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**Special edition**

# A methodology for dynamic calibration of inertial dynamometers for wheelchairs

## Uma metodologia para calibração dinâmica de dinamômetros inerciais para cadeiras de rodas

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## ABSTRACT

Every day, wheelchair users face countless obstacles that make their social inclusion a real challenge. In this way, it is important that assistive technologies be constantly developed and improved. An example is the dynamometer, which helps in training to characterize the performance of the wheelchair user. In this work, we present a methodology for the dynamic calibration of an inertial dynamometer for wheelchair users, which aims to assist in the rehabilitation and to enable them to perform day-to-day activities independently. The dynamometer is placed on a structure elevated in relation to the ground, at a known height. At the upper end, a wire is attached to the dynamometer cylinder and at the lower end, a known weight is used to enforce acceleration on the cylinder. The wheelchair is placed on top of the cylinder with known different weights corresponding to the user's weight for each repetition of the experiment. The wire is then wrapped around the cylinder and the object is dropped freely, rotating the cylinder. The measurement of the system acceleration is given by an encoder. Data collected in the tests enable to get the system inertial characteristics for each applied weight, allowing to set calibration curve and to evaluate the performance when the propulsion in the dynamometer is imposed by the wheelchair user. This work describes the methodology proposed for calibrating the complete device allowing the quantification of measured values such as power, torque and speed imposed by the user. The calibration steps can be easily reproduced at a low cost and very good performance.

**Keywords**: Assistive technologies; Inertial dynamometer; Physical evaluation of wheelchair users; Physical conditioning of wheelchair users; Quality of live for wheelchair

## RESUMO

Todos os dias, os cadeirantes enfrentam inúmeros obstáculos que tornam sua inclusão social um verdadeiro desafio. Dessa forma, é importante que as tecnologias assistivas sejam constantemente desenvolvidas e aprimoradas. Um exemplo é o dinamômetro, possibilita a avaliação do desempenho, o que pode ser utilizado no treinamento de cadeirantes. Neste trabalho, é apresentado uma metodologia para calibração dinâmica de um dinamômetro inercial para cadeirantes, que visa auxiliar no condicionamento físico bem como mensurar o seu desempenho. O dinamômetro é colocado sobre uma estrutura elevada em relação ao solo, a uma altura conhecida. Na extremidade superior, um fio é preso ao cilindro do dinamômetro e, na extremidade inferior, um peso conhecido é usado para forçar a aceleração do cilindro. A cadeira de rodas é colocada no topo do cilindro com pesos conhecidos diferentes, correspondentes ao peso do usuário a cada repetição do experimento. O fio é então enrolado em torno do cilindro e o objeto é solto livremente, girando o cilindro. A medição da aceleração do sistema é dada por um *encoder*. Os dados coletados nos testes permitem obter as características inerciais do sistema para cada peso aplicado, permitindo definir a curva de calibração e avaliar o desempenho quando a propulsão no dinamômetro é imposta pelo cadeirante. Este trabalho descreve a metodologia proposta para calibrar o dispositivo completo permitindo a quantificação dos valores medidos como potência, torque e velocidade imposta pelo usuário. As etapas de calibração podem ser facilmente reproduzidas com baixo custo e bom desempenho.


**Palavras-chave**: Tecnologias assistivas; Dinamômetro inercial; Avaliação física de cadeirantes; Condicionamento físico de cadeirantes; Qualidade de vida para cadeirantes

# 1 INTRODUCTION

According to the last census prepared by the Brazilian Institute of Geography and Statistics, 6.7% of the Brazilian population has some type of disability (Instituto Brasileiro de Geografia e Estatística [IBGE], 2010). This highlights the importance of the development of low-cost assistive technologies for this group of people and justifies the design of a compact inertial dynamometer for wheelchair users, which helps health professionals in the diagnosis of diseases and which enables rehabilitation and also the development of motor skills of wheelchair users.

