applied sciences

Review

Laboratory Assessment of Manual Wheelchair Propulsion

Bartosz Wieczorek [1] and Maciej Sydor [2,*]

[1] Institute of Machine Design, Faculty of Mechanical Engineering, Poznan University of Technology, Piotrowo 3, 60-965 Poznań, Poland
[2] Department of Woodworking and Fundamentals of Machine Design, Faculty of Forestry and Wood Technology, Poznań University of Life Sciences, 60-637 Poznań, Poland
* Correspondence: maciej.sydor@up.poznan.pl

Featured Application: A review of laboratory methods for measuring manual wheelchairs' propulsion efficiency and user interactions supports the development of wheelchairs that are more efficient, comfortable, and adaptable to individual needs.

Abstract: Self-propelled manual wheelchairs offer several advantages over electric wheelchairs, including promoting physical activity and requiring less maintenance due to their simple design. While theoretical analyses provide valuable insights, laboratory testing remains the most reliable method for evaluating and improving the efficiency of manual wheelchair drives. This article reviews and analyzes the laboratory methods for assessing the efficiency of wheelchair propulsion documented in the scientific literature: (1) A wheelchair dynamometer that replicates real-world driving scenarios, quantifies the wheelchair's motion characteristics, and evaluates the physical exertion required for propulsion. (2) Simultaneous measurements of body position, motion, and upper limb EMG data to analyze biomechanics. (3) A method for determining the wheelchair's trajectory based on data from the dynamometer. (4) Measurements of the dynamic center of mass (COM) of the human–wheelchair system to assess stability and efficiency; and (5) data analysis techniques for parameterizing large datasets and determining the COM. The key takeaways include the following: (1) manual wheelchairs offer benefits over electric ones but require customization to suit individual user biomechanics; (2) the necessity of laboratory-based ergometer testing for optimizing propulsion efficiency and safety; (3) the feasibility of replicating real-world driving scenarios in laboratory settings; and (4) the importance of efficient data analysis techniques for interpreting biomechanical studies.

Keywords: ergometer; motion analysis; EMG analysis; biomechanical analysis; personal transportation; disability; ergonomics; assistive technology

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1. Introduction

Wheelchairs are personal mobility aids designed to stabilize a seated body position and enable movement. This makes them essential tools for people with disabilities or temporal mobility impairments [1–3]. Wheelchairs can be customized to meet the specific needs of individual users, or they can be used as versatile devices for the occasional transportation of various individuals in institutional settings. Concerning power sources for movement, three classes of wheelchairs are recognized: caregiver-controlled, electrically powered, and manually propelled. These three power sources can be employed independently, alternately, or simultaneously. The choice of wheelchair class depends on factors such as the severity and type of disability, as well as the intended use of the wheelchair. For instance, individuals with profound musculoskeletal impairments typically use caregiver-controlled wheelchairs or electrically powered wheelchairs. Older people and people with obesity, who rarely use wheelchairs daily due to their ability to walk independently, may employ electrically powered wheelchairs only for traversing challenging terrain or covering longer distances [4].

A characteristic group of wheelchair users comprises individuals who cannot walk independently but have partially or fully functional upper limbs. These individuals lead active and independent lifestyles, relying on manual wheelchairs for mobility in various aspects of their lives, both indoors and outdoors. Compared to their electrically powered counterparts, manual wheelchairs offer several advantages, including increased physical activity, more compact dimensions for easier maneuverability indoors and on public transportation, and superior reliability and durability due to their simplified design [5].

Each wheelchair consists of a body support system and a drive system. In a manual wheelchair, the main components of the body support system are a seat with a cushion, a backrest, side guards, and a footrest with additional leg support components. The drive system usually consists of two rear wheels with push-rims, two front self-aligning wheels, and parking brakes. These two systems are marked with different colors and shown in Figure 1.

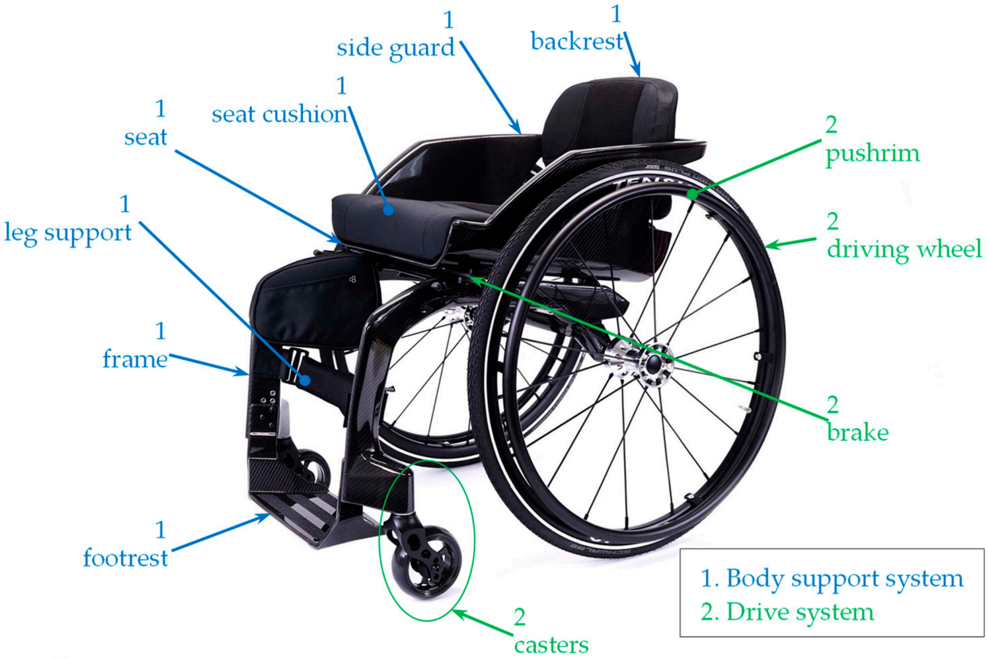

Figure 1. Subsystems of a manual wheelchair (*Freeasy* model, manufactured by Cosmotech, Gliwice, Poland; source: own study).

