Self-presentation

1. Personal data and education

Full name: ***Bartosz Wieczorek***

ORCID: **0000-0003-0808-298X**

Higher education at Poznan University of Technology, Faculty of Mechanical Engineering and Transport, completed in 2012. Mechanical Engineering degree course in Virtual Design Engineering. The studies were completed with the professional title *MA Eng.*

Doctoral studies at Poznan University of Technology, Faculty of Mechanical Engineering and Transport completed in 2015. Studies leading to a degree of *doctor of engineering sciences* in the field of technical sciences, discipline of mechanical engineering and operation.

I received my doctoral degree in technical sciences for my thesis entitled "Studies on the development of locomotion means of assistive technology (on the example of innovative wheelchairs and their families)". The thesis was written under the direction of Prof. Bogdan Branowski and Dr Marek Zabłocki. The thesis was positively reviewed by Prof. Marek Gawrysiak and Prof. Piotr Gendarz.

2. Training

Training course on "Research project management" organised by the National Centre for Research and Development completed in 2017.

Training in the use of the Cosmed K5 metabolic measurement instrument, including the process of pre-calibrating the instrument, performing tests according to selected protocols, along with discussion and interpretation of results. Organized by the company "Mikropolis – authorized and exclusive representative of COSMED Srl. in Poland" in 2022

PART-66, PART-147 and human factors training organised by Poznan University of Technology in 2022

2. Employment

Period of employment: 2015 – 2016

Venue: Poznan University of Technology, Faculty of Engineering and Transport, Department of Fundamentals of Mechanical Engineering

Position: Assistant

Period of employment: 2016 – 2000

Venue: Poznan University of Technology, Faculty of Engineering and Transport, Department of Fundamentals of Mechanical Engineering

Position: Assistant Professor

Period of employment: 2020 – present

Venue: Poznan University of Technology, Faculty of Mechanical Engineering, Institute of Machine Construction

Position: Assistant Professor

Period of employment: 2017 – 2020

Venue: Poznan University of Technology, Faculty of Engineering and Transport, Department of Fundamentals of Mechanical Engineering

Position: Project manager for the project entitled "Research on the biomechanics of manual wheelchair propulsion for innovative manual and hybrid propulsions" (LIDER/7/0025/L_7/15/NCBR/2016), funded by the National Centre for Research and Development

Period of employment: 2021 – present

Venue: Poznan University of Technology, Faculty of Mechanical Engineering, Institute of Machine Construction

Position: key R&D personnel and administrative staff in the project entitled "Innovative Wheelchair Propulsion Systems – Design, Prototype, Research" (Rzeczy są dla ludzi/0004/2020), funded by the National Centre for Research and Development

3. Indication of scientific achievement

As an achievement, resulting from Article 219, paragraph 1 of the Act of 1 January 2022 "Conditions for conferring the degree of habilitated doctor – Act on Higher Education and Science" (Journal of Laws 2021.478 i.e.), I indicate a series of ***28*** of thematically-related publications published between 2016 and 2022 (in accordance with Article 219.1.2b) and ***12*** patents granted between 2016 and 2022 by the Patent Office of the Republic of Poland (in accordance with Article 219.1 point 2c).

The above publications and patents of technical constructions form a thematically linked sequence of works comprising a scientific achievement defined as:

Development of manual wheelchair propulsions in terms of adapting them to the individual user's needs and improving selected biomechanical parameters

A detailed list of the articles and patents forming the related thematic series that make up the scientific achievement is presented in sections 3.1 and 3.2. I declare the scope of my scientific endeavours consisting of publications and patents as a contribution to the development of the discipline ***Mechanical Engineering***. An outline of the research topic which resulted in the scientific achievement is included in chapter 3.4. The following chapters present a summary of the work carried out as part of the declared scientific achievement