The World Health Organization defined that quality of life is the perception of the person in relation to their life and their value systems, as well as in relation to their goals, expectations and concerns (The World Health Organization Quality of Life [WHOQOL], 1995). Zuchetto and Castro (2002), defined that the quality of life is related to the state of health, longevity, job satisfaction, family relationships and disposition for life.

Wheelchair users are gradually gaining spaces that allow an improvement in their quality of life, such as: insertion in the labor market, accessible buildings and public roads, accessible transportation, among others (Cardoso, 2011). However, there are still several obstacles that prevent the full exercise of citizenship by these individuals. Lima, Carvalho, Santos and Marinho (2013) recognized that physical barriers can be configured as agents of social exclusion for wheelchair users to the extent that they prevent their attendance in environments for this reason.

Physical capacity is also directly associated with the quality of life of wheelchair users. The low capacity for physical resistance coexists with an increased number of medical complications and greater dependence during daily activities. This decrease in physical capacity can lead to secondary conditions such as obesity, gastrointestinal problems, respiratory complications, muscle pain and others. Coronary heart disease is also highly related to physical inactivity along with obesity, diets high in fat, smoking and stress (Vieira, 2012, p. 8).

Considering the challenges faced by wheelchair users, this work aims to propose a methodology for calibrating an inertial dynamometer dedicated to wheelchair users The inertial dynamometer is a build simple and low-cost equipment, that could be used to assess physical fitness and conditioning of professional wheelchair athletes, since sport is seen as a means of significant social improvement. Then, the inertial dynameter could contribute in the future to improve quality of life of wheelchair users.

## 2 METHODOLOGY

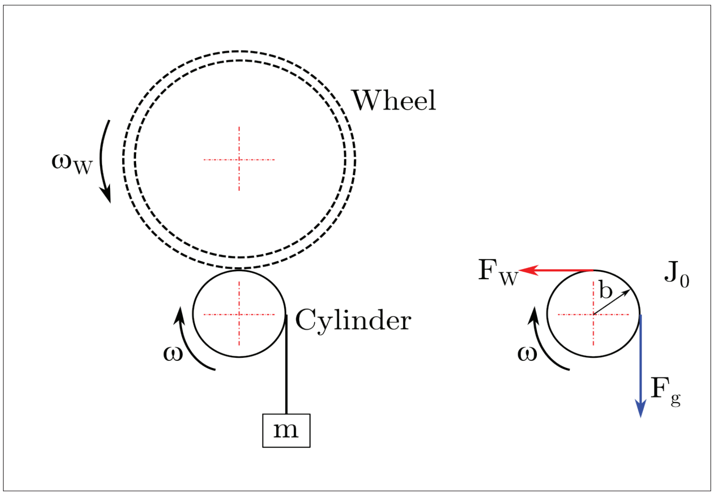
Inertial dynamometers are advantageous because they are easy to use, as they do not require additional control and cooling and provide torque and mechanical power curves during the test. These dynamometers are composed of inertia cylinders, rotated by the propulsion source with driving wheels directly coupled to the dynamometer (Martins, 2006).

In this section, the theoretical model is described, with the definition of the main variables that need to be investigated. Next, the physical model is presented, with the dimensions and measurement devices.

## 2.1 Theoretical model

The practical experiment of calibrating the measurement system consists of using the gravitational potential energy to rotate the inertia cylinder (Figure 1). When the wheelchair is placed on top of the cylinder, its wheels start to rotate, accelerating until a top speed is reached. Here, only the cylinder dynamics is mathematically modeled and thus the wheelchair can be replaced in the model by the friction force FW, what is a force that acts in a direction contrary to the cylinder rotation.