Smith, Sakakibara, and Miller [6] reviewed factors influencing wheelchair users' involvement in social and community activities. Although the cited article focuses primarily on participation and does not address the efficiency of wheelchair propulsion, the authors concluded that the physical effort required to propel a wheelchair is related to the level of participation. If wheelchair propulsion requires excessive physical effort or causes discomfort, users participate in social activities less frequently to avoid further strain. This highlights the importance of continuous improvements in manual wheelchair drive systems.

Factors related to the user, the design of the wheelchair, and environmental factors impact the manual wheelchair's drive system efficiency. Individual physical limitations and functional abilities are pivotal wheelchair user-related factors. The muscular strength and endurance, cardiovascular fitness, and medical conditions affecting these characteristics affect the propelling of a manual wheelchair. The range of motion on the push-rim [7], propulsion technique [8], including the position of the hands on the wheelchair's push-rims [9], the angle of the push, and the push frequency [10] influence the effectiveness of the wheelchair's motion. Good technique minimizes energy loss [11] and maximizes forward motion [12]. At the same time, experience and adaptation of the muscular system to the specifics of the wheelchair drive system lead to improved performance over time [13,14].

The design of the wheelchair significantly impacts its drive efficiency [15]. Factors, such as the quality of the dimensional fit of the wheelchair to the user, the rigidity of the frame, the size of the wheels, the type of tires, the cushioning, and the weight of the wheelchair, are essential. These factors are determined by the possibility of customizing the body support system to the user's size, disability, and preferences. Customization options for wheelchairs often include seat height, seat angle, backrest height, and wheel angle relative to the vertical axis (camber) [16]. The backrest height significantly affects wheelchair user well-being. It influences posture, propulsion efficiency, and muscle activation. Adjusting the backrest angle influences the biomechanical efficiency of wheelchair propulsion. A 10-degree recline in the backrest can increase biomechanical efficiency by 10% [17]. The ergonomic design of the backrest should aim to support the spine's natural curvature. A backward adjustable thoracic support helps maintain a neutral pelvic tilt and higher lumbar lordosis, which are beneficial for posture. This adjustment also results in lower back muscle activation, potentially reducing the risk of back pain [18]. Users of ultralight wheelchairs often do not adjust the backrest height when purchasing a new wheelchair. This suggests that user training is needed to maximize the benefits of backrest height fit [19]. A lower backrest height reduces the risk of upper limb injuries in wheelchair users, but it is also important to consider other factors. The choice of backrest height should be tailored to the individual user's needs and preferences [20]. The rear wheel camber significantly affects push force during manual wheelchair propulsion. The push time, angle, and abduction vary between 3 and 6 degrees of camber [21]. However, increased camber angles, such as 15 degrees, lead to higher loading on the upper extremities, increasing the risk of injury despite a larger push-rim effective force [22].

Proper maintenance of a wheelchair also affects the efficiency of the wheelchair propulsion [23]. Keeping all mechanisms in good condition and the tires inflated to the correct pressure has a significant effect on the ease of use of the wheelchair [24]. Some wheelchair users may use devices to assist with manual propulsion, such as gloves with grip-enhancing materials or wheelchair accessories designed to improve performance.

Weather conditions, e.g., wind, rain, and temperature, are crucial when analyzing the performance of the wheelchair drive system. Adverse weather conditions make it more challenging to drive a wheelchair. The type of surface and terrain affects performance. Smooth and level surfaces like sidewalks are more accessible to drive on than uneven terrain. Side inclination, uphill, and downhill gradients also affect the power required for propulsion [25].

Therefore, effective manual wheelchair propulsion is a multifaceted issue influenced by a complex interplay of factors encompassing the user's physical capabilities, wheelchair design characteristics, and environmental conditions. Optimizing these factors leads to a more comfortable and less physically demanding wheelchair experience for the user. Emerging methods, described in scientific documents, intended for analyzing and optimizing manual wheelchair drives hold the potential to significantly improve the quality of life for wheelchair users. To substantiate this hypothesis, a comprehensive review and analysis of laboratory methods documented in the scientific literature were conducted to assess their efficiency in evaluating wheelchair propulsion [26].

The intricate interactions among these factors and the potential benefits of optimization necessitate a comprehensive approach to laboratory measurement and analysis of wheelchair propulsion. This study reviews experimental testing methods for manual wheelchairs to identify valid and reliable test methods and strategies for optimizing manual wheelchair drives.

The primary objective of this study is to critically evaluate and identify laboratory experimental testing methods for manual wheelchairs that are supported by solid evidence in scientific documents. The goal is to establish a foundation for developing and implementing evidence-based strategies to optimize manual wheelchair propulsion for improved user comfort and reduced physical exertion.

This study employs a narrative literature review approach to gather relevant research findings on experimental testing methods for manual wheelchairs. This review focuses on identifying and critically evaluating studies that have employed objective and controlled experimental protocols to assess the effectiveness of different wheelchair designs, user techniques, and environmental factors on propulsion performance.

This justifies the following research questions.

1. What laboratory testing methods have been employed in scientific research to evaluate the effectiveness of manual wheelchair propulsion?
2. Which laboratory testing methods are most valid and reliable for assessing wheelchair propulsion performance?
3. What future research directions are needed to enhance understanding of manual wheelchair propulsion further and optimize its drive effectiveness?

2. Experimental Testing Methods

2.1. Dynamometer

A wheelchair dynamometer is a stationary testing device used to measure the propulsion parameters of manual wheelchairs. There are three primary methods for measuring these parameters [27]: mobile ergometers, based on an electromagnetic brake mounted in the wheelchair [28]; stationary ergometers in which the wheelchair is set on a treadmill [29]; and stationary roller ergometers [30].

De Klerk et al. in 2020 [31] compared 50 wheelchair ergometers and highlighted the advantages and disadvantages of different ergometers used to test wheelchair propulsion under laboratory conditions. They noticed that each type of ergometer has advantages and limitations, and the choice of equipment should depend on specific research goals and requirements. The cited authors also emphasize the diversity and lack of consensus in this respect, which suggests the need for further research and standardization efforts to improve the usefulness of laboratory tests of wheelchair drives. However, it is highlighted that roller ergometers allow the use of a personal wheelchair, which can be significant in studying the interaction of a specific person's wheelchair with their wheelchair.