3.1 List of scientific publications included in the scientific achievement

A1	**Wieczorek, B**, Kukla, M., & Warguła, Ł. (2022). Describing a Set of Points with Elliptical Areas: Mathematical Description and Verification on Operational Tests of Technical Devices. Applied Sciences, 12(1), 445	Ministry of Science and Higher Education score: 100 points	Impact factor: 2.679
In the article, I was the creator of the research hypothesis and the originator of the research. My tasks included developing the research methodology and preparing the article. I performed the mathematical analysis of the experiments used in the work. I took an active part in the implementation of the research experiments presented in the publication. ***My percentage share was 80%***			
A2	Warguła, Ł., Kukla, M., **Wieczorek, B.**, & Krawiec, P. (2022). Energy consumption of the wood size reduction processes with employment of a low-power machines with various cutting mechanisms. Renewable Energy, 181, 630-639	Ministry of Science and Higher Education score: 140 points	Impact factor: 8.001
In this article, I was responsible for performing the analysis of the results in terms of describing a set of points with elliptic areas and participated in the implementation of the experiment. ***My percentage share was 10%***			
A3	Kukla, M., **Wieczorek, B.**, Warguła, Ł., Górecki, J., & Giedrowicz, M. (2021). An Analytical Modelling of Demand for Driving Torque of a Wheelchair with Electromechanical Drive. Energies, 14(21), 7315	Ministry of Science and Higher Education score: 140 points	Impact factor: 3.004
In this article, I was responsible for analysing the measurement signal to determine the centre of gravity of the human body and developing the results obtained in this aspect. In addition, I participated in the implementation of the bench experiment and was involved in the verification of the article content. ***My percentage share was 15%***			
A4	Kukla, M., **Wieczorek, B.**, Warguła, Ł., & Berdychowski, M. (2021). An analytical model of the demand for propulsion torque during manual wheelchair propelling. Disability and Rehabilitation: Assistive Technology, 16(1), 9-16	Ministry of Science and Higher Education score: 70 points	Impact factor: 2.500
In this article, I was responsible for verifying and correcting the developed wheelchair drive torque model. I took part in the implementation of the experiment and was in charge of verifying the content of the article. ***My percentage share was 35%***			
A5	**Wieczorek, B.**, Kukla, M., Warguła, Ł., Rybarczyk, D., Giedrowicz, M., & Górecki, J. (2021). The Impact of the Human Body Position Changes During Wheelchair Propelling on Motion Resistance Force: A Preliminary Study. Journal of Biomechanical Engineering, 143(8), 081008	Ministry of Science and Higher Education score: 70 points	Impact factor: 2.097