Figure 1 – Schematic diagram of forces and angular velocity on the cylinder




Source: Authors (2023)

The equation of motion of the rotating cylinder can be derived using the moment balance on the cylinder (or the Laplace equations) to:

$$J_0 \omega + B_n \omega = T - T_W \quad (1)$$

where $J_0$ is the cylinder mass inertia around the rotary axis, $B_n$ is the dissipative coefficient (friction at the cylinder bearings), $T$ is the torque applied by the suspended mass, and $T_n$ is the wheel resisting torque. This last term represents the resistance of the wheelchair as a whole, and should increase with the weight imposed by the subject. It is computed as a product from the friction force and the cylinder radius *b*:

$$T_W=F_W\, b \tag{2}$$

The driving torque is applied here by the suspended mass, so it is computed as:

$$T=bF_g=b\, m\, g \tag{3}$$

where m is the suspended mass and g is the gravity acceleration.

In the above equations, the cylinder inertia can be computed and determined experimentally with a small error. The coefficient $B_n$ is also small when using bearings. It can be obtained experimentally by applying the driving torque without the wheelchair. Considering that the values of variables *b*, *m*, *g* are also known, then the wheel torque is the incognita that needs to be found, as function of the cylinder angular speed.

If the angular speed variation in time is also known, then the wheel torque can be computed by:

$$T_W=mgb-J_0\, \omega\, -B_n\, \omega \tag{4}$$

from which the friction force on the wheel can be computed using Eq. (2). Also, from Eq. (4), the power associated with the wheel torque can be estimated by the product between the wheel torque and the angular speed:

$$P_W=T_W\, \omega \tag{5}$$

where the power is given in Watt if the angular speed is expressed in rad/s.

In the present work, the angular speed, measured using the encoder, is approximated by a cubic polynomial, so that:

$$\omega \cong \omega_{ap}=a_0+a_1\, t^1+a_2\, t^2+a_3\, t^3 \quad (6)$$

and the angular acceleration is then easily obtained by derivation:

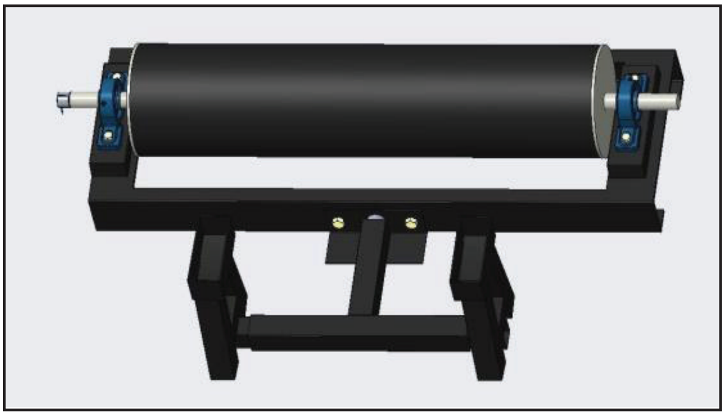
$$\dot{\omega}_{ap}=a_1+2a_2\, t^1+3a_3\, t^2 \quad (7)$$

Equations (6) and (7) are then used to obtain the angular velocity and accelerations to compute the wheel torque on Eq. (4) and the wheel power from Eq. (5). The friction force depends on the vertical load applied to the contact point on the wheels, and thus it is expected that different wheel power curves should be obtained for different loads. These experiments and values are presented and discussed in the next sections.

## 2.2 Materials

The proposed dynamometer is a very simple and consists of a small number of parts. A drawing of the dynamometer, composed of the rotating cylinder, bearings and structure is shown in Figure 2. The cylinder is wide enough to accommodate different sizes of wheelchairs. The dimensions of the inertia cylinder and the properties of the materials used are described in Table 1.