Wheelchair treadmills are commonly used to investigate wheelchair propulsion performance. Unlike traditional treadmills designed for runners, wheelchair treadmills feature a platform to accommodate a wheelchair, enabling users to propel themselves against the treadmill belt while seated. These treadmills can be adjusted to simulate various terrains, including hills and flat surfaces [32]. Wheelchair treadmills offer an effective alternative to instrumented push-rims for measuring temporal and kinetic parameters. Research has demonstrated strong correlations between measurements obtained from treadmills and during driving [33].

As part of Poznan University of Technology's scientific activities in Poland, a stationary roller dynamometer was developed to measure wheelchair drive characteristics, such as torque, speed, and energy consumption as a function of time. Such a specialized test stand was patented, built, and validated [34]. This test stand records the rotational parameters of a wheelchair's driving wheels and can simulate inclined surfaces. Additionally, the stand has sensors to measure critical biomechanical parameters of propelling the wheelchair. Figure 2 illustrates the information flow within the dynamometer system.

The stationary roller dynamometer shown in Figure 3 consists of a support frame (1) to which a weighing pan (3) is attached using strain gauges (2). The strain gauges measure the pressures under each wheel of the wheelchair, and based on this, the position of the center of mass (COM) of the human–wheelchair system is determined. Due to the sensitivity of strain gauge scales to longitudinal loads, three linear guides (4) are used to allow only vertical movement of the weighing scales relative to the support frame. The weighing pan is equipped with a wheelchair frame clamping system (5) and two double traction rollers

(6) that ensure slip-free contact with the wheelchair's driving wheels, a critical factor in accurate testing.

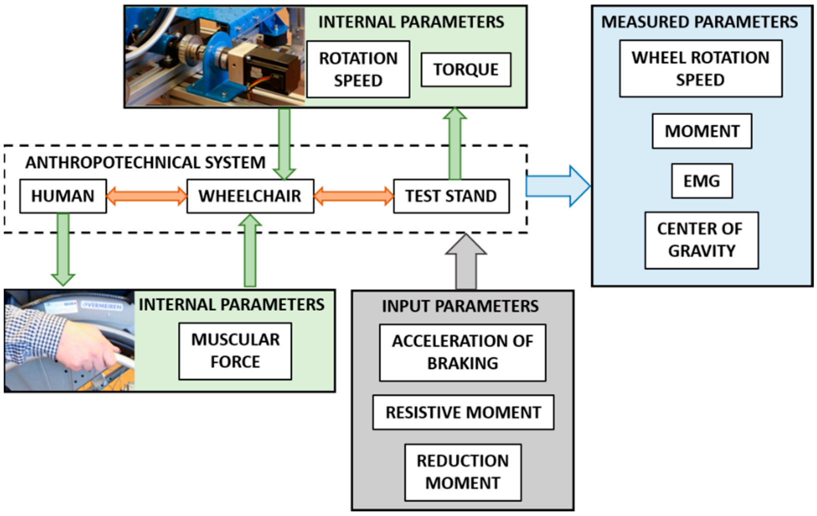

Figure 2. Information flow diagram for wheelchair propulsion biomechanics study on the stationary roller dynamometer (source: [34]).

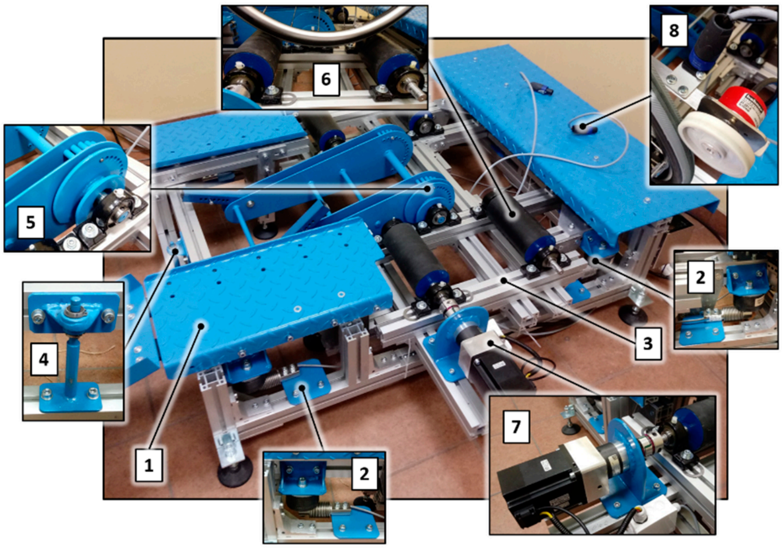

Figure 3. View of the stationary roller dynamometer with details of the most essential elements (own study): 1—support frame, 2—strain gauges, 3—weighing pan, 4—linear guides, 5—clamping system, 6—traction rollers, 7—BLDC motor, 8—encoder.

The wheelchair frame clamping element, shown in Figure 4, allows the wheelchair to tilt in the sagittal plane. Each traction roller system consists of two rubber-covered, truncated cone-shaped rollers that taper towards the center of the stand. A brushless DC electric motor (BLDC) is attached to the front of each system, making it an active roller. During the test, active rollers receive rotational energy from the wheelchair's driving wheels, which simulates rolling resistance. They can also drive the wheels, which simulate the wheelchair's descent down an incline. The rear roller of the traction roller system is a passive roller whose function is solely to support the wheelchair. Two encoders (8) convert the rotational motion parameters of the driving wheels into electrical signals, enabling independent measurement of the left and right wheels.

