wheelchair propulsion. This method, also facilitated by the previous ergometer [7], provides data not disclosed by other methods, though it does not fit in the framework set in this paper.

**Measurements on a wheelchair ergometer**

As WCE designs differ, their measurement possibilities also differ. Some estimate power output with a coast-down test, while others can measure torque directly or indirectly. Measurement validity is closely tied to the validity of the mechanical strain the WCE imposes on the user, yet this is not often reported in the literature. Potentially because this data is considered to be internal data. Due to the variation in WCEs, a variety of methods are employed to validate the measurement validity, there is currently no ‘gold standard’. In general, most authors provide limited information on the calibration and validation of their devices.

Flywheel ergometers are dependent on the validity of the bicycle ergometer they are based on. Wheelchair propulsion is of much lower intensity than cycling. While readily available, bicycle ergometers should be treated with care. There is variation between bicycle ergometers [65] and the validity of bicycle ergometers during incremental power tests can be lower than expected compared to steady-state exercise tests [66]. The determination of power output could be inaccurate [7], as was demonstrated in some “turbo trainers” [67]. Moreover, some bicycle ergometers do not include the power required to accelerate the flywheel in their calculations [66].

Langbein et al. [68] used a calibration rig to compare the ergometer output with a torque sensor. They fully characterized the eddy-current brake of their WCE with this device. Similar techniques have also been used in the calibration of bicycle ergometers [66]. A test with intermittent speeds, akin to those in wheelchair propulsion, was not performed. Alternatively, the VP100H ergometer was validated with the use of a two-dimensional force transducer platform [56]. Errors in force and power ranged from 0.89% to 7.56% and from 0.41% to 6.74%, respectively. The higher error rates were attributed to trunk movements during the tests.
In another study, Hutzler et al. [69] also used a force transducer to validate the force readings of their ergometer. They performed a static test against a simulated external load and reported errors of “below 5%”. No other information about this test was presented. The WheelMill system, presented by Klaesner et al. [61], showed similarities with a measurement wheel, but measurement error was substantial

Alternatively, the emphasis can be put on the outcome parameters. The measurement capabilities of the device could be defined as the concurrent validity of the WCE with an established field protocol, which mainly depends on the validity of the simulation and testing protocols. Mason et al. [27] compared physiological outcomes between TM, overground, and WCE propulsion. They found significant differences in oxygen consumption and heart rate between modalities. However, they did not standardize the load between exercise modalities. Koontz et al. [70] compared handrim kinetics in a quantitative and qualitative analysis. They found significant correlations between overground and WCE propulsion, but large differences between modes were found. Again, inertia and friction between modalities was not standardized.

One comparison of peak aerobic performance in the field and on a WCE ergometer was found. Burkett et al. [71] found similar physiological response patterns and magnitudes in a field and WCE test. Van der Scheer et al. [72] found a weak relationship between 15m overground sprint outcomes and a Wingate test on a WCE. However, the purpose of this test was not necessarily to compare the two modalities, but to compare the two tests. If anything, these results suggest that the WCE testing environment is not yet able to closely emulate overground conditions.

Reliability of outcome parameters was extensively studied by researchers. It is not only dependent on the mechanical reliability of the WCE but is also influenced by the reliability of the testing environment, protocols, and biological variance. Bhambhani et al. [73] specifically looked into the reliability of a maximal graded exercise test on a WCE in wheelchair users with cerebral palsy [74] and spinal-cord injury [73]. They concluded that physiological responses during graded exercise tests on a WCE ergometer are highly reliable. Similar results were found by Burkett et al. [71] in spinal-cord injury patients on their ergometer. The ergometer of Theisen et al. [48] was tested with sedentary patients and sportsmen. They also concluded that results are reproducible on their ergometer. In another study, Keyser et al. [75] performed 30-minute bouts of constant work-rate wheelchair ergometry. They showed that, in able-bodied participants, the oxygen uptake and heart rate is highly reliable. In a similar test, Finley et al. [76] showed that most kinetic and kinematic variables obtained during wheelchair ergometry are reliable unless when fatigued.
Ergonomics & Sensory feedback

Ergonomics

Treadmills and roller ergometers allow the use of the personal wheelchair. However, in flywheel ergometers the chair is attached to the flywheel and cannot be exchanged with another chair. A similar problem is found in integrated ergometers. Yet, to compensate for this, it was found that integrated ergometers, like the WCE described by Burkett et al [71], and Niesing et al. [7], use highly adaptable seating, making integrated ergometers ideal for experimenting with ergonomic settings, but not for testing the original wheelchair-user configuration. For example, the apparatus described by Niesing et al. [7] consists of a frame with two independently mounted wheels and an adjustable seat and backrest that are mounted on a console with a hydraulic foot. Wheels, camber, handrim form and configuration could all be altered and were evaluated in the past decades [2].

Proprioceptive feedback

Proprioceptive feedback in a wheelchair consists of the force on the handrim, but also of the feeling of motion, and response of the seating and backrest. The validity of the first components is determined by the mechanical validity of the simulation. It is also influenced by the configuration of the wheelchair-user interface, which affects the mechanical advantage of the user [13]. Another addition that can be made is to allow the wheels to roll backward when on a virtual incline or accelerate when on a decline [58]. Finally, due to the absence of wind, there is also no sensation of air drag. This could be added with the addition of a fan, but has not yet been done in wheeled mobility studies before and the contribution might be negligible.

A second component, vestibular perception, is more difficult to simulate on a stationary platform. As the wheelchair is fastened or integrated in a WCE, there is no risk of tipping or toppling. Treadmills provide realistic sensory feedback to the user. In contrast to WCEs, the wheelchair is not fixated and the user needs to ‘stabilize’ the wheelchair. De Groot et al. [77] found a small difference in mechanical efficiency between the computer-controlled ergometer and overground propulsion. This difference is likely due to the fact that the trunk needs to be stabilized during overground wheelchair propulsion but not as much during wheelchair ergometry, which is a problem that arises with almost every form of ergometry. Indeed, Veeger et al. found a small difference in trunk movement during treadmill propulsion and wheelchair propulsion on the ergometer [78].

One example was found of a system that simulated up- and downslopes, and cross-slopes [61]. Moreover, the platform of the ergometer at Human Engineering Research Laboratories [79], the University of Melbourne [80], and University of
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Louvain [48] can simulate slopes in the forward-backward direction. However, these systems are the exceptions to the norm as the majority does not include any form of vestibular feedback.