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<tr><td colspan="4"><i>In the article, I was the creator of the research hypothesis and the originator of the research. I developed the research methodology and participated in the implementation of the experiment. Above that, I prepared the content of the article, participated in the analysis of the results and the mathematical elaboration of the measured result. My percentage share was 50%</i></td></tr>
<tr><td>A6</td><td>Wieczorek, B., Kukla, M., & Warguła, Ł. (2021). The symmetric nature of the position distribution of the human body center of gravity during propelling manual wheelchairs with innovative propulsion systems. Symmetry, 13(1), 154. Ministry of Science and Higher Education score: 70 points, Impact factor: 2.713</td><td>Ministry of Science and Higher Education score: 70 points</td><td>Impact factor: 2.713</td></tr>
<tr><td colspan="4"><i>In the article, I was the creator of the research hypothesis and the originator of the research. I developed the research methodology and participated in the implementation of the experiment. In addition, I prepared the content of the article, participated in the analysis of the results and the mathematical elaboration of the measured result. The paper uses patented prototypes of which I was a co-author. My percentage share was 60%</i></td></tr>
<tr><td>A7</td><td>Wieczorek, B., & Kukla, M. (2020). Biomechanical Relationships Between Manual Wheelchair Steering and the Position of the Human Body's Center of Gravity. Journal of biomechanical engineering, 142(8), 081006</td><td>Ministry of Science and Higher Education score: 70 points</td><td>Impact factor: 2.097</td></tr>
<tr><td colspan="4"><i>In the article, I was the creator of the research hypothesis and the originator of the research. I developed the research methodology and participated in the implementation of the experiment. In addition, I prepared the content of the article, participated in the analysis of the results and the mathematical elaboration of the measured result. The paper uses patented prototypes of which I was a co-author. My percentage share was 70%</i></td></tr>
<tr><td>A8</td><td>Wieczorek, B., Kukla, M., Rybarczyk, D., & Warguła, Ł. (2020). Evaluation of the biomechanical parameters of human-wheelchair systems during ramp climbing with the use of a manual wheelchair with anti-rollback devices. Applied Sciences, 10(23), 8757</td><td>Ministry of Science and Higher Education score: 70 points</td><td>Impact factor: 2.679</td></tr>
<tr><td colspan="4"><i>In the article, I was the creator of the research hypothesis and the originator of the research. I developed the research methodology and participated in the implementation of the experiment. In addition, I prepared the content of the article, participated in the analysis of the results and the mathematical elaboration of the measured result. The paper uses patented prototypes of which I was a co-author. My percentage share was 40%</i></td></tr>
<tr><td>A9</td><td>Wieczorek, B., Warguła, Ł., & Rybarczyk, D. (2020). Impact of a hybrid assisted wheelchair propulsion system on motion kinematics during climbing up a slope. Applied Sciences, 10(3), 1025.</td><td>Ministry of Science and Higher Education score: 70 points</td><td>Impact factor: 2.679</td></tr>
<tr><td colspan="4"><i>In the article, I was the creator of the research hypothesis and the originator of the research. I developed the research methodology and participated in the implementation of the experiment. In addition, I prepared the content of the article, participated in the analysis of the results and the mathematical elaboration of the measured result. The paper uses patented prototypes of which I was a co-author. My percentage share was 60%</i></td></tr>
<tr><td>A10</td><td>Wieczorek, B., & Kukla, M. (2019). Effects of the performance parameters of a wheelchair on the changes in the position of the</td><td>Ministry of Science and Higher</td><td>Impact factor: 2.740</td></tr>
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	centre of gravity of the human body in dynamic condition. PloS one, 14(12), e0226013	Education score: 100 points	
In the article, I was the creator of the research hypothesis and the originator of the research. I developed the research methodology and participated in the implementation of the experiment. In addition, I prepared the content of the article, participated in the analysis of the results and the mathematical elaboration of the measured result. The paper uses patented prototypes of which I was a co-author. ***My percentage share was 60%***			
A11	**Wieczorek, B.** (2021). Methods of Determining Trajectory for Wheelchair with Manual Pushrims Drive. In IOP Conference Series: Materials Science and Engineering (Vol. 1016, No. 1, p. 012004). IOP Publishing	Ministry of Science and Higher Education score: 5 points	---
My percentage share was 100%			
A12	**Wieczorek, B.**, & Kukla, M. (2020). Methods for measuring the position of the centre of gravity of an anthropotechnic human-wheelchair system in dynamic conditions. In IOP Conference Series: Materials Science and Engineering (Vol. 776, No. 1, p. 012062). IOP Publishing	Ministry of Science and Higher Education score: 5 points	---
In the article, I was the creator of the research hypothesis and the originator of the research. I developed the research methodology and participated in the implementation of the experiment. In addition, I prepared the content of the article, participated in the analysis of the results and the mathematical elaboration of the measured result. The paper uses patented prototypes of which I was a co-author. ***My percentage share was 60%***			
A13	**Wieczorek, B.**, Warguła, Ł., Kukla, M., Kubacki, A., & Górecki, J. (2020). The effects of ArUco marker velocity and size on motion capture detection and accuracy in the context of human body kinematics analysis. Technical Transactions, 117(1)	Ministry of Science and Higher Education score: 20 points	---
In the article, I was the creator of the research hypothesis and the originator of the research. I developed the research methodology and participated in the implementation of the experiment. In addition, I prepared the content of the article, participated in the analysis of the results and the mathematical elaboration of the measured result. The paper uses patented prototypes of which I was a co-author. ***My percentage share was 60%***			
A14	Warguła, Ł., Kukla, M., & **Wieczorek, B.** (2020). The impact of wheelchairs driving support systems on the rolling resistance coefficient. In IOP Conference Series: Materials Science and Engineering (Vol. 776, No. 1, p. 012076). IOP Publishing	Ministry of Science and Higher Education score: 5 points	---
In this article, I took part in the implementation of the experiment and the analysis of the results. ***My percentage share was 10%***			
A15	**Wieczorek B.** (2019): Biomechanical research on designing wheelchair propulsion systems, In: Research on the biomechanics of manual wheelchair drive for innovative manual and hybrid drives, **ed. Bartosz Wieczorek**, Publishing House Kazimierz Pulaski University of Technology and Humanities in Radom, pp. 11-24.	Ministry of Science and Higher Education score: 20 points	---