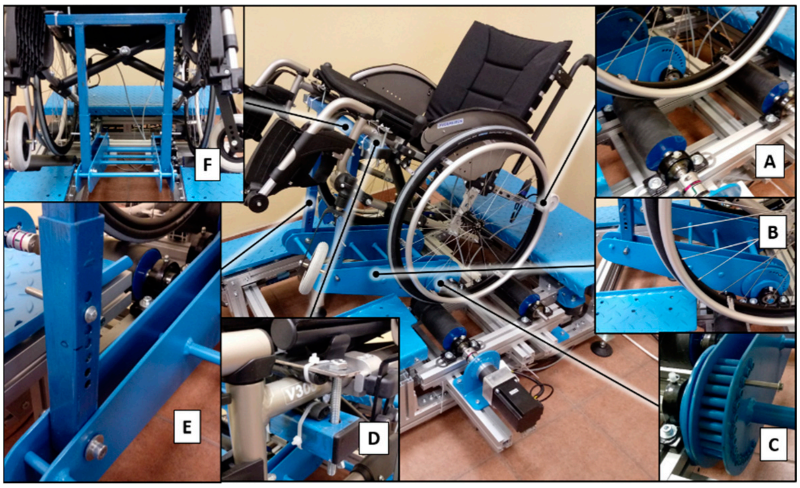

Figure 4. Wheelchair secured to the stationary roller dynamometer (source: own study): (**A**)—traction rollers, (**B**)—weight-scale lever, (**C**)—safety pin, (**D**)—clamps securing the wheelchair frame, (**E**)—lever arm height adjuster, (**F**)—fastened wheelchair frame.

Figure 4 illustrates the method used to secure the wheelchair for testing. To clamp the wheelchair, it is rolled onto the traction rollers (A). The wheelchair frame (F) is then fixed using clamps (D). The wheelchair frame clamping element has two adjustments. The first allows tilting the weight-scale lever (B). The tilt angle is set using a perforated disc and the safety pin (C). This adjustment allows one to simulate the ascents or descents of a hill. The second adjustment (E) adjusts the height of the lever arm to the height of the wheelchair frame.

The system for measuring the electromyographic muscle activity of the person driving the wheelchair is a separate component that can work independently of the stand. However, its use during the tests expands the results and allows for more complete conclusions.

2.2. Test Stand and Method of Motion Capture

The kinematics of human body segments is one of the most essential biomechanical parameters during wheelchair propulsion [35–39]. The propulsion cycle of a manual wheelchair can be divided into two phases, i.e., the push phase and the recovery phase [40]. During the push phase, mechanical energy is transferred to the wheel's push-rim through hand contact with the rim; during the recovery phase, the hand is displaced in preparation for the next push phase. During the push phase, the hand moves along with the rim. In the recovery phase, the hand can move along different paths, which can be classified based on the shape of the hand projection on the sagittal plane [41]. The literature distinguishes four stroke patterns: semicircular, single-looping, arc, and double-looping [35]. These stroke patterns are shown in Figure 5.

Analyzing the kinematics of body segments of a person driving a wheelchair requires the development of a measurement stand and a data processing method. A method, along with the stand, is described in the publication *The method of measuring motion capture in wheelchairs during actual use–description of the method and model of measuring signal processing* [42]. The method employed an OpenCV algorithm called AruCo to locate markers (QR codes) placed on the filmed upper limb. By utilizing readily available algorithms, the authors developed a low-cost and user-friendly test apparatus consisting of a modular attachment that can be integrated with a wheelchair. This module, shown in Figure 6, consists of a GoPro HERO 7 camera (a) and a light (b) mounted on a boom (c) permanently connected to the wheelchair frame. During the tests, the human body was equipped with markers (d), and, in addition, it was possible to use electrodes that measured the EMG signal (e). The apparatus designed in this way makes it possible to relate the measured muscle activity to the kinematics of the human body.

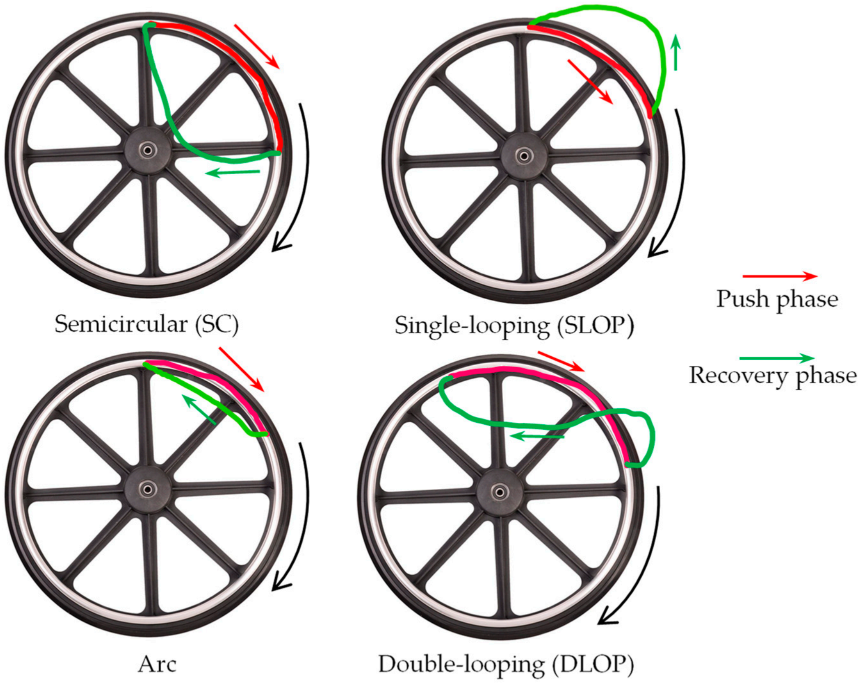

Figure 5. Stroke patterns of the wheelchair propulsion (based on the methodology outlined in [35]).

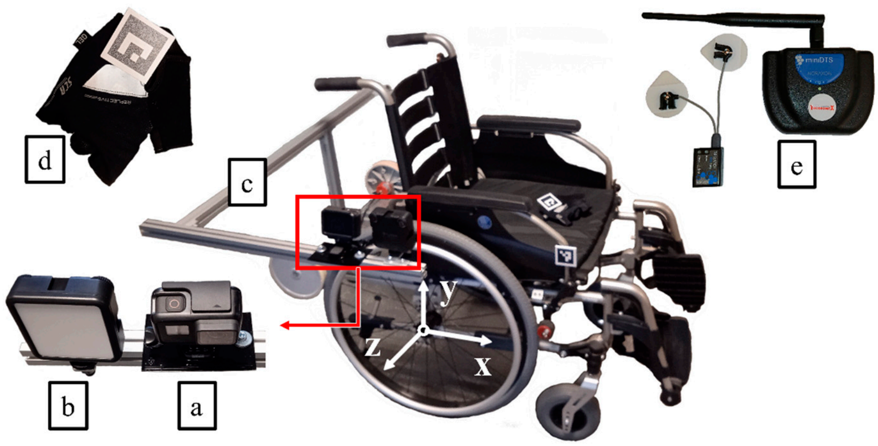

Figure 6. Measurement apparatus used in the study: (**a**)—camera, (**b**)—illuminating lamp, (**c**)—boom, (**d**)—AruCo marker, (**e**)—EMG device (source: [42]).