**Visual feedback**

Wheelchair propulsion in the field is accompanied by optical flow. The subject uses visual cues to steer the wheelchair in the right direction. On a treadmill the user receives some feedback on heading as they need to stay in the centre of the belt [81], but they are more or less stable in the environment. On a WCE the user needs some form of feedback to know where they are (in virtual space). Most ergometers provide limited feedback in the form of speed and/or direction. Other ergometers provide a moderate form of feedback on a screen. Very little is known about what feedback to use. For example, the ergometer presented by Wu et al. [55] provides visual feedback of the surface that is currently being simulated and when a transfer is made.

Finally, the most extensive feedback of the position of the wheelchair can be given by employing virtual reality (VR) on semi-immersive 180° screens or head mounted displays. This implementation was only found in one WCE for regular handrim wheelchairs [60]. A study [82] with powered wheelchairs has shown that self-chosen speed is lower when the environment is more immersive. The incorporation of haptics into VR simulations of the built environment provides a powerful tool that should allow wheelchair users to directly participate in the design and testing of accessible environments, and it is a motivational tool [83]. VR technology has rapidly improved over the past few years, but it is scarcely used in this line of research. Newer systems no longer need extensive setups with multiple screens, but could use commercially available head mounted displays.

The WCE described by Harrison et al. [60] is specifically used as a simulator. It is used to test how wheelchair users interact with the built environment. Hence, they implemented a more advanced system for visual feedback. This allows users to participate in the design and testing of accessible environments. Another example of a setup with visual feedback is the treadmill at Pittsburgh [79]. Finally, visual feedback can be used to enhance or induce motor learning [84], or as a motivational tool [85].

**Auditory feedback**

Auditory cues could be used in learning tasks or to increase immersion [83]. Additionally, they can be used to enforce a preferred cadence. No examples of auditory feedback were found in the literature regarding WCEs. Nevertheless, all WCEs and treadmills could be a suitable platform for studies that include a form of auditory feedback would it fit the needs of the researcher.
Testing capabilities

Biomechanics & motor learning

All lab-based modalities provide considerable advantages for researchers when compared to overground testing. Both the treadmill and ergometer environments are relatively easy to standardize. Moreover, they can be expanded with extra equipment that is necessary for biomechanics and motor learning studies. Indeed, motor learning during overground propulsion \[115,116\] and treadmill \[81,84,117\] or ergometer propulsion \[77\] show somewhat similar results. However, in overground and ergometer propulsion, it is possible for the self-selected speed to change during motor learning. It has also been argued that wheelchair propulsion on an ergometer is less complex and therefore might produce different learning outcomes, but De Groot et al. \[77\] found similar results for ergometer, treadmill, and overground modalities after a 3-week practice period. As discussed in the previous sections, there is little information available on the ecological validity of biomechanics testing on treadmills \[21,25,26\] and ergometers \[27,70–72\].

Aerobic

Exercise testing and training benefit from task specificity. Submaximal aerobic tests (or training protocols for that matter), often used in motor learning and biomechanics studies, can be performed on any wheelchair treadmill or WCE. Submaximal tests are either predictive or performance tests, where predictive tests are used to estimate peak aerobic capacity and performance tests involve measuring responses to typical physical activities or interventions \[118\].

Peak oxygen uptake and power output are used to indicate peak physical capacity \[119\] which can be used to evaluate the effect of training programmes. Historically, the majority of studies performed were using arm crank ergometers (ACEs) in favour of wheelchair ergometry \[120\]. ACEs were used as early as 1971 by Stoboy et al. \[121\] to measure exercise capacity in wheelchair users. They offer some noticeable benefits as they are a low-cost, portable and non-specific measuring tool for upper body work capacity \[122\]. They allow for the measurement of upper body fitness in isolation of context, which is useful for inter-group comparisons or for the assessment of individuals who do not use their wheelchair during activities of daily living, rehabilitation, or their sports activities \[122\]. Peak oxygen uptake is similar in ACE and wheelchair ergometry tests, but external power output is higher in the ACE condition due to a better (bio-)mechanical transmission of internal power and lower skill requirement \[123\].
Table 1.1. Characteristics of all wheelchair ergometers found: an overview of their measurement and simulation capabilities