Figure 2 – An overview of the proposed inertial dynamometer



Source: Authors (2023)

Table 1 – Dimensions and characteristics of the inertia cylinder

| Component | Material | Specific mass ($kg/m^3$) | Internal Diameter (m) | External Diameter (m) | Length (m) |
|---|---|---|---|---|---|
| Outer flange | Steel | 7.870 | 0.0254 | 0.170 | 0.010 |
| Inner flange | Steel | 7.870 | 0.0254 | 0.165 | 0.010 |
| Shaft | Steel | 7.870 | - | 0.0254 | 1.000 |
| pipe | PVC | 1.370 | 0.165 | 0.170 | 0.760 |

Source: Authorship (2023)

Initially, the average physiological characteristics of wheelchair users were investigated so that it was possible to design the measurement system (World Para Athletics Rankings, 2020). Based on these wheelchair speed data, and using CREO software, the inertia cylinder was dimensioned considering the acceleration time in each one second propulsion cycle.

### 2.3 Inertial dynamometer dimensioning

For the dimensioning of the dynamometer, physiologies of para-athletics were used, for reference to the maximum speeds. The results of the 10 best competitors listed in the world ranking were used in the 100 m category, T54, men (World Para Athletics Rankings, 2020). Class T54 refers to athletes with normal trunk function who present some sequelae in the lower limbs (Confederação Brasileira de Atletismo [CBAt], 2020). Then, the average speed of the athletes in the race was calculated and with this the general average of these values was established, as shown in Table 2.

The velocity data in Table 2 were used to predict the maximum values expected in the tests and, with this, to establish which rotation transducer is more suitable for measuring the angular velocity of the inertia cylinder. For the measurement of the rotation, an encoder of the incremental type of 360 pulses per revolution was used, coupled to the axis of the cylinder and the data were acquired byopen-source software. The incremental encoder is a device that provides incremental pulses of electrical voltage that can be converted into rotation knowing its size in degrees (Broadcom, 2021). The selection of the encoder depends on the physical phenomenon to be measured, that is, the device must be able to read more quickly than the occurrence of the phenomenon, in this case the angular speed of the axis. The resolution is the measure of the smallest measurable increment (Thomsen, 1997), which in the case of the encoder is the number of electrical pulses that the device output by the encoder during one 360 degrees revolution of the shaft. The maximum expected angular velocity of the axis must then be calculated to select the encoder. From the maximum linear speed expected in the wheelchair and the diameter of the wheel and cylinder, the maximum expected rotation of the cylinder is calculated. Considering the resolution of the encoder and the maximum angular velocity of the cylinder shaft, the minimum time between each pulse is calculated to specify the encoder according to the datasheet.

Table 2 – Average speed calculated for the 10 best competitors listed in the world ranking in the category 100 m T54, male

| World Classification (T54, 100m, male) | time(s) | Average speed(m/s) |
|---|---|---|
| 1° | 14.19 | 7.047 |
| 2° | 14.52 | 6.887 |
| 3° | 14.68 | 6.812 |
| 4° | 14.75 | 6.780 |
| 5° | 14.76 | 6.775 |
| 6° | 15.40 | 6.493 |
| 7° | 15.67 | 6.382 |
| 8° | 15.94 | 6.274 |
| 9° | 16.59 | 6.028 |
| 10° | 17.43 | 5.737 |
| General average | 15.39 | 6.496 |

Source: Authorship (2023)

Considering the maximum linear speed developed in the wheelchair of 6.5 m/s (Table 2), also knowing that the external diameter of the cylinder is 0.170 m, it is obtained that the maximum angular speed expected on the axle is equivalent to 76.4 rad / so it represents approximately 730 revolutions per minute (rpm). The selected encoder, therefore, must be able to measure above 730 rpm for proper measurement.