Due to the implementation of OpenCV class algorithms [43,44] in a new application and the prototype nature of the test apparatus, the correctness of the operation of this apparatus was first verified, and its accuracy was determined. The results of this research were published in a paper titled *The effects of AruCo marker velocity and size on motion capture detection and accuracy in the context of human body kinematics analysis* [45]. This study found that a potential error in marker detection was related to the quality of the camera and the speed of marker movement. At the same time, the speed of movement of the marker had the most dominant influence on the value of the error and the risk of its occurrence. This relationship is shown in Figure 7.

Based on analysis of the test results, both the apparatus and the data acquisition method were valid, as the relative error for different hand speeds during wheelchair propulsion did not exceed 6% [45].

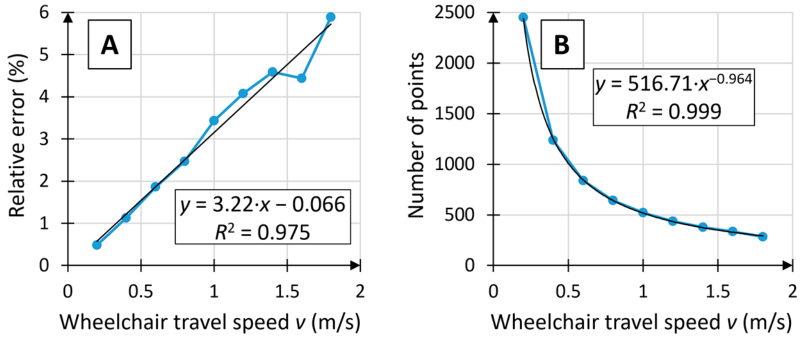

Figure 7. Relative error (**A**) and number of detection points (**B**) as a function of marker speed (adapted from [45]).

2.3. Determining Wheelchair Trajectory Based on Dynamometer Data

Using fixed wheelchair dynamometers in biomechanical testing can limit the ability to capture the dynamic movement of the human–wheelchair system during propulsion. Traditional wheelchairs employ differential steering, where individual wheel speeds control direction and movement [46]. Replicating this user-controlled steering in laboratory settings can be challenging, especially when users lack sensory feedback, which may disrupt the study. To address this, it is crucial to inform participants about the intended wheelchair trajectory during testing. A method for determining such a trajectory, known as the trapezoid method, is described in detail in two articles, *Methods of Determining Trajectory for Wheelchair with Manual Pushrims Drive* [47] and *Bézier curve based trajectory planning for an intelligent wheelchair to pass a doorway* [48], and is called the trapezoid method. This method divides the wheelchair's movement into trapezoidal segments based on the differential steering principle. The turning radius (R) is determined by the speed difference between the left (v_L) and right (v_P) drive wheels and the wheelbase (L) (Figure 8).

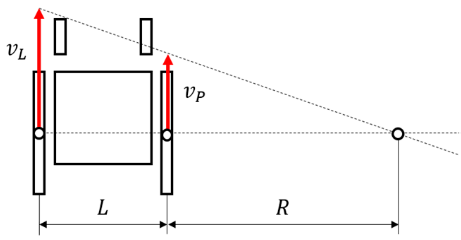

Figure 8. Determination of the turning radius R, using the trapezoid method based on known values of left wheel speed v_L, right wheel speed v_P, and wheelbase L (source: [47]).

When measuring the kinematic parameters of the wheelchair, the left wheel path s_L and right wheel path s_P were measured independently in the same unit of time t, dividing the movement of the wheelchair into equal intervals and modeling these intervals as trapezoids, in which the base is equal to the wheelbase L and the sides are equal to the lengths of the distance traveled by the left wheel s_L and the right wheel s_P (Figure 9A,B).

According to the trapezoid method, the wheelchair movement should first be divided into equal time intervals for which the paths of the left wheel s_L and the right wheel s_P are known (Figure 6a,b). Then, it is required to calculate the angle α of inclination relative to the horizontal straight line connecting the ends of the left wheel path s_L and the right wheel s_P (1).

$$\alpha = atan\left(\frac{s_L^i - s_P^i}{L}\right) \tag{1}$$

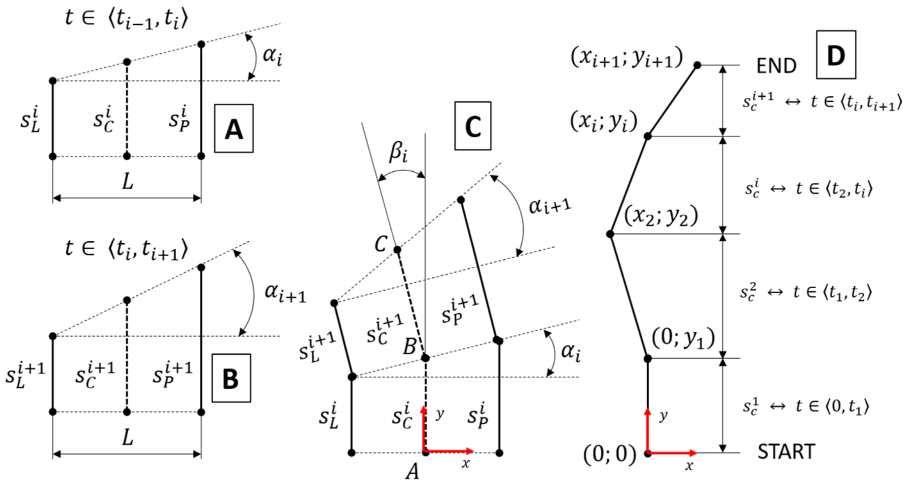

Figure 9. The partitioning of the wheelchair trajectory into trapezoidal segments (source: [47]): (**A**)—distance covered in the first iteration, (**B**)—distance covered in the second iteration, (**C**)—a combination of distances covered in the analyzed iterations, (**D**)—trajectory determined based on the specified iterations.