| Article (year + reference) | Category | Ergonomics | Measurements | Inertia | Rolling resistance | Air drag | Slope$^1$ | Left/ right | Feed-back | Validity/reliability | Remarks |
|----------------------------|----------|------------|--------------|---------|-------------------|---------|----------|-------------|-----------|----------------------|---------|
| 1967 [44], 2001 [86]       | Roller ergometer | ++ personal wheelchair | +/- distance and time | - roller mass not matched | +/- internal friction of WCE | - No | - No | - No | +/- V | [44]$^a$ |
| 1970 [87], 1977 [88], 1979 [89], 1981 [90], 1982 [91], 1991 [92], 1995 [93], 1998 [94], 2000 [95] | Flywheel ergometer | - integrated wheelchair | + power output, speed | +/- fixed mass flywheel | + brake | - No | - No | - No | +/- V | [75,76,87,89,96], [97]$^b$ |
| 1972 [58]                  | Roller ergometer | ++ personal wheelchair | + power output, speed | + variable mass flywheel | + brake | + motor | + motor | - No | +/- V | [58]$^b$ |
| 1978 [63]                  | Integrated ergometer | - integrated wheelchair | ++ torque, speed | + variable mass flywheel | + brake | - No | - No | + Yes | +/- V | Commercially available bicycle ergometers |
| 1983 [80]                  | Roller ergometer | ++ personal wheelchair | + power output, speed | - roller mass not matched | + brake | - No | - No | - No | +/- V | Some bicycle ergometer parts |
| 1983 [98]                  | Roller ergometer | ++ personal wheelchair | + power output, speed | +/- fixed mass roll | + motor | - No | - No | - No | +/- V |  |
| 1987 [71]                  | Integrated ergometer | +/- integrated, limited | + power output, speed | + variable mass flywheel | + brake | - No | - No | - No | +/- V | [71]$^b$ |
| 1988 [99], 1989 [100]      | Hybrid ergometer | ? | + power output | +/- fixed mass flywheel | + brake | - No | - No | - No | +/- V | [99]$^a$ |
| 1989 [64]                  | Integrated ergometer | - integrated wheelchair | + power output, speed | - n.a. | - n.a. | - n.a. | - n.a. | - n.a. | +/- V | Isokinetic ergometer |
| 1990 [7]                   | Integrated ergometer | +/- integrated, adjustable | ++ 3D-handrim and seat kinetics | + motor | + motor | + motor | ++ motor | + Yes | +/- V | Simulator |
| Article (year + reference) | Category | Ergonomics | Measurements | Inertia | Rolling resistance | Air drag | Slope<sup>†</sup> | Left/right | Feedback | Validity/reliability | Remarks |
|---------------------------|----------|------------|--------------|--------|-------------------|---------|----------------|-----------|---------|------------------|---------|
| 1990 [101] Roller ergometer | ++ personal wheelchair | + speed | + variable mass roller | + ? | - | No | - | No | +/- V | | |
| 1991 [102], 1991 [62] Flywheel ergometer | - integrated wheelchair | + power output, speed | +/- fixed mass flywheel | - n.a. | - n.a. | - n.a. | - No | + | +/- V | Watt controlled |
| 1993 [103] Hybrid ergometer | - integrated wheelchair | + power output, speed | +/- fixed mass flywheel | +/ - Cateye CS1000 | - No | + Yes | + Yes | - No | +/- V | Turbo trainer |
| 1993 [68] Roller ergometer | ++ personal wheelchair | + power output, speed | +/- fixed mass flywheel + electromagnetic brake | - No | - No | + Yes | +/- V | | |
| 1996 [96], 2006 [104], 2014 [105] Hybrid ergometer | ++ personal wheelchair | + power output, speed | +/- fixed mass flywheel + brake | - No | - No | - No | +/- V | | |
| 1993 [59] Roller ergometer | ++ personal wheelchair | ++ tangential force, speed | + motor | + motor | + motor | ++ motor | - No | +/- V | | Rollers attached to flywheel |
| 1996 [48] Roller ergometer | ++ personal wheelchair | + power output, speed | + variable mass roller | + electromagnetic brake | + | + | + Yes | +/- V | + P | |
| 1996 [107] Hybrid ergometer | ++ personal wheelchair | ++ tangential force, speed | + variable mass roller | + Velodyne | - No | - No | + Yes | +/- V | | |
| 1998 [108] Roller ergometer | ++ personal wheelchair | ++ torque, speed | +/- fixed mass rollers | ? | - No | - No | - No | +/- V | | |
| 2000 [69] Roller ergometer | ++ personal wheelchair | ++ tangential force, speed | + motor | + motor | + motor | + | + Yes | +/- V | | Commerical |
| 2001 [56], 2008 [53], 2015 [109] Roller ergometer | ++ personal wheelchair | + power output, speed | + equal to 35 or 75 kg | + hysteresis brake, adaptable to camber | - No | + brakes | - No | +/- V | | |
| 2001 [57] Roller ergometer | ++ personal wheelchair | ++ torque, speed | +/- fixed mass rollers | + motor | + motor | ++ motor | + Yes | + V | + P | |
| Article (year + reference) | Category | Ergonomics | Measurements | Inertia | Rolling resistance | Air drag | Slope† | Left/ right | Feedback | Validity/ reliability | Remarks |
|---------------------------|----------|------------|--------------|---------|--------------------|---------|--------|------------|----------|----------------------|---------|
| 2001 [85] Roller ergometer | ++ personal wheelchair | +/- distance and time | +/- fixed mass rollers | + electromagnetic brake | - No | - No | + Yes | + V | | Exergaming, portable |
| 2002 [51] Roller ergometer | ++ personal wheelchair | + power output, speed | +/- fixed mass rollers | + adjusting internal friction | - No | - No | - No | +/- V | + | Adjustable incline |
| 2003 [110] Roller ergometer | ++ personal wheelchair | +/- distance and time | ? | ? | ? | + Yes | +/- V | |
| 2004 [60] Roller ergometer | ++ personal wheelchair | +/- distance and time | + variable mass rollers | + mechanical brake | - No | + | + Yes | ++ VR | [60]† | Immersive simulation |
| 2007 [54], 2012 [111] Roller ergometer | ++ personal wheelchair | + power output, speed | +/- fixed mass rollers | +/- passive | - No | - No | + Yes | +/- V | [70]‡ | |
| 2008 [112] Roller ergometer | ++ personal wheelchair | +/- distance and time | - roller mass not matched | + brake | - No | - No | - No | ? | |
| 2011 [113] Hybrid ergometer | ++ personal wheelchair | + power output, speed | + flywheel ratio adjustable | + brake | - No | - No | - No | +/- V | | Rollers attached to flywheel |
| 2013 [114] Roller ergometer | ++ personal wheelchair | + torque, speed | +/- variable mass rollers | +/- passive | - No | - No | + Yes | +/- V | |
| 2013 [55] Roller ergometer | ++ personal wheelchair | + power output, speed | +/- fixed mass rollers | + pneumatic brake | - No | - No | + Yes | +/- V | [55]‡ | |
| 2014 [61] Roller ergometer | ++ personal wheelchair | + power output, speed | + motor | + motor | - No | - No | + Yes | + V | + P | Inclines and slopes |
| 2015 [40] Roller ergometer | +/- personal wheelchair | + 3D handrim forces | + motor | + motor | + motor | + motor | + Yes | +/- V | [40]‡ | Measurement wheels |

† Full table in article; ‡ Mechanical simulation of slope (i.e. constant torque on roller); a: reliability study; b: validity study; c: more detail possible with instrumented treadmill; VR: virtual reality; V: visual; P: proprioceptive; G: game
Nevertheless, peak physical capacity can also safely be determined on treadmills or WCEs [120]. Wheelchair ergometry provides additional insights on top of peak oxygen uptake on performance and mobility in daily life [118] as the wheelchair settings and propulsion technique influence external power output. To reach peak physical capacity the load has to be incremented in small steps. On a treadmill this can be achieved by increasing resistance with a pulley or by increasing the slope inclines. Increasing gradient is less safe and has some ergonomic issues at high slopes. By using a pulley system, the posture of the participant does not change and the resolution of the increments is higher [120]. On a WCE the same tests can be performed if a variable braking system is implemented. As the wheelchair is tethered to the WCE the test is also safer than on a treadmill and the participant does not have to adjust their posture for inclines.

Anaerobic
A recent systematic review on anaerobic exercise testing in rehabilitation by Krops et al. [124] showed that for the upper extremities valid ACE, WCE, and overground tests are available. Overground testing is limited to sprint tests, while ACE and WCE can also be used for modified Wingate (mWAnT) protocols. In contrast, there appear to be no tests available for anaerobic testing on treadmills. The main outcome parameters for mWAnT and sprint tests are power output and peak velocity. Peak velocity may be useful in WCEs that cannot measure power output as it moderately correlates with peak power [125]. Again, the specificity of using WCEs can be seen as an advantage or disadvantage based on the goal of the measurement [122].

