The impact of wheelchairs driving support systems on the rolling resistance coefficient

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Abstract. The 21st century is characterized by an increase in the obesity of society, including people with disabilities. The increase in the weight of people in wheelchairs requires them to have more power to drive these types of vehicles. Diseases and a varied level of disability or infirmity may lead to the inability to overcome the resistance of a vehicle driven by muscle power, such as a wheelchair. The solution to this problem are systems supporting the motion of this type of vehicles among which we can distinguish electric-manual hybrid drives that add energy to the drive system and systems that reduce the amount of force necessary for the movement of the cart lowering at the same time of its moving speed. Systems and mechanisms that have been developed for this purpose contain an increased number of cooperating elements than in a classic wheelchair, leading to an increase in rolling resistance. The article presents the methodology and test results of rolling resistance coefficients of wheelchairs with innovative systems supporting their propulsion showing that the tested auxiliary drives generate an increase in rolling resistance of vehicles for the disabled from 30% to 75%.

1. Introduction

Vehicle rolling resistance is one of the basic movement resistances [1]. The functionality of vehicles propelled by muscle power is significantly influenced by internal resistances of the vehicle. Especially disabled or infirm people may stop using vehicles whose exploitation requires driving force beyond their physical capabilities. Researchers around the world are conducting research on vehicles [2–7] and road surfaces [8–10] to reduce rolling resistance. In the automotive industry, the main area of research concerns car tires [11–13] and tire pressure monitoring systems [14]. Vehicle designers for disabled and infirm people develop electric vehicles in which muscle strength is not used. Such units are disadvantageous from the medical point of view, because they do not force the disabled to be active, leading, among other things, to muscle weakness and circulatory problems. It indicates that the preferred solutions are vehicles whose driving system supports the movement of disabled people, and does not replace them. Such solutions used in wheelchairs can be divided into mechanical or electrical ones. The mechanical ones include lever drives [15–17] or using multi-speed transmission [18, 19]. Electric support is characterized, for example, by a wheelchair with a hybrid electric-manual drive [20]. Drives supporting the movement of the disabled allow reducing the force that is necessary for the movement of the vehicle, allowing for the exploitation of wheelchairs by people who previously did not have enough strength to put it into motion. However, the mechanisms used are characterized by internal resistance, through which part of the energy supplied by people with disabilities is lost. The article presents the results of research on rolling resistance of innovative wheelchairs equipped with
multi-speed gears and a hybrid electric-manual drive. Referring to the results of wheelchair tests before the application of these innovative construction solutions.

2. Research object and methodology

The research object was a wheelchair AR-450 ARmedical equipped with hybrid electric – manual drive unit [20] (figure 1) and wheelchair V300 Vermeiren ACTIVE equipped with multi-speed gear [18, 19, 21] (figure 2).

![Figure 1. Wheelchair AR-450 ARmedical: a) classic construction, b) equipped with hybrid electric-manual drive unit.](image1)

![Figure 2. Wheelchair V300 Vermeiren ACTIVE: a) classic construction, b) equipped with multi-speed gear.](image2)

The research was carried out on a prototype research stand prepared on the basis of patent application P.424484 concerning the methodology for measuring the rolling resistance coefficient of objects equipped only with the chassis and using the developed device for these tests in accordance with patent application P.424483. It is a module of a station for studying biomechanics of wheelchair users [22–24]. The test method makes it possible to determine the coefficient of rolling resistance by measuring the rolling resistance force. It combines features of road and stand tests. The core of the method is to determine the rolling resistance coefficient during the movement of the test object at a constant speed, which makes it possible to exclude the influence of inertia forces on the system. The assumed research methodology determines the implementation of a measurement test in uniform motion with a constant speed of movement of the test object relative to the supporting surface. In addition, the analysis of the rolling friction coefficient should be carried out without transitions,
acceleration and stopping of the test object, because in these states there are additional resistance called resistance of inertia. These resistances result from the characteristics of uniformly accelerated or delayed motion. The measurement was carried out at a speed of not more than 15 km h⁻¹, because for such a range of motion speed of the test object, resistance of air force is negligible small regardless of the front drag coefficient of the test object [25]. Before the start of the measurement test, the mass of the tested object was checked, because knowledge of the mass is necessary to determine the rolling resistance coefficient by measuring the rolling resistance force. The value of the rolling resistance coefficient \( f_t \) was determined from the following Eq. (1):

\[
f_t = \frac{F_t}{m \cdot g}
\]  

where: \( f_t \) – rolling resistance coefficient, \( m \) – mass (kg), \( g \) – acceleration of gravity (m s⁻²), \( F_t \) – rolling resistance force (N).