The trajectory of a wheelchair can be described as a change in the position in the space of a point that is the center of the rear axle of the driving wheels. Therefore, for each trapezoid describing the path in equal time intervals t, you should determine the path of the center of the axis $s_{C,}$ which is the average of the paths traveled by the left wheel s_L and the right wheel s_P (2).

$$s_C^i = \frac{s_P^i - s_L^i}{2} \tag{2}$$

To model wheelchair movement using the trapezoidal method, the entire wheelchair path is approximated by a series of trapezoids. The initial trapezoid, which encloses the wheels' paths and the axle's center, has a base parallel to the x-axis. The point representing the center of the axle at time $t = 0$ serves as the origin of the coordinate system. Subsequent trapezoids are constructed such that their bases align with the line connecting the endpoints of the left s_L and right wheel s_P paths from the preceding propulsion cycle. Additionally, the center points of the driving wheel axle from the previous interval's end and the new interval's beginning must coincide, as illustrated in point B of Figure 9.

To specify the trajectory of a wheelchair movement, it is sufficient to determine the coordinates of the position of the center point of the drive wheel axle for the end of each of the separated propulsion compartments (Figure 6d). The coordinates $x_0 = 0$ and $y_0 = 0$ are taken as the first point. The coordinates of the second point are $x_1 = 0$ and $y_1 = s_{C1}$. The coordinates of each subsequent point are determined using Equation (3):

$$\begin{aligned} x_i &= x_{i-1} + s_C^i \cdot \sin(\beta_i) \\ y_i &= y_{i-1} + s_C^i \cdot \cos(\beta_i) \end{aligned} \tag{3}$$

The angle β, representing the overall curvature of the wheelchair's trajectory, is determined by summing the angular deviations between the wheelchair's centerline and the line connecting the ends of the left wheel path (s_L) and the right wheel path (s_P). (4).

$$\beta_i = \beta_{i-1} + \alpha_{i-1} \tag{4}$$

The described trapezoid method simulates wheelchair driving with a dynamometer more similar to real-world conditions.

2.4. Determining Changes in the Position of the Center of Mass (COM)

One of the most essential biomechanical parameters impacting the efficiency of wheelchair propulsion is the position of the COM of the human–wheelchair system. This parameter directly impacts both the propulsion efficiency and stability of the wheelchair. In the so-called active wheelchairs, intentional instability of the human–wheelchair system is deliberately incorporated into the wheelchair's design to reduce reliance on torso balancing while maintaining proper push-rim propulsion. This intentional instability enhances maneuverability and obstacle-crossing capabilities [4]. However, because active wheelchairs are less stable, they require specific skills from the user to control them effectively. As a result, active wheelchairs are typically tailored for individuals with enhanced physical fitness and maneuvering abilities, enabling them to fully capitalize on the advantages of this intentional instability.

In human–wheelchair anthropo-technical systems, studying changes in the COM under dynamic conditions is essential. Numerous factors influence the current position of the COM. In addition to the constantly changing position of the torso, the wheelchair frame dynamics are influenced by the moving masses of the user's arms during manual wheelchair propulsion [49]. Measuring the COM position under dynamic conditions has been extensively documented in the literature [50–52].

The method presented in [53] involves determining the COM (barycenter) of the person–wheelchair system using four strain-gauge-measuring scales (Figure 10). Each scale measures the vertical reaction R_i at one of the four support points of the system. These signals allow for determining the projections of the COM in the XY plane, simplifying the analysis to a two-dimensional area.

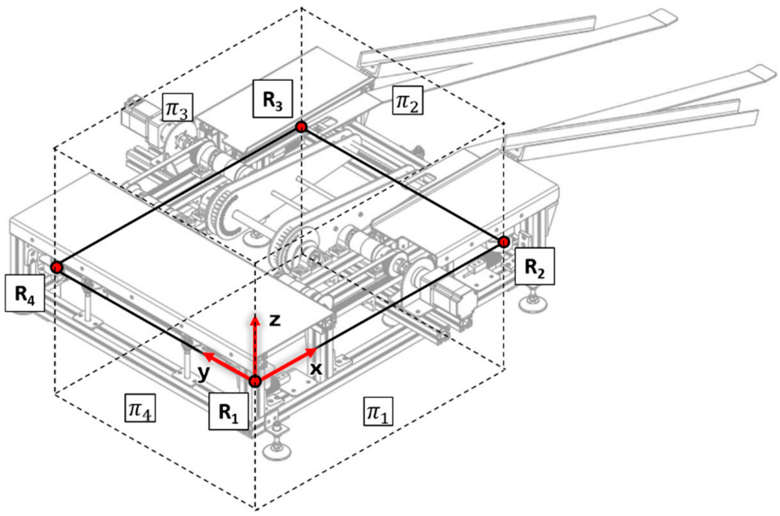

Figure 10. Schematic diagram of the test stand with the reactions determined using strain gauge scales in four measurement planes (source: [34]).

To determine the position of the COM, the distances f_{12}, f_{23}, f_{43}, and f_{14} between successive points of applied reaction forces R_i are measured, balancing the moments in each of the four analyzed planes π_i (Figure 11). These distances indicate the distribution of forces between pairs of scales, simplifying the calculations to a one-dimensional space.

