Cost-effective power assessment in paralympic wheelchair athletes

Evaluación económica de la potencia en atletas paralímpicos en silla de ruedas

Authors

Carlos Talayero [1]
Ignacio López-Moranchel [2]
Raúl Díaz-López [2]
Olga López-Torres [2]

[1, 2] Universidad Europea de Madrid (España)

Corresponding author:
Carlos Talayero
carlosalberto.talayero@universidadeuropea.es

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Resumen

Introducción: la medición de la potencia en el deporte es clave para mejorar el rendimiento, pero en el ámbito paralímpico existen limitaciones tecnológicas y económicas para su evaluación.
Objetivo: desarrollar y validar un método de estimación de potencia para atletas en silla de ruedas, especialmente aplicable durante entrenamientos en banco de rodillos, sin necesidad de dispositivos costosos.
Metodología: se realizaron pruebas de desaceleración (coast-down test) en pista y banco de rodillos, a diferentes velocidades (10, 15 y 20 km/h), midiendo distancia recorrida y aceleración. Se calcularon fuerza resistente, potencia, y esfuerzo en el aro de impulsión usando ecuaciones de dinámica vehicular.
Resultados: los valores obtenidos en pista mostraron una desviación del 3,8% respecto a los datos medidos por acelerómetro, lo que valida la metodología. En banco de rodillos, los resultados coinciden con los de pista para velocidades menores a 12 km/h. A velocidades superiores, se observan diferencias atribuibles a la resistencia aerodinámica.
Discusión: los hallazgos coinciden con estudios previos sobre la resistencia al rodamiento y la dinámica del desplazamiento en silla de ruedas. La metodología permite ajustar el entrenamiento al representar de forma realista el esfuerzo.
Conclusiones: se ofrece una solución económica y fiable para estimar la potencia en atletas paralímpicos, con aplicabilidad directa en la planificación del entrenamiento.

Palabras clave

Atletas en silla de ruedas; potencia mecánica; rendimiento; resistencia a la rodadura.

Abstract

Introduction: power measurement in sports is essential to enhance performance, but technological and economic limitations hinder its application in Paralympic contexts.
Objective: to develop and validate a power estimation method for wheelchair athletes, particularly during training on roller benches, without the need for expensive devices.
Methodology: coast-down tests were carried out on track and roller bench at different speeds (10, 15 and 20 km/h), measuring stopping distance and acceleration. Drag force, power, and handrim effort were calculated using vehicle dynamics equations.
Results: track values deviated only 3.8% from accelerometer data, validating the method. On roller benches, values matched those of track up to 12 km/h; at higher speeds, aerodynamic resistance caused noticeable deviations.
Discussion: findings align with previous studies on rolling resistance and wheelchair dynamics. The methodology allows realistic representation of effort during training.
Conclusions: a cost-effective and reliable solution for power estimation in Paralympic athletes is provided, with direct applications in training planning.

Keywords

Performance; power; rolling resistance; wheelchair athletes.

Introduction

In recent years, the measurement of power has become a pivotal aspect in evaluating and enhancing performance in physical activity and sports. Power measurement is extensively utilized in various sports to optimize training and performance outcomes (Bergstrom et al., 2014; Borszcz et al., 2018; Hill, 1993; Sitko et al., 2022). For example, in cycling, devices such as encoders and strain gauges are widely used to measure power output and to assess an athlete's functional threshold power, which has been shown to correlate with endurance performance (Borszcz et al., 2018; Sitko et al., 2022). Similarly, the critical power concept, which represents the highest sustainable power output over a given period, has been a focal point of numerous studies aiming to understand an athlete's capacity and performance (Bergstrom et al., 2014; Hill, 1993)

Despite the abundance of commercial devices available for conventional sports, there is a significant gap when it comes to less prevalent sports, particularly Paralympic wheelchair athletics (track and marathon according to the International Paralympic Committee, Section III, Rule 14). Recent reviews have emphasized the growing role of biomechanical technologies to optimize sports performance and inform individualized training strategies, analyzing systematically biomechanical variables, highlighting the importance of kinematic and kinetic assessment to enhance technical execution and reduce injury risk (Monterrosa Quintero et al., 2025).