Synopsis & Perspectives
The aim of this review was twofold: first, to create an overview of the available lab-based equipment used in research. This was done by collecting and examining existing literature from internet databases and resulted in 50 unique wheelchair ergometers. Second, to assess this equipment on their ability to simulate and measure wheelchair propulsion in the laboratory. This was based on a number of criteria: accurate simulation of friction and inertia, reliable and valid measurement capabilities, realistic feedback and ergonomic soundness.

In general, treadmills were found to provide a mechanically realistic simulation of wheelchair propulsion, with the exception of air drag. Other advantages were: limited realistic steering (if no sliders/rubber bands are used), realistic contribution of trunk movement, and being able to use the personal wheelchair. WCE design was found to be more heterogeneous than treadmills. A surplus of different designs was found in the research literature. The WCEs were divided into three groups: roller-, flywheel-, and integrated ergometers. Each approach was found to have its own
advantages and disadvantages (Table 1.2). An advantage shared by all ergometers is the possibility of performing acceleration tasks.

With a vast array of different ergometers found in the literature, it is evident that there is little standardization among research centres. While having options allows researchers to choose the most pertinent device for their specific research questions, the comparability of results and applicability of existing knowledge remains somewhat limited without the standardization of measurement equipment [126]. This exemplifies the need for consensus among institutions on what lab-based research should look like.

The impact of using different WCE designs on propulsion technique and physiological parameters is not known as few comparison studies are available. Moreover, there is currently no overview of what device fits best in what situation. The diversity in equipment is especially troubling as research in this field often relies on small sample sizes, which increases the importance of combining evidence from different studies. In wheelchair sports this is even more apparent as restrictions on data sharing are further limit the availability of information [127]. Studies should therefore always include the specific settings and power output that was used.

In this paper the simulation aspect of an instrument was defined as the realistic simulation of the frictional and inertial components of (translational) wheelchair propulsion. A WCE does not by default simulate the translational inertia of overground propulsion. This implies that in passive systems the inertia of the roller or flywheel has to be matched to the weight of the wheelchair-user combination and active systems need to simulate the required inertia with a brake or motor. Most researchers aimed for a simulation of static friction to simulate rolling friction and a fixed inertia for their system. Some also incorporated the ability to simulate slopes and air drag. The ability to produce a valid and reliable mechanical strain is also closely tied to the measurement capabilities of the device.

It should be noted that the model used as a reference can be seen as a minimal model that describes most of the important forces acting on a wheelchair during straight forward motion. For physiological testing, a minimal model for straight-line wheelchair propulsion is probably sufficient. However, to accurately simulate the biomechanics of real-life situations, especially when turning is involved, requires more advanced models that include additional inertial and frictional properties [45]. From that perspective, most ergometers do give the ability to turn, but the simulation might be inaccurate. Another important factor is the effect of movements by the participants [50]. On a treadmill, these movements realistically influence the
Table 1.2. Generalization of the advantages and disadvantages of different ergometer types

|                        | Treadmills                          | Roller ergometer                  | Flywheel ergometer               | Integrated ergometer                  |
|------------------------|-------------------------------------|-----------------------------------|----------------------------------|----------------------------------------|
| **Advantages**         | Can use personal wheelchair         | Can use personal wheelchair       | Uses commercially available parts| Suited for implementation of different simulation models |
|                        | Mechanically realistic              | Anaerobic/sprint testing feasible | Can be suitable for ergonomic testing | Suitable for ergonomic testing |
|                        | Realistic slope                     |                                   |                                  |                                        |
|                        | Good for fixed speeds               |                                   |                                  |                                        |
| **Disadvantages**      | Additional instruments required     | Internal friction and inertia influences simulation | Cannot use personal wheelchair  | Cannot use personal wheelchair |
|                        | No air drag                         | Potentially high base load        | Inertia is fixed                 | Electronic control system required |
|                        | No acceleration tasks               |                                   | Wheels not independent           |                                        |
|                        | Difficult for fixed power outputs   |                                   | Not always suited for acceleration tasks | Most expensive to build |


wheelchair, but as most ergometers cannot incorporate kinematics in their simulation models, which might impact their validity somewhat.

There is a need for international collaboration to define the standards that WCEs should adhere to. If only the mechanics of the ergometers are considered, there are already large differences to be observed. It is unreasonable to expect that studies where a different mechanical strain is imposed on users can yield similar results. Concurrent validity of different WCEs is a research topic that has not yet been explored. The difference in equipment observed in this study adds to the variation already present in the testing protocols, further increasing diversity in research. All in all, there is a need for a commercially available line-up of wheeled mobility ergometry that allows a standardized protocol of wheeled mobility and testing in the clinical and adapted sports setting around the world [1].

**Conclusion**

The kinetic, kinematic, and physiological components of wheelchair propulsion can be studied in the laboratory on a treadmill or a wide variety of wheelchair ergometers. The simulation that these instruments provide is not always the same. Moreover, different levels of feedback are provided for the subjects. Different calibration methods were reported in the literature. In addition to this, researchers also employed different validation procedures. Often nothing was reported. Many questions about the measurement instruments that are used in studies are still left unanswered. Consequently, the evidence-base of performance enhancing factors and risks associated with wheelchair propulsion is limited due to the diversity in equipment, testing and measurement principles. Comparison studies are needed to evaluate the differences between approaches. There is an increasing need for ergometric standardization and general agreement to enable proper comparison of results.
A review of wheelchair ergometers

References

[1] de Groot S, Vegter RJ, Vuijk C, van Dijk F, Plaggenmarsch C, Sloots M, et al. WHEEL-I: Development of a wheelchair propulsion laboratory for rehabilitation. J Rehabil Med 2014;46:493–503.

[2] van der Woude LHV, Veeger HE, Dallmeijer AJ, Janssen TW, Rozendaal LA. Biomechanics and physiology in active manual wheelchair propulsion. Med Eng Phys 2001;23:713–33.

[3] Vanlandewijck Y, Daly D, Theisen D. Field test evaluation of aerobic, anaerobic, and wheelchair basketball skill performances. Int J Sports Med 1999;20:548–54.

[4] Vinet A, Bernard PL, Poulain M, Varray A, Le Gallais D, Micallef JP. Validation of an incremental field test for the direct assessment of peak oxygen uptake in wheelchair-dependent athletes. Spinal Cord 1996;34:288–93.

[5] Goosey-Tolfrey VL, Leicht CA. Field-based physiological testing of wheelchair athletes. Sports Med 2013;43:77–91.