The distances f_i (Figure 12) are marked on the sides of the rectangle defined by the points of application of the reaction forces

R_i. Then, through points P_i on the sides of the rectangle, two lines can be drawn that intersect at a single point in the XY plane, determining the coordinates of the COM of the person–wheelchair system for a single measurement (Equations (5) and (6)).

$$x = \frac{-\frac{L_2 f_{12}}{f_{43}-f_{12}} - f_{14}}{\left(\frac{f_{23}-f_{14}}{L_1}\right) - \left(\frac{L_2}{f_{43}-f_{12}}\right)} \tag{5}$$

$$y = \frac{\left(\frac{f_{23}-f_{14}}{L_1}\right)\left(\frac{L_2 f_{12}}{f_{43}-f_{12}}\right) - \left(\frac{f_{23}-f_{14}}{L_1}\right) f_{14}}{\left(\frac{f_{23}-f_{14}}{L_1}\right) - \left(\frac{L_2}{f_{43}-f_{12}}\right)} + f_{14} \tag{6}$$

The described method allows the coordinates of the position of the COM in the horizontal plane to be determined [53–55]. Considering the use of this method in the stand described in Section 2.1, the measurement signal from the strain gauges is accessed. Delivering a measurement signal at 100 Hz is of significance in this case. Due to a simple method of converting the measurement signal and a high measurement frequency, it was possible to measure changes in the position of the COM under dynamic conditions characteristic of wheelchair propulsion. The disadvantage of the above method is that it does not measure the position of the COM in the vertical plane. However, this problem was solved by analytically determining the position of the COM vertically using data obtained from human body motion capture (Section 2.2).

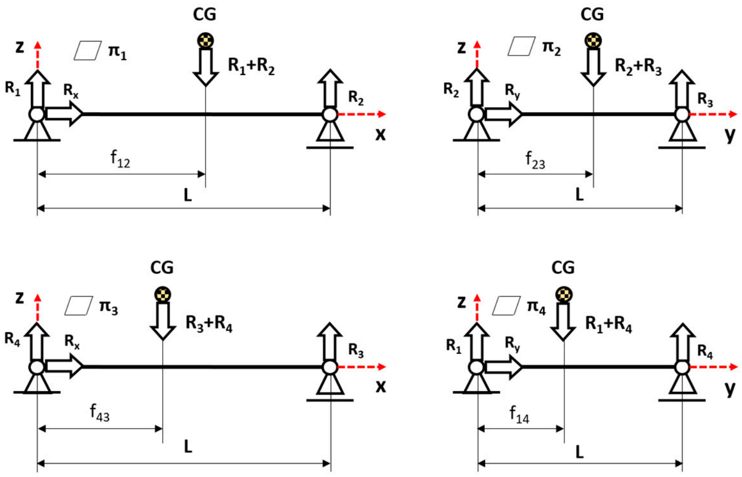

Figure 11. Schematic diagrams of the beams showing the position of the center of mass (COM) of the person in the wheelchair on each of the four measurement planes (source: [34]).

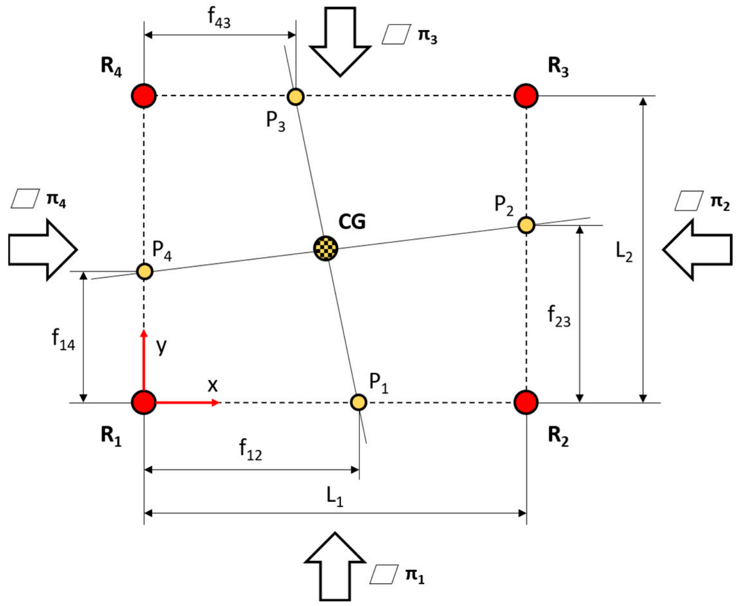

Figure 12. Schematic diagram of the method for determining the position of the center of mass (COM) in the XY plane (source: [34]).

3. Methods of Result Analysis

Analyzing experimental data provides valuable information about how different wheelchair features and their adjustments affect user comfort and overall wheelchair performance. This information helps to make informed decisions about which wheelchair best fits a particular user [56]. Conducting biomechanical research that evaluates the effects of a wheelchair's drive system on the human body requires the development of specialized methods for analyzing the research results. Such a need has been identified in the analysis of changes in the position of the COM of the human sitting in a wheelchair.

The variation in the position of the COM is imaged using a point cloud that is difficult to interpret statistically and implement into mathematical models. Therefore, a method of describing a set of points with elliptical areas was worked out. The exact algorithm of the method and its application to the analysis of selected experiments are described in a publication titled "Describing a Set of Points with Elliptical Areas: Mathematical Description and Verification on Operational Tests of Technical Devices" [57].

Representing a set of points using elliptical areas enables replacing any number of points with an ellipse that depicts their distribution on a plane (Figure 13). This method is particularly effective for sets of points in which the number of vectors leading to points R_{i} (11) larger than the average length of the leading vector $\vec{R}$ (12) is similar to the number of vectors smaller than the average length of the leading vector. This relationship can be verified by calculating the value of the distribution uniformity coefficient ΔP (Equation (9)) for the analyzed points $P(x_i;\, y_i)$ relative to the geometric COM $\vec{P}(\overline{x};\, \overline{y})$ of the analyzed set (Equations (10) and (11)). For the method to be effective, the value of the ΔP factor should be close to 0.5.

$$R_i = \sqrt{x_i^2 + y_i^2} \tag{7}$$

$$\overline{R} = \frac{\sum_{i=1}^{n} R_i}{n} \tag{8}$$

$$\Delta_P = \frac{n_{min}}{n} \tag{9}$$

$$\overline{x} = \frac{\sum_{i=1}^{n} x_i}{n} \tag{10}$$

$$\overline{y} = \frac{\sum_{i=1}^{n} y_i}{n} \tag{11}$$

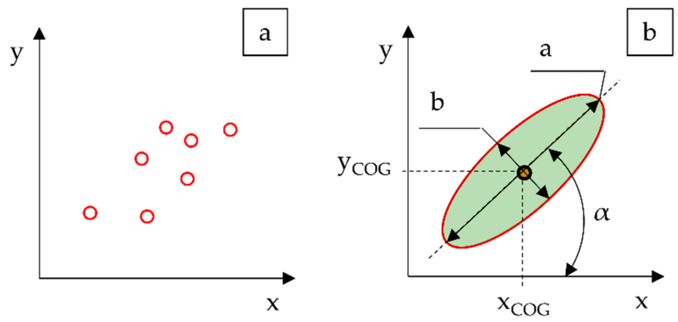

Figure 13. Schematic illustration of the method of replacing an arbitrary set of points (**a**) with an ellipse defining the area of points on the analyzed plane (**b**) (source: [57]).