There are some mobile applications that allow the recording of power, based on the mass, acceleration and speed of a body, although this is not possible for static roller benches used in wheelchair training. The existing devices for direct power measurement in these sports are not only scarce but also prohibitively expensive, such as *Kickr Endurance Resistance Attachment*. This gap underscores the need for more accessible and cost-effective methodologies to measure power in Paralympic sports.

The primary objective of this study is to develop and validate a methodology for calculating the working power of wheelchair athletes, especially during training, on roller benches, who lack access to specialized measurement devices such as torque benches. The methodology involves measuring the resistive force against the movement of the wheelchair in the track (coast down) where direct measurement of dynamic parameters such as acceleration and speed is possible to validate the results, and comparing these values with data measured in a roller bench, where direct power measurement is not possible without external devices (torquemeter attached to the roller bench).

Rolling resistance, a critical factor affecting wheelchair propulsion, has been extensively studied in recent literature. Various methods have been employed to evaluate rolling resistance, including dynamometer-based coast-down tests and inverse dynamics simulations (Kwarciak et al., 2009; Ott et al., 2021; Ott & Pearlman, 2021; Rooijmans, 2021; Teran & Ueda, 2015). These studies highlight the complexities involved in accurately measuring rolling resistance and its impact on manual wheelchair propulsion. For instance, a study (Ott & Pearlman, 2021) conducted a scoping review of rolling resistance testing methods, emphasizing the diverse factors that influence rolling resistance in wheelchairs. On the other hand, exist studies that further explored the calculation of rolling resistance from the kinematics and hand rim forces of wheelchair users, providing insights into the biomechanical aspects of wheelchair propulsion (Rooijmans, 2021). Other study (Kwarciak et al., 2009). (Teran & Ueda, 2015). These contributions are essential for developing accurate and reliable methods to assess and improve wheelchair performance.

The hypothesis of this study is that, through the equation of drag of a wheelchair obtained from a coast-down test at, at least, two speeds, the power used by the athlete at each speed can be obtained with enough reliability for the common wheelchair velocities (below 30 km/h) in a roller bench, and the aim of this study was to develop and validate a practical methodology for estimating the effective power output of wheelchair athletes using only low-cost tools. It is noticeable that the friction will vary depending on the track, the tires setup and the roller bend material and diameter so the power will be different for each case. The approach is based on vehicle dynamics equations and coast-down tests conducted on both track and roller bench, enabling comparison between theoretical models and empirical data, and offering a useful framework for practical training in Paralympic sport.

Method

This was a quantitative, correlational, and exploratory study aimed at validating a biomechanical method for power estimation in wheelchair athletes using non-invasive and low-cost tools. The methodological strategy involved coast-down testing and dynamic calculations to compare theoretical and empirical results under different conditions.

Participants

The study involved a single experienced female wheelchair athlete (T54 category) with a total system mass (athlete + wheelchair) of 66 kg. The rear axle supported 60 kg and the front wheel 6 kg. The same wheelchair was used in all tests, equipped with 14-inch handrims and 70 cm wheels.

Procedure

Two test environments were used: outdoor athletics track and a roller bench with adjustable resistance. For the track test, the athlete accelerated to 10 km/h and 15 km/h and then coasted to a stop on a straight section, avoiding curves to eliminate cornering resistance. Speed was measured with a Sigma BC 12.0 speedometer and tire pressure was maintained at 80 psi (rear) and 60 psi (front).

On the roller bench, the same wheelchair configuration was used, with tests performed at 10, 15, and 20 km/h. Stopping distances were measured in terms of wheel revolutions via video analysis. Two resistance levels were tested: "horizontal" (low) and "slope" (high), adjusted using magnetic and screw systems.

Instruments

- Sigma BC 12.0 cycle computer (Sigma-Elektro GmbH) for speed measurement.
- Topeak Shuttle Gauge for tire pressure.
- Sony Xperia V with "Accelerometer Meter" app (sampling at 100 Hz) for acceleration data.
- Standard roller bench with adjustable resistance via magnets and mechanical screws.