[6] van der Woude LH, de Groot S, Janssen TW. Manual wheelchairs: Research and innovation in rehabilitation, sports, daily life and health. Med Eng Phys 2006;28:905–15.

[7] Niesing R, Eijskoot F, Kranse R, Den Ouden A, Storm J, Veeger H, et al. Computer-Controlled Wheelchair Ergometer. Med Biol Eng Comput 1990;28:329–38. https://doi.org/10.1007/BF02446151.

[8] Hartung GH, Lally DA, Blancq RJ. Comparison of treadmill exercise testing protocols for wheelchair users. Eur J Appl Physiol 1993;66:362–5.

[9] Rasche W, Janssen TW, Van Oers CA, Hollander AP, Van der Woude LH. Responses of subjects with spinal cord injuries to maximal wheelchair exercise: comparison of discontinuous and continuous protocols. Eur J Appl Physiol 1993;66:328–31.

[10] Van der Woude L, De Groot G, Hollander A, Schenau G, Rozendal R. Wheelchair Ergonomics and Physiological Testing of Prototypes. Ergonomics 1986;29:1561–73. https://doi.org/10.1080/00140138608967269.

[11] Hofstad M, Patterson PE. Modelling the propulsion characteristic of a standard wheelchair. J Rehabil Res Dev 1994;31:129–129.

[12] van Ingen Schenau G, Cavanagh P. Power equations in endurance sports. J Biomech 1990;23:865–81.

[13] Cooper RA. A systems approach to the modeling of racing wheelchair propulsion. J Rehabil Res Dev 1990;27:151–62.

[14] Barbosa TM, Forte PMG, Morais JE, Coelho E. Partial contribution of rolling friction and drag force to total resistance of an elite wheelchair athlete, Institute for Sports Research; 2014.

[15] Coe PL. Aerodynamic characteristics of wheelchairs. vol. 80191. National Aeronautics and Space Administration, Scientific and Technical Information Branch; 1979.

[16] Frank T, Abel E. Drag forces in wheelchairs. Proc Ergon Man Wheelchair Propuls State Art 1993.

[17] Bascou J, Sauret C, Lavaste F, Pillet H. Is bearing resistance negligible during wheelchair locomotion? Design and validation of a testing device. Acta Bioeng Biomech 2017;19.

[18] Voigt ED, Bahn D. Metabolism and pulse rate in physically handicapped when propelling a wheel chair up and incline. Scand J Rehabil Med 1969;1:101–6.
Chapter 1

[19] Bennedik K, Engel P, Hildebrandt G. Der Rollstuhl: experimentelle Grundlagen zur technischen und ergometrischen Beurteilung handbetriebener Krankenfahrzeuge. Schindele; 1978.

[20] van Ingen Schenau GJ. Some fundamental aspects of the biomechanics of overground versus treadmill locomotion. Med Sci Sports Exerc 1980;12:257–61.

[21] Kwarciai AM, Turner JT, Guo L, Richter WM. Comparing handrim biomechanics for treadmill and overground wheelchair propulsion. Spinal Cord 2011;49:457–62.

[22] Hedrick B, Wang YT, Moeinzadeh M, Adrian M. Aerodynamic positioning and performance in wheelchair racing. Adapt Phys Act Q 1990;7:41–51.

[23] Lakomy HK, Campbell I, Williams C. Treadmill performance and selected physiological characteristics of wheelchair athletes. Br J Sports Med 1987;21:130–3. https://doi.org/10.1136/bjsm.21.3.130.

[24] Chénier F, Gauthier C, Gagnon D. Effects of a wheelchair stabilization and safety system on spatiotemporal and kinetic parameters during motorized treadmill propulsion, 2015.

[25] Chénier F, Champagne A, Desroches G, Gagnon DH. Unmatched speed perceptions between overground and treadmill manual wheelchair propulsion in long-term manual wheelchair users. Gait Posture 2018;61:398–402.

[26] Stephens CL, Engsberg JR. Comparison of overground and treadmill propulsion patterns of manual wheelchair users with tetraplegia. Disabil Rehabil Assist Technol 2010;5:420–7.

[27] Mason B, Lenton J, Leicht C, Goosey-Tolfrey V. A physiological and biomechanical comparison of over-ground, treadmill and ergometer wheelchair propulsion. J Sports Sci 2014;32:78–91. https://doi.org/10.1080/02640414.2013.807350.

[28] De Groot S, Zuidergeest M, van der Worde L. Standardization of measuring power output during wheelchair propulsion on a treadmill: pitfalls in a multi-center study. Med Eng Phys 2006;28:604–12.

[29] Vegter RJ, Lamoth CJ, de Groot S, Veeger DH, van der Worde LH. Variability in bimanual wheelchair propulsion: consistency of two instrumented wheels during handrim wheelchair propulsion on a motor driven treadmill. J Neuroengineering Rehabil 2013;10:9-0003-10–9. https://doi.org/10.1186/1743-0003-10-09.

[30] Asato KT, Cooper RA, Robertson RN, Ster J. SMART/sup Wheels: development and testing of a system for measuring manual wheelchair propulsion dynamics. IEEE Trans Biomed Eng 1993;40:1320–4.

[31] van Drongelen S, van der Worde LH, Janssen TW, Angenot EL, Chadwick EK, Veeger DH. Mechanical load on the upper extremity during wheelchair activities. Arch Phys Med Rehabil 2005;86:1214–20.

[32] Gaglio A, Liang J, Daigle S, Hsiao-Weckslers E. Design of a Universal Instrumented Wheelchair Hand Rim. J Med Devices 2016;10:030956.

[33] Goosey-Tolfrey VL, Fowler NE, Campbell IG, Iwinski SD. A kinetic analysis of trained wheelchair racers during two speeds of propulsion. Med Eng Phys 2001;23:259–66.

[34] Limroongreungrat W, Wang YT, Chang L, Geil MD, Johnson JT. An instrumented wheel system for measuring 3-D pushrim kinetics during racing wheelchair propulsion. Res Sports Med 2009;17:182–94.

[35] Mallakzadeh M, Akbari H. Design and Fabrication of an Instrumented Handrim to Measure the Kinetic and Kinematic Information by the Hand of User for 3D Analysis of Manual Wheelchair Propulsion Dynamics. J Med Signals Sens 2014;4:256–66.
[36] Sauret C, Dabonneville M, Couétard Y, de Saint Rémy N, Kauffmann P, Cid M, et al. Zeroing of six-component handrim dynamometer for biomechanical studies of manual wheelchair locomotion. Comput Methods Biomech Biomed Engin 2014;17:416–22.