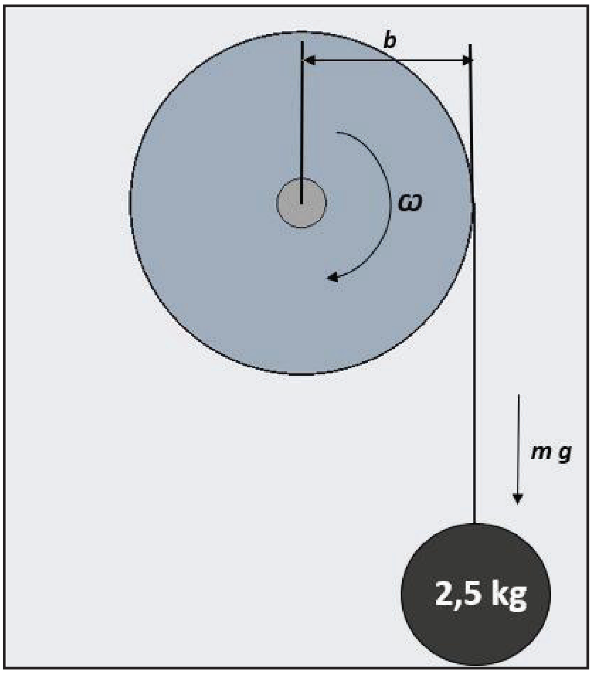
The selected encoder is manufactured by Broadcom, model HEDS- 5500 (Figure 3) and has a resolution of 360 pulses per rotation and performs measurements at speeds above 730 rpm, thus meeting what was established in the design.

Figure 3 – Incremental Encoder HEDS


Source: Broadcom (2021)

## 2.4 Experimental methodology

Figure 4 – Schematic diagram of the measurement strategy



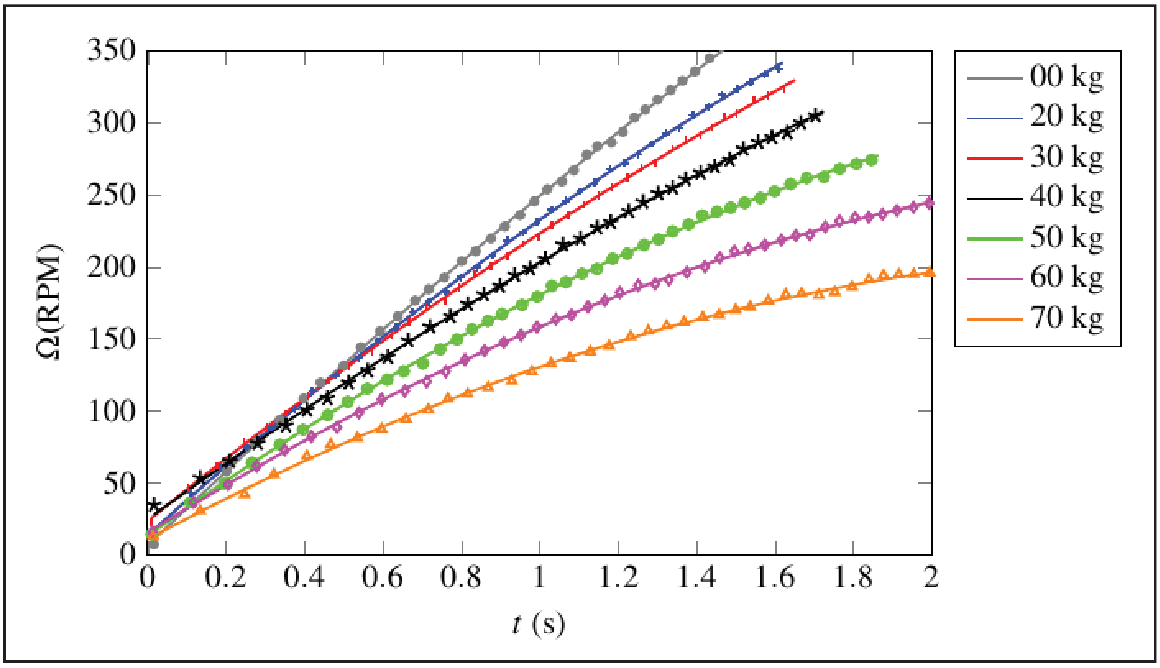

Source: Authors (2023)

To characterize the wheel power curves, different loads are applied to the wheelchair. The loads are constant masses of 10, 20, 30, 30, 40, 50, 60 and 70 kg placed individually on the seat. The system was driven by a suspended mass of 2.5 kg shown in Figure 4.