<table>
<tr><td colspan="4"><i>My percentage share was 100%</i></td></tr>
<tr><td>A16</td><td>Wieczorek B. (2019): Methodology for determination of kinematic-dynamic parameters of the human-wheelchair anthropotechnical system, In: Research on the biomechanics of manual wheelchair drive for innovative manual and hybrid drives, ed. Bartosz Wieczorek, Publishing House Kazimierz Pulaski University of Technology and Humanities in Radom, pp. 93-107. Ministry of Science and Higher Education score: 20 points</td><td>Ministry of Science and Higher Education score: 20 points</td><td>---</td></tr>
<tr><td colspan="4"><i>My percentage share was 100%</i></td></tr>
<tr><td>A17</td><td>Wieczorek B., Kukla M. (2019): Procedure for measuring the biomechanical parameters of the wheelchair propulsion process with the use of a wheelchair dynamometer, In: Research on the biomechanics of manual wheelchair drive for innovative manual and hybrid drives, ed. Bartosz Wieczorek, Publishing House Kazimierz Pulaski University of Technology and Humanities in Radom, pp. 53-63</td><td>Ministry of Science and Higher Education score: 20 points</td><td>---</td></tr>
<tr><td colspan="4"><i>In the article, I was the creator of the research hypothesis and the originator of the research. I developed the research methodology and participated in the implementation of the experiment. In addition, I prepared the content of the article, participated in the analysis of the results and the mathematical elaboration of the measured result. The paper uses patented prototypes of which I was a co-author.</i> <i>My percentage share was 60%</i></td></tr>
<tr><td>A18</td><td>Wargula, Ł., Wieczorek, B., & Kukla, M. (2019). The determination of the rolling resistance coefficient of objects equipped with the wheels and suspension system–results of preliminary tests. In MATEC Web of Conferences (Vol. 254, p. 01005). EDP Sciences.</td><td>Ministry of Science and Higher Education score: 5 points</td><td>---</td></tr>
<tr><td colspan="4"><i>In this article, I verified the developed research methodology. In addition, I took part in the experiment being carried out and in the design and construction of the prototype under study.</i> <i>My percentage share was 10%</i></td></tr>
<tr><td>A19</td><td>Wieczorek B. (2019): Adaptive modes supporting propulsion of a manual wheelchair, In: Research on the biomechanics of manual wheelchair drive for innovative manual and hybrid drives, ed. Bartosz Wieczorek, Publishing House Kazimierz Pulaski University of Technology and Humanities in Radom, pp. 135-145</td><td>Ministry of Science and Higher Education score: 20 points</td><td>---</td></tr>
<tr><td colspan="4"><i>My percentage share was 100%</i></td></tr>
<tr><td>A20</td><td>Wieczorek B., Górecki J. (2019): Design and engineering of a test stand for testing human wheelchair anthropotechnical systems, In: Research on the biomechanics of manual wheelchair drive for innovative manual and hybrid drives, ed. Bartosz Wieczorek, Publishing House Kazimierz Pulaski University of Technology and Humanities in Radom, pp. 41-52</td><td>Ministry of Science and Higher Education score: 20 points</td><td>---</td></tr>
<tr><td colspan="4"><i>In this article, I was the creator of the design methodology described. I developed the described design procedures and construction problems. In addition, I prepared the content of the article, participated in the analysis of the results and the mathematical elaboration of the measured result. The paper uses patented prototypes of which I was a co-author.</i> <i>My percentage share was 80%</i></td></tr>
<tr><td>A21</td><td>Wieczorek B. (2019): Prototype of an internal gear hub for wheelchairs with a hand rim propulsion system, In: Research on the biomechanics of manual wheelchair drive for innovative manual and hybrid drives, ed. Bartosz Wieczorek, Publishing House</td><td>Ministry of Science and Higher Education</td><td>---</td></tr>
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	Kazimierz Pulaski University of Technology and Humanities in Radom, pp. 147-162	score: 20 points	
My percentage share was 100%			