Data Analysis

There are numerous methods to obtain the resistance to movement of a moving object (vehicle, machinery, wheelchair, etc.). For athletic wheelchairs, which typically have three wheels, both direct and indirect measurement methods have been employed, each with specific limitations and considerations (Kwarciak et al., 2009; Ott, 2020; Ott et al., 2021; Ott & Pearlman, 2021; Rooijmans, 2021; Teran & Ueda, 2015). Given that the objective is to provide the athlete with a "low cost" methodology, the coast down test will be used, consisting of letting the wheelchair roll freely from a given speed to its total stop, measuring the distance traveled in a horizontal plane.

To avoid the influence of curves on a standard athletics track, the test speeds were set at 10 km/h and 15 km/h. These speeds were measured using a cycling speedometer (Sigma BC 12.0, Sigma-Elektro GmbH) attached to a rear wheel. Higher speeds were not considered because the stopping distance would exceed the length of a track's straight section, which would introduce the additional variable of cornering rolling resistance.

In this study, coast down tests on the track were performed at speeds of 10 km/h and 15 km/h with rear tire pressures of 80 psi (measured with a Topeak Shuttle Gauge, Topeak ©) and a front tire pressure of 60 psi. The total mass of the wheelchair and athlete was 66 kg, with a weight distribution of 60 kg on the rear axle and 6 kg on the front axle. 14 inches rings are mounted on the wheels.

This test methodology allows for the assessment of tire pressure influence on rolling resistance for different surface types, as well as the impact of other geometric parameters that affect rolling (e.g., camber and toe), that is out of the scope of this investigation.

a. Wheelchair rolling resistance in roller bench

Similarly to the track tests, the distance (in wheel revolutions) from the reference speeds (10 km/h, 15 km/h and 20 km/h) to a complete stop was recorded. To ensure accuracy, the number of wheel turns was determined via video recording. Since the problem of distance travelled and cornering does not exist on the roller bench, an additional measurement at 20 km/h is added to increase the accuracy of the regression curve. The results obtained with two points (10 and 15 km/h) will be compared to the ones obtained with three points (20 km/h added).

For the same wheelchair configuration as in the track (same mass and tire pressure), coast down tests were also conducted on a rolling bench with two resistance settings that represent typical slopes that can be found during a marathon. The "horizontal" setting was used as the reference to be compared with the track test, while the "slope" setting was established according to the maximum achievable effort of the athlete at 20 km/h. These resistance adjustments were made using the bench's screws and magnets. For each set up, two repetitions were done.

b. Vehicular dynamics equations

The general equation of drag of a moving vehicle can be expressed as follows:

$$Rt = Rg + Rr + Ra$$

Where Rt is y total resistance (N), Rg the gravitational drag (N), Rr the Rolling resistance (N) and Ra the aerodynamical drag (N).

In turn, each of the resistances can be expressed as follows:

$$Rg = m * g * \sin \alpha$$

$$Rr = fr * m * g * \cos \alpha$$

$$Ra = \frac{1}{2} * \rho * v^2 * Cx * Af$$

Where m is the mass (kg), g the gravity acceleration (9,81 m/s2), α the angle of the track (º), fr the rolling coefficient that usually depends on the velocity (no units), ρ the air density (kg/m3), v the body – air relative speed (m/s), Cx the longitudinal drag coefficient (no units) and Af the frontal area of the moving object (m2).

On the other hand, the kinetic energy of a moving body is expressed as:

$$E_k = \frac{1}{2} * m * v^2$$

The energy (measured in Joules) is also the result of multiplying the acting force by the distance traveled (work). For this study, and considering the low speeds achieved, we can assume that the total drag force remains nearly constant during the braking event. Given this, the force can be determined once the energy (derived from the mass and speed) and the stopping distance are known.