## 3 RESULTS

The measured angular speed in time and the approximated polynomial curves are shown in Figure 5. The marks on each curve represent the experimental points, and the solid lines are the approximated polynomial curves. The cubic approximation showed to be adequate to model the physical behavior of the angular seed in time. It was observed that the speed increase is almost linear for the empty wheelchair. The maximum speed obtained from 70 kg is around 40% smaller than the empty case (0 kg). The intermediate values are well distributed between 0 and 70 kg.

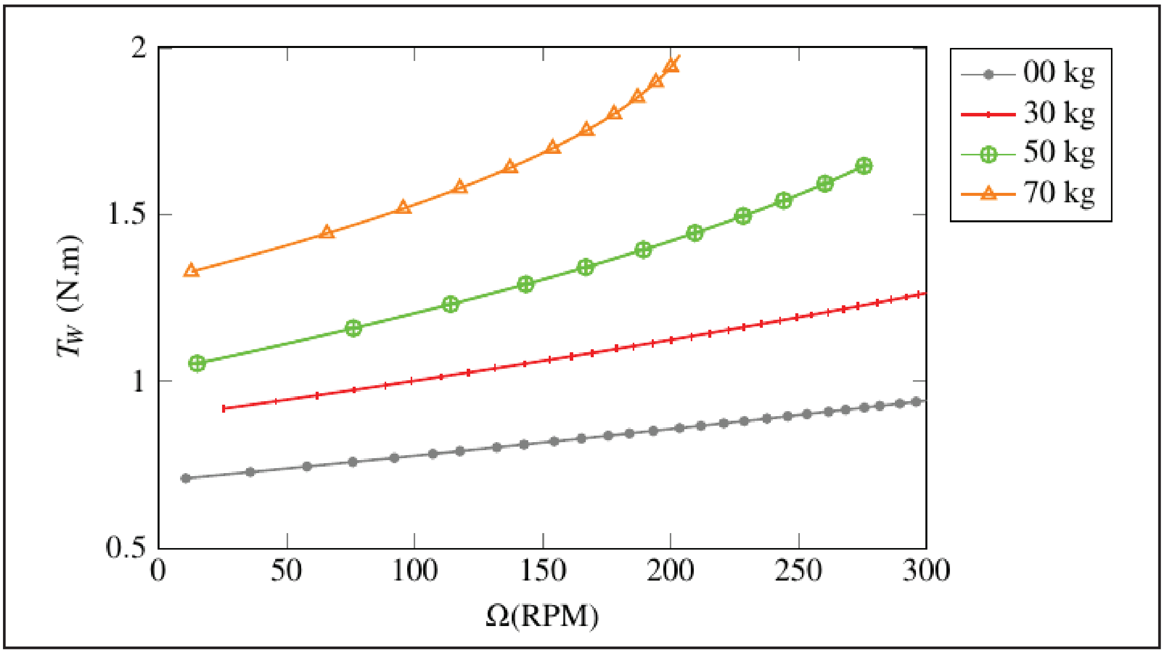
Figure 5 – Angular speed (Win RPM) as function of time for different values of subject mass on the wheelchair




Source: Authors (2023)

From the curves obtained for each load case on the wheelchair, the torque is computed using Eq. (4). In Figure 6 the curves of wheel torque as a function of rotation associated with each load are shown. It is important to recall that the wheel torque resists the driving torque from the suspended mass. The curves show that the larger loads impose more resistance to the increase in rotation, as expected. The curves are well behaved and the cubic interpolation showed to be adequate.