[37] Guo L, Kwarcia AM, Rodriguez R, Sarkar N, Richter WM. Validation of a biofeedback system for wheelchair propulsion training. Rehabil Res Pract 2011;2011:590780. https://doi.org/10.1155/2011/590780.

[38] Cooper RA. SMARTWheel: From concept to clinical practice. Prosthet Orthot Int 2009;33:198–209. https://doi.org/10.1080/03093640903082126.

[39] Nikooyan AA, Veeger H, Chadwick E, Praagman M, van der Helm FC. Development of a comprehensive musculoskeletal model of the shoulder and elbow. Med Biol Eng Comput 2011;49:1425–35.

[40] Chénier F, Bigras P, Aissaoui R. A new wheelchair ergometer designed as an admittance-controlled haptic robot. IEEEASME Trans Mechatron 2014;19:321–8.

[41] Gagnon DH, Jouval C, Chénier F. Estimating pushrim temporal and kinetic measures using an instrumented treadmill during wheelchair propulsion: A concurrent validity study. J Biomech 2016;49:1976–82.

[42] Dallmeijer AJ, van der Woude LH, Hollander AP, van As HH. Physical performance during rehabilitation in persons with spinal cord injuries. Med Sci Sports Exerc 1999;31:1330–5.

[43] Dallmeijer AJ, Hopman MT, van As HH, van der Woude LH. Physical capacity and physical strain in persons with tetraplegia; the role of sport activity. Spinal Cord 1996;34:729–35.

[44] Brouha L, Krobath H. Continuous recording of cardiac and respiratory functions in normal and handicapped persons. Hum Factors 1967;9:567.

[45] Chénier F, Bigras P, Aissaoui R. A new dynamic model of the wheelchair propulsion on straight and curvilinear level-ground paths. Comput Methods Biomech Biomed Engin 2015;18:1031–43.

[46] Hou Z-C, Lu Y, Lao Y, Liu D. A new trifilar pendulum approach to identify all inertia parameters of a rigid body or assembly. Mech Mach Theory 2009;44:1270–80.

[47] Salimi Z, Ferguson-Pell MW. Ergometers Can Now Biomechanically Replicate Straight-Line Floor Wheelchair Propulsion: Three Models Are Presented, American Society of Mechanical Engineers; 2013, p. V03AT03A045-V03AT03A045.

[48] Theisen D, Francaux M, Fayt A, Sturbois X. A new procedure to determine external power output during handrim wheelchair propulsion on a roller ergometer: a reliability study. Int J Sports Med 1996;17:564–71. https://doi.org/10.1055/s-2007-972896.

[49] Sauret C, Vaslin P, Dabonneville M, Cid M. Drag force mechanical power during an actual propulsion cycle on a manual wheelchair. Irbm 2009;30:3–9.

[50] Sauret C, Vaslin P, Lavaste F, de Saint Remy N, Cid M. Effects of user’s actions on rolling resistance and wheelchair stability during handrim wheelchair propulsion in the field. Med Eng Phys 2013;35:289–97.

[51] Aissaoui R, Arabi H, Lacoste M, Zalzal V, Dansereau J. Biomechanics of manual wheelchair propulsion in elderly: system tilt and back recline angles. Am J Phys Med Rehabil 2002;81:94–100.

[52] Faupin A, Gorce P, Thevenon A. A wheelchair ergometer adaptable to the rear-wheel camber. Int J Ind Ergon 2008;38:601–7. https://doi.org/10.1016/j.ergon.2008.01.008.
Chapter 1

[53] Faupin A, Campillo P, Weissland T, Gorce P, Thevenon A. The effects of rear-wheel camber on the mechanical parameters produced during the wheelchair sprinting of handibasketball athletes. J Rehabil Res Dev 2004;41.
[54] Koontz AM, Yang Y, Price R, Tolerico ML. Multisite comparison of wheelchair propulsion kinetics in persons with paraplegia. J Rehabil Res Dev 2007;44:449.
[55] Wu J. Comparison of Manual Wheelchair Propulsion in “Real-world” and Computer Simulated Environments 2012.
[56] Devillard X, Calmels P, Sauvignet B, Belli A, Denis C, Simard C, et al. Validation of a new ergometer adapted to all types of manual wheelchair. Eur J Appl Physiol 2001;85:479–85.
[57] DiGiovine CP, Cooper RA, Boninger ML. Dynamic calibration of a wheelchair dynamometer. J Rehabil Res Dev 2001;38:41–55.
[58] Brauer RL. An ergonomic analysis of wheelchair wheeling. University of Illinois at Urbana-Champaign, 1972.
[59] Van der Woude L, van Krmen E, Ariens G, Rozendal R, Veeger H. Physical strain and mechanical efficiency in hubcrank and handrim wheelchair propulsion. J Med Eng Technol 1995;19:123–31.
[60] Harrison CS, Grant M, Conway BA. Haptic interfaces for wheelchair navigation in the built environment. Presence Teleoperators Virtual Environ 2004;13:520–34.
[61] Klaesner J, Morgan KA, Gray DB. The Development of an Instrumented Wheelchair Propulsion Testing and Training Device. Assist Technol 2014;26:24–32. https://doi.org/10.1080/10400435.2013.792020.
[62] Martel G, Noreau L, Jobin J. Physiological-Responses to Maximal Exercise on Arm Cranking and Wheelchair Ergometer with Paraplegics. Paraplegia 1991;29:447–56.
[63] Dreisinger TE, Carson WL. Wheelchair Ergometer 1980.
[64] Samuelsson K, Larsson H, Tropp H. A wheelchair ergometer with a device for isokinetic torque measurement. Scand J Rehabil Med 1989;21:205–8.
[65] Guiraud T, Leger L, Long A, Thebault N, Passeleurg P. Vo2 requirement at different displayed power outputs on five cycle ergometer models: a preliminary study. Br J Sports Med 2010;44:449–54. https://doi.org/10.1136/bjsm.2007.044826.
[66] Abbiss C, Quod M, Levin G, Martin D, Laursen P. Accuracy of the Velotron ergometer and SRM power meter. Int J Sports Med 2009;30:107–12.
[67] Davison RR, Corbett J, Ansley L. Influence of temperature and protocol on the calibration of the Computrainer electromagnetically-braked cycling ergometer. Int SportMed J 2009;10:66–76.
[68] Langbein W, Robinson C, Kynast L, Fehr L. Calibration of a new wheelchair ergometer: the wheelchair aerobic fitness trainer. IEEE Trans Rehabil Eng 1993;1:49–58.
[69] Hutzler Y, Vanlandewijck Y, Van Vlierberghe M. Anaerobic performance of older female and male wheelchair basketball players on a mobile wheelchair ergometer. Adapt Phys Act Q 2000;17:450–65.
[70] Koontz AM, Worobey LA, Rice IM, Collinger JL, Boninger ML. Comparison between overground and dynamometer manual wheelchair propulsion. J Appl Biomech 2012;28:412–9.
[71] Burkett LN, Chisum J, Cook R, Norton B, Taylor B, Ruppert K, et al. Construction and validation of a hysteresis brake wheelchair ergometer. Adapt Phys Act Q 1987;4.
A review of wheelchair ergometers