For a rotating solid, the energy can be written as:

$$E_k = \frac{1}{2} * I * \omega^2$$

Where I is the inertia moment (kg.m2) and ω is the rotating speed (rad/s). For the bench tests, the inertia of all the rotating masses should be considered (wheels plus the roller). For the current study, a mass of 13 kg is measured with a diameter of 115 mm for the rotating cylinder of the bench, and 1.2 kg for the wheels.

Finally, the power (W) required to maintain a given speed can be calculated by multiplying the force (N) by the speed (m/s).

Using the forces obtained for different speeds and rolling conditions (track and bench), F-v (force-speed) and P-v (power-speed) diagrams can be plotted, and polynomial equations can be derived for each scenario. The diagrams are valid for the tested data: mass, inertia, track-tire friction (depends on the tire, the track, the inflation pressure, the ambient humidity and the temperature mainly) and weight distribution; but the methodology allows a fast update for new conditions.

c. Correlation

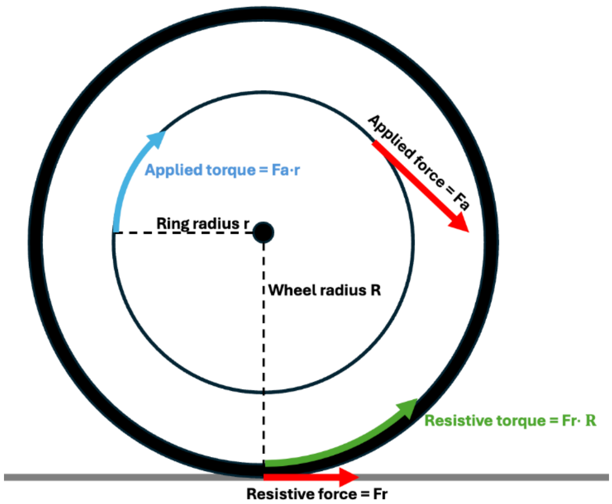
To validate the data obtained from the track tests, the acceleration of the wheelchair is measured at 10 km/h and 15 km/h with a SONY XPERIA V device using the app "Accelometer Meter" at a rate of 100 Hz.

With the acceleration and the mass, the force can be calculated to, finally, obtain the power by multiplying the force times the speed.

Once validated the methodology with the track calculations with the real power data, they are compared to the bench calculations, assuming the differences due to friction and aerodynamic effects.

However, it is necessary to determine the force the athlete applies to the drive ring at each resistance and speed. As shown in figure 1, the resistive torque on the wheel is equated to the torque applied on the ring. Given that torque (N·m) is equal to force (N) multiplied by distance (m), the force on the ring (Fa) can be obtained by knowing the distances (radius of the wheel and radius of the ring).

Figure 1. Forces and torques diagram on the wheel



In this study, the wheel has a diameter of 70 cm and the ring has a diameter of 14 inches. Although commercial units are used for denomination, calculations are performed using the International System of Units.

Results

Table 1 presents the mean values for the two measurements for each coast down test on track (distance travelled from 10 and 15 km/h) and on the roller bench (distance and wheel turns from 10, 15 and 20 km/h) and the calculations used to determine the drag force, power, torque on the wheel, and the necessary force applied in the ring (Fa).

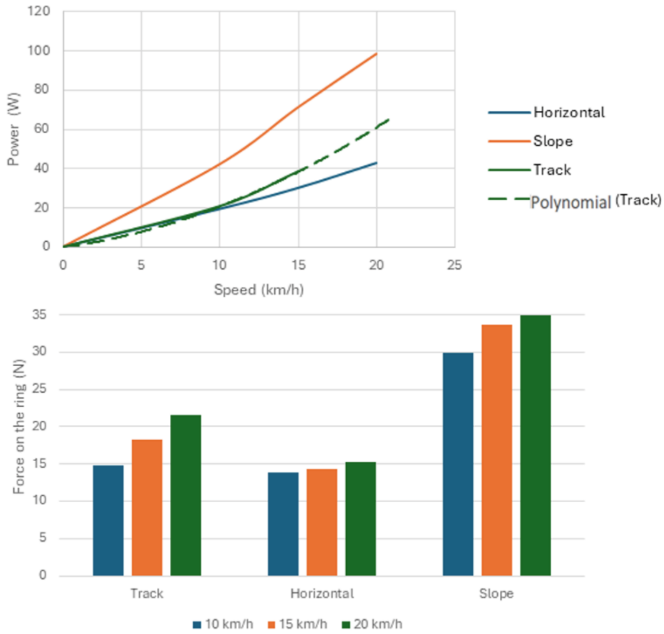
Table 1. Measured results and calculated data for the rolling resistance calibration (coast down on track)