Research was carried out on a hard surface covered with porcelain tiles, in series of ten repetitions for each measurement test. The research was carried at tire pressure of 1.5 bar and maximum pressure of 6 bar (the wheelchair with multispeed gear was tested at maximum pressure of 4 bar due to change of tires after modification) and the total weight of the wheelchair of 130 kg in order to compare the obtained results with the results of wheelchairs with modification that were tested under such assumptions [26]. The wheelchair weight before and after modernization is shown in table 1.

|                | Wheelchair AR-450 ARmedical equipped with hybrid electric-manual drive unit | Wheelchair V300 Vermeiren ACTIVE equipped with multi-speed gear |
|----------------|--------------------------------------------------------------------------------|------------------------------------------------------------------|
| Before retrofitting | 25 kg                                                                          | Before retrofitting                                              |
| After retrofitting   | 48.5 kg                                                                         | After retrofitting                                               |
| Before retrofitting   | 27 kg                                                                          | After retrofitting                                               |
| After retrofitting   | 72.5 kg                                                                         |                                                                   |

3. Research result

The results of force measurement tests using the described research methodology are presented in figure 3, indicating the characteristics of force measurement from the beginning of movement to the stopping of the test object. The characteristics of the force values when moving at a constant speed are shown in figure 4. The result of the tests of the average force necessary for the movement of a wheelchair with hybrid-electric drive with constant speed is shown in table 2, and the wheelchair with multi-speed gear in table 3. The results include the tire pressure in the tested wheelchairs.

![Figure 3](image-url)

**Figure 3.** The characteristics of force changes in a function of time while towing a wheelchair where: a – acceleration, b – movement stabilization, c – movement delay.
Figure 4. The characteristics of force changes in a function of time while towing a wheelchair in the range of stable movement where: blue line – the characteristics of force in a function of time, black line – trend line (linear).

Table 2. The average force value while towing a wheelchair with hybrid - electric drive in the range of stable movement.

| No. | Tire pressure: 1.5 bar | Tire pressure 6 bar |
|-----|------------------------|---------------------|
|     | F (N) | SD* | F (N) | SD* |
| 1.  | 35.3  | 5.1  | 34.3  | 4.7 |
| 2.  | 36.7  | 7.2  | 38.4  | 6.9 |
| 3.  | 37.2  | 6.9  | 40.1  | 7.1 |
| 4.  | 39.0  | 8.0  | 36.0  | 3.0 |
| 5.  | 34.2  | 7.4  | 33.2  | 5.6 |
| 6.  | 38.1  | 5.0  | 37.1  | 6.5 |
| 7.  | 36.5  | 4.4  | 36.5  | 3.9 |
| 8.  | 42.1  | 5.6  | 37.8  | 6.1 |
| 9.  | 33.5  | 3.4  | 32.9  | 6.9 |
| 10. | 39.8  | 4.7  | 34.4  | 4.4 |

| F (N) | SD** | F (N) | SD** |
|-------|------|-------|------|
| 37.2  | 2.5  | 36.1  | 2.2  |

F – average force (N); DS* – standard deviation for the mean
DS** – standard deviation for a single measurement

Table 3. The average force value while towing a wheelchair with multispeed gear in the range of stable movement.

| No. | Tire pressure: 1.5 bar | Tire pressure: 4 bar |
|-----|------------------------|---------------------|
|     | F (N) | SD* | F (N) | SD* |
| 1.  | 37.2  | 5.1  | 31.1  | 6.1 |
| 2.  | 39.1  | 4.9  | 33.2  | 7.3 |
| 3.  | 39.1  | 6.7  | 36.2  | 7.2 |
| 4.  | 44.1  | 8.4  | 31.8  | 5.6 |
| 5.  | 42.5  | 7.6  | 37.2  | 6.8 |
| 6.  | 37.1  | 4.0  | 25.3  | 7.4 |
| 7.  | 34.2  | 5.5  | 29.4  | 5.3 |
| 8.  | 36.3  | 5.3  | 26.0  | 6.5 |
| 9.  | 35.2  | 6.4  | 36.2  | 8.2 |
| 10. | 40.0  | 5.9  | 29.4  | 8.7 |