[72] van der Scheer JW, de Groot S, Vegter RJK, Veeger D (HEJ), van der Woude LHV. Can a 15 m-overground wheelchair sprint be used to assess wheelchair-specific anaerobic work capacity? Med Eng Phys 2014;36:432–8. https://doi.org/10.1016/j.medengphy.2014.01.003.

[73] Bambhani YN, Eriksson P, Steadward RD. Reliability of Peak Physiological-Responses during Wheelchair Ergometry in Persons with Spinal-Cord Injury. Arch Phys Med Rehabil 1991;72:559–62.

[74] Bambhani YN, Holland LJ, Steadward RD. Maximal aerobic power in cerebral palsied wheelchair athletes: validity and reliability. Arch Phys Med Rehabil 1992;73:246–52.

[75] Keyser R, Rodgers M, Rasch E. Reliability of cardiorespiratory measurements during wheelchair ergometry. J Rehabil Res Dev 2001;38:423–30.

[76] Finley M, Rodgers M, Rasch E, McQuade K, Keyser R. Reliability of biomechanical variables during wheelchair ergometry testing. J Rehabil Res Dev 2002;39:73–81.

[77] de Groot S, Veeger HEJ, Hollander AP, van der Woude LHV. Influence of task complexity on mechanical efficiency and propulsion technique during learning of hand rim wheelchair propulsion. Med Eng Phys 2005;27:41–9. https://doi.org/10.1016/j.medengphy.2004.08.007.

[78] Veeger HE, van der Woude LH, Rozendal RH. A computerized wheelchair ergometer. Results of a comparison study. Scand J Rehabil Med 1992;24:17–23.

[79] Cooper RA, Ding D, Simpson R, Fitzgerald SG, Spaeth DM, Guo S, et al. Virtual reality and computer-enhanced training applied to wheeled mobility: an overview of work in Pittsburgh. Assist Technol 2005;17:159–70.

[80] Motloch W, Brearley M. A Wheelchair Ergometer for Assessing Patients in their Own Wheelchairs. Prosthet Orthot Int 1983;7:50–1.

[81] de Klerk R, Lutjeboer T, Vegter RJ, van der Woude LH. Practice-based skill acquisition of pushrim-activated power-assisted wheelchair propulsion versus regular handrim propulsion in novices. J Neuroengineering Rehabil 2018;15:56.

[82] Mahajan HP, Dicianno BE, Cooper RA, Ding D. Assessment of wheelchair driving performance in a virtual reality-based simulator. J Spinal Cord Med 2013;36:322–32.

[83] Inman DP, Loge K, Cram A, Peterson M. Learning to drive a wheelchair in virtual reality. J Spec Educ Technol 2011;26:21–34.

[84] Leving MT, Vegter RJ, Hartog J, Lamoht CJ, de Groot S, van der Woude LH. Effects of Visual Feedback-Induced Variability on Motor Learning of Handrim Wheelchair Propulsion. PloS One 2015;10:e0127311.

[85] O’Connor TJ, Fitzgerald SG, Cooper RA, Thorman TA, Boninger ML. Does computer game play aid in motivation of exercise and increase metabolic activity during wheelchair ergometry? Med Eng Phys 2001;23:267–73.

[86] Balestra G, Frassinelli S, Knaflitz M, Molinari F. Time-frequency analysis of surface myoelectric signals during athletic movement. IEEE Eng Med Biol Mag 2001;20:106–15.

[87] Brattgard SO, Grimby G, Hook O. Energy expenditure and heart rate in driving a wheelchair. Scand J Rehabil Med 1970;2:143–8.

[88] Wicks JR, Lymburner K, Dinsdale SM, Jones NL. The use of multistage exercise testing with wheelchair ergometry and arm cranking in subjects with spinal cord lesions. Paraplegia 1977;15:252–61. https://doi.org/10.1038/sc.1977.38.

[89] Glaser RM, Foley DM, Laubach LL, Sawka MN, Suryaprasad AG. An exercise test to evaluate fitness for wheelchair activity. Paraplegia 1979;16:341–9. https://doi.org/10.1038/sc.1978.66.
Chapter 1

[90] Knowlton RG, Fitzgerald PI, Sedlock DA. The mechanical efficiency of wheelchair dependent women during wheelchair ergometry. Can J Appl Sport Sci Can Sci Appl Au Sport 1981;6:187–90.

[91] Skrinar G, Evans W, Ornstein L, Brown D. Glycogen utilization in wheelchair-dependent athletes. Int J Sports Med 1982;3:215–9.

[92] Gimenez M, Predine E, Marchand M, Servera E, Ponz JL, Polu J-M. Implications of lower-and upper-limb training procedures in patients with chronic airway obstruction. Chest 1992;101:279S-288S.

[93] Kerk JK, Clifford PS, Snyder AC, Prieto TE, O’Hagan KP, Schot FK, et al. Effect of an abdominal binder during wheelchair exercise. Med Sci Sports Exerc 1995;27:913–9.

[94] Keyser RE, Rodgers MM, Gardner ER, Russell PJ. Oxygen uptake during peak graded exercise and single-stage fatigue tests of wheelchair propulsion in manual wheelchair users and the able-bodied. Arch Phys Med Rehabil 1999;80:1288–92.

[95] Stewart MW, Melton-Rogers SL, Morrison S, Figon SF. The measurement properties of fitness measures and health status for persons with spinal cord injuries. Arch Phys Med Rehabil 2000;81:394–400.

[96] Ambridge S, Tepper S, Gilbert W, Kyle R, Mundy J, Russo S. Reliability of Submaximal Graded Exercise Testing of Male Subjects with SCI Using a Wheelchair Ergometer. Cardiopulm Phys Ther J 1996;7:3–8.

[97] Glaser RM, Collins SR. Validity of Power Output Estimation for Wheelchair Locomotion. Am J Phys Med Rehabil 1981;60:180–9.