Track test						
Speed (km/h)	Distance travelled (m)	Kinetic energy (J)	Drag (N)	Power (W)	Wheel torque (N.m)	Force on ring (N)
10	34	255	7,5	20,8	2,6	14,7
15	62	573	9,2	38,5	3,2	18,2
Bench test						
Horizontal						
Speed (km/h)	Distance travelled (m) / Wheel turns before stop	Kinetic energy (J)	Drag (N)	Power (W)	Wheel torque (Nm)	Force on ring (N)
10	8,4 / 3,8	59	7	19	2	14
15	18,1 / 8,25	132	7	30	3	14
20	30,2 / 13,75	234	8	43	3	15
Slope						
Speed (km/h)	Distance travelled (m) / Wheel turns before stop	Kinetic energy (J)	Drag (N)	Power (W)	Wheel torque (Nm)	Force on ring (N)

10	3,8 / 1,75	59	15	42	5	30
15	7,7 / 3,5	132	17	71	6	34
20	13,2 / 6	234	18	99	6	35

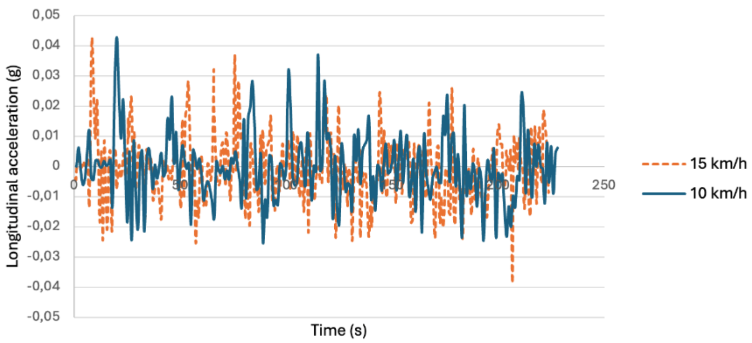
From the calculated data and using second-order polynomials to approximate the data to the parabolic behavior according to Equation (1), the power for each speed is obtained (see figure 2).

Figure 2. Upper: Power vs speed plot for track and bench tests. Lower: Force on the ring for different training conditions and speeds



In figure 3 the results for the registered acceleration values are plot. It is noticeable that the value is not constant due to the impulses of the athlete, with a frequency between 1,2 and 1,5 Hz (resulting in a cadence between 72 and 90 beats per minute).

Figure 3. Longitudinal acceleration of the wheelchair for different speeds



Obtaining the root mean square (RMS) values for both signals is obtained that at 10 km/h the RMS value of the acceleration is 0,11 m/s^2 while at 15 km/h it is 0,137 m/s^2. Multiplying these values by the total mass (66 kg) and by the speed, they give a power of 19,9 W at 10 km/h and 37,7 W at 15 km/h.

Track coast-down tests at 10 and 15 km/h showed consistent kinetic energy losses and drag force estimations. The calculated power values were 20.8 W and 38.5 W, respectively. These were validated by accelerometry, which yielded 19.9 W and 37.7 W—an error margin of 3.8% and 2% for the studied athlete and test conditions.

Discussion

The primary objective of this study was to develop and validate a practical methodology for calculating the working power of wheelchair athletes using coast down tests and direct power readings. This approach aims to provide a reliable and accessible means of power assessment in track for athletes in wheelchair sports. As can be seen in table 1 and in figure 2, the power calculated from the coast down data is very similar to the one obtained by the acceleration measurement: for 10 km/h, the theoretical value is 20,8 W and the measured is 19,9 W (3,8%) while at 15 km/h the difference is from 38,5 W to 37,7 W (2%).