Applying the method on a set of points that satisfies the properties described above results in its replacement by an ellipse defined by the five parameters of the position of the center of the ellipse x_{COG} (12) and y_{COG} (13), the angle of inclination of the directional line α (14), the length of the half-axis a (15) parallel to the directional line and the length of the half-axis b (16) perpendicular to the directional line.

$$x_{COG} = \frac{\sum_{i=1}^{n} x_i}{n} \tag{12}$$

$$y_{COG} = \frac{\sum_{i=1}^{n} y_i}{n} \tag{13}$$

$$\alpha = \tan^{-1}\left(\frac{\sum_{i=1}^{n}(x_i - \overline{x})(y_i - \overline{y})}{\sum_{i=1}^{n}(x_i - \overline{x})^2}\right) \tag{14}$$

$$a = 2\sigma_x = 2\sqrt{\frac{\sum_{i=1}^{n}\left(x'_i - \overline{x'}\right)^2}{n}} \tag{15}$$

$$b = 2\sigma_y = 2\sqrt{\frac{\sum_{i=1}^{n}\left(y'_i - \overline{y'}\right)^2}{n}} \tag{16}$$

The position of the COM within the human–wheelchair system significantly influences propulsion efficiency and fall risk [4]. Given the complex interactions between the human and the wheelchair, experimentally studying the dynamic changes in the COM position is crucial. Rapidly determining the COM location can enhance user well-being and overall wheelchair performance.

4. Summary and Conclusions

Analysis of the scientific literature reveals that laboratory methods for measuring wheelchair propulsion can be broadly categorized into two primary approaches: wheelchair dynamometer-based and biomechanical analysis. The wheelchair dynamometer-based methods analyze propulsion efficiency, total muscle effort, power output during propulsion cycles, and energy expenditure. Biomechanical analysis methods assess body position and posture, joint angles, muscle activity, center of mass (COM) changes, and the trajectory of wheelchair movement during propulsion.

While real-world propulsion measurement has various methodological limitations, wheelchair dynamometers remain the most reliable laboratory apparatus for assessing propulsion efficiency. This is because they measure the forces and torques the wheelchair generates during propulsion, which are the key determinants of these performance metrics. Biomechanical analysis methods can also provide valuable insights into wheelchair propulsion performance, but they are generally considered less valid and reliable than dynamometer-based methods. Biomechanical measurements are often indirect and can be influenced by factors such as joint alignment and muscle activation patterns. Both groups of laboratory testing methods require the efficient processing of large datasets to extract meaningful insights. Integrating diverse methods for wheelchair drive measurement is considered the most effective approach for comprehensive evaluation and analysis.

Based on the literature analyses presented, the following conclusions can be drawn:

1. Manual wheelchairs have many advantages and cannot be entirely replaced by electric wheelchairs, so developing ways to power them efficiently is worth learning about [58]. There is a noticeable trend of adapting the manual propulsion system to the individual physical capabilities of the user. This is achieved through hybrid drives or add-on modules like the anti-rollback system.
2. Multiple factors, including human characteristics, wheelchair design, and environmental conditions, influence the efficiency, safety, and comfort of manual wheelchair propulsion for individuals with mobility limitations [59]. Optimizing these factors can enhance the overall experience of using a manual wheelchair.
3. A wheelchair dynamometer has two functions: to simulate the actual operation conditions during laboratory testing and to measure several biomechanical parameters [31]. The simulation is achieved by changing the tilt angle of the wheelchair and controlling the dynamic force applied to the driving wheel of the wheelchair. The biomechanical parameters measured by the dynamometer include the COM position, measurement of wheelchair and human body kinematics, measurement of muscle effort using surface electromyography, and analysis of exhaled gases. Such a comprehensive evaluation of wheelchairs allows for gaining new knowledge for wheelchair design, user adjustment and fitting, and propulsion technique training.

The dynamometer eliminates the physical linear motion of the wheelchair. Lack of sensation of wheelchair motion may interfere with the tests performed and lead to erroneous results [60]. It is, therefore, necessary to provide the user with information about the trajectory of the wheelchair during laboratory testing [47].

The location of the COM within the human–wheelchair biomechanical system is pivotal in determining propulsion efficiency and overall stability. For this reason, it is essential to study changes in the position of the COM under dynamic conditions [55].

Conducting biomechanical tests means collecting data at high frequency. This results in a large amount of data on which to base an analysis of the impact of the technical measure on humans. Working with large datasets is challenging and requires a lot of computational resources. Therefore, it is necessary to develop analysis methods that replace datasets located in a three-dimensional space with several parameters describing a geometric figure approximating the range of variation in the measured data [57].

Further research is needed to develop more personalized wheelchair designs that better accommodate users' physical characteristics and needs. This could involve advancements in adjustable features, seating systems, and manual and hybrid propulsion mechanisms [61].

Technological advancements drive changes in laboratory testing methods. Wearable sensors hold immense potential in optimizing manual wheelchair propulsion. The real-time tracking of a user's propulsion parameters, like push force, stroke rate, and efficiency, allows for the development of personalized optimization strategies for propulsion, empowering users to improve their performance and maximize comfort over time [62].

The growing trend of electric drives in individual transportation, progressively replacing or complementing human muscle power, is becoming more prevalent [63,64]. Environmental concerns, technological advancements, and the pursuit of convenience drive the trend toward electric vehicles. This shift is noticeable across various vehicles, such as bicycles, scooters, and other mobility devices, designed for people with disabilities. This trend has been associated with the mechanization of wheelchair propulsion and steering [65]. Nevertheless, the scientific literature raises questions about whether this path is optimal and advocates for innovative solutions that utilize human muscle power more efficiently [61,66]. This approach aligns well with current sustainability principles.

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