[98] Coutts KD, Rhodes EC, McKenzie DC. Maximal exercise responses of tetraplegics and paraplegics. J Appl Physiol 1983;55:479–82.

[99] Lees A, Arthur S. An investigation into anaerobic performance of wheelchair athletes. Ergonomics 1988;31:1529–37.

[100] Eriksson P, Lofstrom L, Ekblom B. Aerobic power during maximal exercise in untrained and well-trained persons with quadriplegia and paraplegia. Scand J Rehabil Med 1988;20:141–7.

[101] Cooper RA. An exploratory study of racing wheelchair propulsion dynamics. Adapt Phys Act Q 1990;7:74–85.

[102] Lasko-McCarthey P, Davis JA. Effect of work rate increment on peak oxygen uptake during wheelchair ergometry in men with quadriplegia. Eur J Appl Physiol 1991;63:349–53.

[103] Linden AL, Holland GJ, Loy SF, Vincent WJ. A physiological comparison of forward vs reverse wheelchair ergometry. Med Sci Sports Exerc 1993;25:1265–8.

[104] Kotajarvi BR, Basford JR, An K-N, Morrow DA, Kaufman KR. The effect of visual biofeedback on the propulsion effectiveness of experienced wheelchair users. Arch Phys Med Rehabil 2006;87:510–5.

[105] Bloemen MA, de Groot JF, Backx FJ, Westerveld RA, Takken T. Arm Ergometry versus Wheelchair: Propulsion for Testing Aerobic Fitness in Wheelchair. Med Sci Sports Exerc 2014;46:644.

[106] Yim SY, Cho KJ, Park CI, Yoon TS, Han DY, Kim SK, et al. Effect of wheelchair ergometer training on spinal cord-injured paraplegics. Yonsei Med J 1993;34:278–86.

[107] Mulroy SJ, Gronley JK, Newsam CJ, Perry J. Electromyographic activity of shoulder muscles during wheelchair propulsion by paraplegic persons. Arch Phys Med Rehabil 1996;77:187–93.
A review of wheelchair ergometers

[108] Goosey V. Symmetry of the elbow kinematics during racing wheelchair propulsion. Ergonomics 1998;41:1810–20.

[109] Mason BS, Lemstra M, van der Woude LH, Vegter R, Goosey-Tolfrey VL. Influence of wheelchair configuration on wheelchair basketball performance: Wheel stiffness, tyre type and tyre orientation. Med Eng Phys 2015;37:392–9.

[110] Tam EW, Mak AF, Lam WN, Evans JH, Chow YY. Pelvic movement and interface pressure distribution during manual wheelchair propulsion. Arch Phys Med Rehabil 2003;84:1466–72.

[111] Qi L, Wakeling J, Grange S, Ferguson-Pell M. Effect of velocity on shoulder muscle recruitment patterns during wheelchair propulsion in nondisabled individuals: Pilot study. JRRD 2012;49:1527–36.

[112] Kurt M, Geyik H, Mutlu B, Tatar Y, Nart E. Design, prototype and experimental evaluation of a wheelchair treadmill. Acta Mech Autom 2008;2:71–5.

[113] Vanlandewijck YC, Verellen J, Beckman E, Connick M, Tweedy SM. Trunk strength effect on track wheelchair start: implications for classification. Med Sci Sports Exerc 2011;43:2344–51. https://doi.org/10.1249/MSS.0b013e318223af14.

[114] Hwang S, Kim S, Son J, Kim Y. Torque and power outputs on different subjects during manual wheelchair propulsion under different conditions. J Korean Phys Soc 2012;60:540–3.

[115] Eydieux N, Hybois S, Siegel A, Bascou J, Vaslin P, Pillet H, et al. Changes in wheelchair biomechanics within the first 120 minutes of practice: spatiotemporal parameters, handrim forces, motor force, rolling resistance and fore-aft stability. Disabil Rehabil Assist Technol 2019;1–9.

[116] Hybois S, Siegel A, Bascou J, Eydieux N, Vaslin P, Pillet H, et al. Shoulder kinetics during start-up and propulsion with a manual wheelchair within the initial phase of uninstructed training. Disabil Rehabil Assist Technol 2018;13:40–6.

[117] Vegter RJ, Hartog J, de Groot S, Lamoth CJ, Bekker MJ, van der Scheer JW, et al. Early motor learning changes in upper-limb dynamics and shoulder complex loading during handrim wheelchair propulsion. J Neuroengineering Rehabil 2015;12:1.

[118] Noonan V, Dean E. Submaximal exercise testing: clinical application and interpretation. Phys Ther 2000;80:782–807.

[119] Thompson WR, Gordon NF, Pescatello L, American College of Sports Medicine, American College of Sports Medicine. Guidelines for exercise testing and prescription. Eight EdnPhiladelphia Lippincott Williams Wilkins 2010.

[120] Eerden S, Dekker R, Hettinga FJ. Maximal and submaximal aerobic tests for wheelchair-dependent persons with spinal cord injury: a systematic review to summarize and identify useful applications for clinical rehabilitation. Disabil Rehabil 2018;40:497–521.

[121] Stoboy H, Rich BW, Lee M. Workload and energy expenditure during wheelchair propelling. Paraplegia 1971;8:223–30. https://doi.org/10.1038/sc.1970.41.

[122] Hutzler Y. Anaerobic fitness testing of wheelchair users. Sports Med Auckl NZ 1998;25:101–13.

[123] Glaser RM, Sawka MN, Brune MF, Wilde SW. Physiological responses to maximal effort wheelchair and arm crank ergometry. J Appl Physiol 1980;48:1060–4. https://doi.org/10.1152/jappl.1980.48.6.1060.
Chapter 1

[124] Krops LA, Albada T, van der Woude LH, Hijmans JM, Dekker R. Anaerobic exercise testing in rehabilitation: A systematic review of available tests and protocols. J Rehabil Med 2017;49:289–303. https://doi.org/10.2340/16501977-2213.

[125] Hutzler Y, Grunze M, Kaiser R. Physiological and dynamic responses to maximal velocity wheelchair ergometry. Adapt Phys Act Q 1995;12:344–61.

[126] Gayle G, Davis G, Pohlman R, Glaser R. Track wheelchair ergometry: effects of handrim diameter on metabolic responses. Adapt. Phys. Act., Springer; 1990, p. 101–7.

[127] Goosey-Tolfrey V, Paulson T. Applying strength and conditioning practices to athletes with a disability. Routledge Handb. Strength Cond., Routledge; 2018, p. 50–60.