As can be seen in figure 2 when comparing the track data and the roller bench data, the values of the bench in the horizontal condition match the track data for low speeds (up to 12 km/h). For higher speeds, the following factors can affect the difference between the values: variable rolling resistance and aerodynamic effects.

Although the rolling resistance usually depends on the square of the speed according to empirical models, its value is extremely low (around $0,015+7.10^{-6}.v^2$) (Jazar, 2008)to cause a difference of 20 W (a 33% deviation) at 20 km/h. On the other hand, the aerodynamics drag is increased by a factor of almost 3 between 12 km/h and 20 km/h (considering that the drag depends on the square of the speed according to equation (4)) what would explain most of that difference for the studied athlete. For different athletes the aerodynamic effects will vary depending specially on their size and position on the wheelchair, that is generally affected for particular injuries in paralympic sports.

With the results obtained, the studied athlete could adjust the roller bench resistance for each training cycle to represent reality in a more accurate way. For example, by adjusting the brake to achieve 10 wheel turns before stopping at 20 km/h in the bench (what implies a drag increase of 3 N approximately), the result of the power will be 59 W, that matches the values on the track.

Regarding the applied force, it will provide information related to the training loads for arm exercises. In figure 3, the values required by the athlete are shown.

The results of this study are aligned with previous research on the biomechanical and physiological evaluation of wheelchair athletes. Furthermore, the relevance of assessing both aerobic and anaerobic performance using accessible and structured training approaches has been highlighted in other populations as well, demonstrating significant physiological improvements by following a six-week speed endurance training program (Kaewkamad et al., 2025), supporting the importance of quantifying and optimizing physical output through targeted interventions. A review highlighted the importance of considering ergonomics in the design of sports wheelchairs to optimize athlete performance, emphasizing how factors such as wheel configuration and weight significantly influence rolling resistance and, consequently, the power generated (Ausens Lafuente, 2015). These observations reinforce the validity of the methodological approach adopted in this work, which evaluates the impact of rolling resistance through controlled tests both on the track and on roller benches. Similarly, the need to develop parametric models that enable personalized wheelchair configurations based on the athlete's biometric and biomechanical characteristics is stablished (Moncholí Marco, 2020). In this regard, the methodology presented in this study offers an accessible and adaptable tool to adjust resistance settings on the roller bench, contributing to greater training customization. Lastly, the importance of reproducing competition conditions in controlled environments was previously explored by analyzing the utility of ergometers designed specifically for wheelchair athletes (Brizuela et al., 2002). The results of this work complement these findings, demonstrating that coast-down tests combined with dynamic calculations can provide accurate estimates of the power generated by athletes, even without expensive equipment.

Conclusions

The methodology developed in this study provides a practical approach for estimating power and force applied by wheelchair athletes in various conditions. For the current study conditions, and considering the limitation of a single athlete, the coast-down tests, combined with dynamic calculations, offer reliable means of assessing the performance and efficiency of athletic wheelchairs with errors below 4% for track tests, which is crucial for optimizing training and competition strategies in Paralympic sports.

Moreover, the ability to correlate power measurements with dynamic performance data provides a valuable tool for athletes and coaches. It enables more accurate adjustments to equipment and training regimens, potentially leading to improved performance outcomes.

Future studies should consider incorporating air drag into the model to enhance accuracy, especially at higher speeds. Additionally, expanding the sample size and including a broader range of athletes with different capabilities would help to validate the methodology further and ensure its applicability across diverse athletic populations.

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Authors' and translators' details:

Carlos Talayero	carlosalberto.talayero@universidadeuropea.es	Author and Translator
Ignacio López-Moranchel	Ignacio.lopez@universidadeuropea.es	Author
Raúl Díaz-López	Raul.diaz@universidadeuropea.es	Author
Olga López-Torres	Olga.lopez@universidadeuropea.es	Author