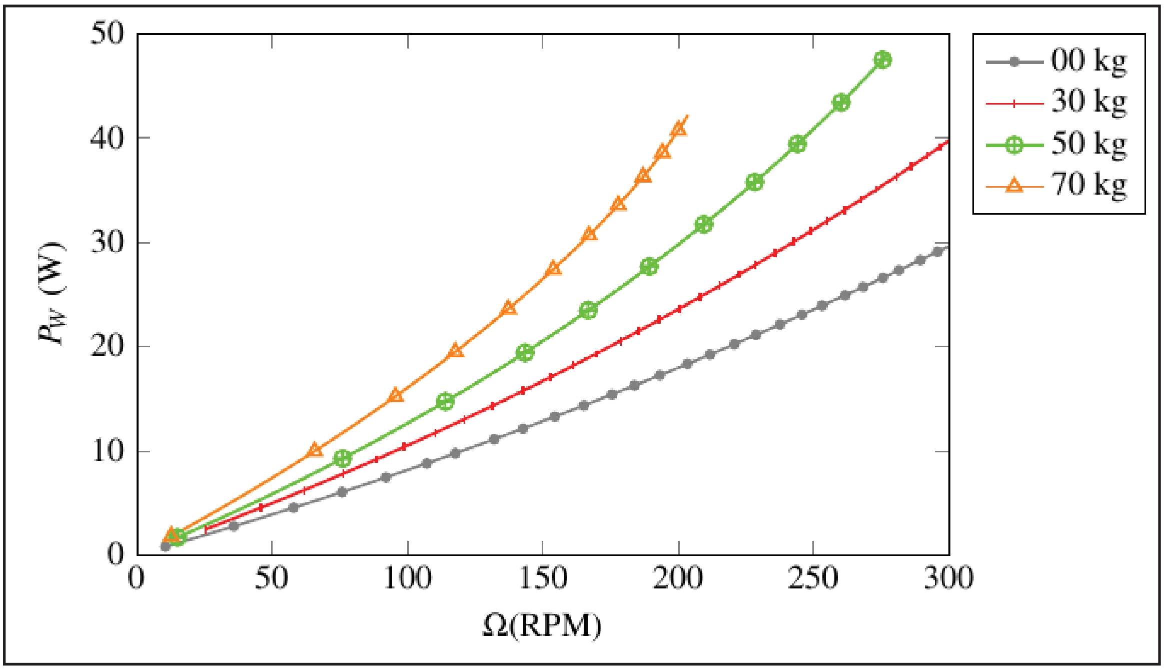
Figure 6 – Wheel torque as function of cylinder angular speed for different values of subject mass




Source: Authors (2023)

Next, in Figure 7, the power associated with each wheel torque is presented. The power gives a measure of the energy extracted from the cylinder rotation. Again, as the load increases, more power is extracted at lower angular speeds. These curves are then suitable to be used as reference for an algorithm that returns the power, if the angular speed is measured and the wheelchair user mass is furnished.

Figure 7 – Wheel power as function of angular speed for different values of applied mass




Source: Authors (2023)

## 4 CONCLUSIONS

In this work, starting from the analysis of the mechanical components of the dynamometer and the schematic design in the Creo Parametric software, it was obtained that the inertia of the cylinder. From the adequate instrumentation of the equipment, it was measured the resistive torque, and consequently, the forces that oppose the motor gesture of the wheelchair user. These forces can be decomposed into inertial forces and rolling frictions. The wheelchair user's mass influences the power dissipated during the tests due to the increase in the total system load due to frictional forces on the contact between the wheels and the dynamometer cylinder. Experimental curves were established, which describe the behavior of the system's total load (inertial and friction) as function of the subject mass on the wheelchair. A cubic polynomial fit was applied to the experimental data, obtaining well behaved curves. These curves are then suitable to be used as a reference for an algorithm that returns the power, if the angular speed is measured and the wheelchair user mass is furnished.

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