| F (N) | SD** | F (N) | SD** |
|-------|------|-------|------|
| 38.5  | 2.9  | 31.6  | 3.9  |

F – average force (N); DS* – standard deviation for the mean
DS** – standard deviation for a single measurement
4. Results analysis
The applied methodology and test stand allowed to determine the rolling resistance coefficients of wheelchairs with innovative drives (table 4) and to compare the results with research results available in literature (figure 5). The value of the rolling resistance coefficients of wheelchair with hybrid electro-manual drive is influenced by: contact of the tire with the surface including convergence of the system, residual friction in the brake system and internal resistances of a brushless electric motor, mainly its bearing and impact of permanent magnets (figure 6a). Rolling resistance of a wheelchair with hybrid electric-manual drive at tire pressure of 1.5 bars increased at about 71%, and at a pressure of 6 bar by about 75%. A wheelchair with a multi-speed transmission is also characterized by an increase in rolling resistance. In this solution, apart from the contact of the tire with the surface, the main resistances result from the number of toothed gears (8) and the number of rolling bearings (8) and sliding bearings (8), the gears used are shown in figure 6b. The use of multi-speed transmission required changing the tires, the tires used had a lower maximum tire pressure (4 bar), hence a comparison of rolling resistance of wheelchairs before and after modernization will be performed at different tire pressures. The coefficient of rolling resistance at the maximum pressure in the wheels (6 bar – wheelchair with classic drive and 4 bar – wheelchair after modernization) increased by about 13%, and at a pressure of 1.5 bar by about 43%. The wheelchair with pneumatic wheels used in wheelchairs on the drive axis had the lowest rolling resistance coefficient, whereas the highest coefficient had the wheelchair with four self-aligning wheels used on the front axis.

Among the designs with wheelchair support systems, a wheelchair with hybrid electric-manual drive is characterized by the highest increase in rolling resistance. However, the electric drive is characterized by a large surplus of torque necessary to drive the wheelchair, not causing a problem for the user to operate the vehicle. On the other hand, internal resistance is definitely more important for users of wheelchairs driven by the power of muscles, because excessive resistance may result in the inability to use the vehicle. The support system consisting of the multi-speed transmission built into the wheel hub acts as a classic planetary gear, and thus, depending on the given gear, increases or decreases the force necessary to drive the wheelchair. The tested object at the pressure anticipated for operation is characterized by a relatively small increase in rolling resistance.

Table 4. The value of rolling resistance coefficient for wheelchairs with innovative propulsion systems.

| wheelchair with hybrid electric-manual drive | wheel pressure | rolling resistance coefficient |
|---------------------------------------------|----------------|-------------------------------|
|                                             | 1.5 bar        | 0.029                         |
|                                             | 6 bar          | 0.028                         |

| wheelchair with multispeed gear             | wheel pressure | rolling resistance coefficient |
|---------------------------------------------|----------------|-------------------------------|
|                                             | 1.5 bar        | 0.030                         |
|                                             | 4 bar          | 0.025                         |
Figure 5. The value of rolling resistance coefficient of wheelchairs and carts with wheels used in wheelchairs in a function of tire pressure: a) cart with non-pneumatic wheels (navy blue on the graph) [22], b) cart with pneumatic wheels (blue on the graph) [27]; light green – wheelchair AR-450 ARmedical (classic construction) [26]; dark green – wheelchair with hybrid electric-manual drive, light violet – wheelchair V300 Vermeiren ACTIVE (classic construction) [26], dark violet – wheelchair with multispeed gear.

Figure 6. The characteristic subassemblies of wheelchairs with innovative drives: a) BrushLessDirect-Current motor, b) a part of the applied multispeed transmission [19].
5. Conclusions
In response to the problems of disabled and infirm people in the 21st century, which are characterized by an increase in body weight, modular drives for retrofitting classic wheelchairs have been developed. They allow disabled people to move with the help of muscles in easy terrain conditions (without gradients, strong gusts of wind, hard surface), this is beneficial as it does not lead to muscular atrophy in case of people moving on these devices. On the other hand, the activation of the electric drive will enable people with disabilities to overcome: greater distances, operation in difficult weather conditions (strong wind) and terrain (hills, marshy terrain). The solution is beneficial for blue-collar workers on wheelchairs because their hands can rest before and after work. However, these systems are characterized by the increase of internal resistance of vehicles, which must be overcome in order to move a wheelchair with such a system. In the case of an electric-manual hybrid wheelchair, it is about 75% which corresponds to the rolling resistance coefficient on a harder surface with a maximum nominal pressure in the wheels of approximately 0.028. On the other hand, a wheelchair with a multi-speed transmission is characterized, on a hard surface with a maximum nominal pressure in wheels, an increase in the rolling resistance coefficient of 13%, and its value is equal to 0.025. The small increase in rolling resistance in a multi-speed transmission should not pose a significant resistance for disabled people, because the solution allows to reduce the value of the applied motor force from the muscle compared to the classic solution. In contrast, the large increase in rolling resistance of the electric-manual hybrid is compensated by the large torque reserve of the electric motor during the drive. It overcomes the internal resistances of the system and can drive the wheelchair by itself. Further research will be carried out on the development of the structures and the determination of their external characteristics. Research can also include the surface test, on which vehicles move and research methodologies to reduce signal pulsation.

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