A22	Branowski B., Zabłocki M., **Wieczorek B.**, Kurczewski P, Torzyński D. (2017): Projektowanie rodziny konstrukcji elektrycznych pojazdów transportowych lub rehabilitacyjnych o wspólnej platformie bazowej, In: Wprowadzenie do inżynierii rehabilitacyjnej: collective work, ed. Marek Zabłocki, Wydział Maszyn Roboczych i Transportu, Politechnika Poznańska, - pp. 187-207	Ministry of Science and Higher Education score: 20 points	---
In this article, I developed the described concept of a family of electric transport or rehabilitation vehicle designs with a common base platform. I co-authored the functional structure describing the idea of this type of device. ***My percentage share was 25%***			
A23	**Wieczorek, B.**, & Warguła, Ł. (2019). Problems of dynamometer construction for wheelchairs and simulation of push motion. In MATEC Web of Conferences (Vol. 254, p. 01006). EDP Sciences	Ministry of Science and Higher Education score: 5 points	---
In this article, I was the creator of the design methodology described. I developed the described design procedures and construction problems. In addition, I prepared the content of the article, participated in the analysis of the results and the mathematical elaboration of the measured result. The paper uses patented prototypes of which I was a co-author. ***My percentage share was 90%***			
A24	Kukla, M., **Wieczorek, B.**, & Warguła, Ł. (2018). Development of methods for performing the maximum voluntary contraction (MVC) test. In MATEC Web of Conferences (Vol. 157, p. 05015). EDP Sciences.	Ministry of Science and Higher Education score: 15 points	---
In this article, I verified the developed research methodology. In addition, I took part in the experiment being carried out and in the design and construction of the prototype under study. ***My percentage share was 10%***			
A25	**Wieczorek, B.**, Górecki, J., Kukla, M., & Wojtokowiak, D. (2017). The analytical method of determining the center of gravity of a person propelling a manual wheelchair. Procedia Engineering, 177, 405-410	Ministry of Science and Higher Education score: 15 points	
In the article, I was the creator of the research hypothesis and the originator of the research. I developed the research methodology and participated in the implementation of the experiment. In addition, I prepared the content of the article, participated in the analysis of the results and the mathematical elaboration of the measured result. ***My percentage share was 80%***			
A26	**Wieczorek, B.**, & Kukla, M. (2021, November). The method of measuring motion capture in wheelchairs during actual use–description of the method and model of measuring signal processing. In IOP Conference Series: Materials Science and Engineering (Vol. 1199, No. 1, p. 012084). IOP Publishing.	Ministry of Science and Higher Education score: 5 points	
In the article, I was the creator of the research hypothesis and the originator of the research. I developed the research methodology and participated in the implementation of the experiment. In addition, I prepared the content of the article, participated in the analysis of the results and the mathematical elaboration of the measured result. ***My percentage share was 90%***			

A27	**Wieczorek, B.** (2022). The Wheelchair Propulsion Wheel Rotation Angle Function Symmetry in the Propelling Phase: Motion Capture Research and a Mathematical Model. Symmetry, 14, p. 576	Ministry of Science and Higher Education score: 70 points	2.713
My percentage share was 100%			
A28	**Wieczorek, B.**, Kukla, M., Warguła, Ł., Giedrowicz, M., & Rybarczyk, D. (2022). Evaluation of anti-rollback systems in manual wheelchairs: muscular activity and upper limb kinematics during propulsion. Scientific Reports, 12(1), 1-15.	Ministry of Science and Higher Education score: 140 points	4.996
In the article, I was the creator of the research hypothesis and the originator of the research. I developed the research methodology and participated in the implementation of the experiment. In addition, I prepared the content of the article, participated in the analysis of the results and the mathematical elaboration of the measured result. ***My percentage share was 70%***			

3.2 List of patents and patent applications included in the scientific achievement

P1	**Wieczorek B.**, Zabłocki M.: Dźwigniowy system napędowy wózka inwalidzkiego, Patent at the Patent Office of the Republic of Poland, no. of exclusive right PL 223141, 2016	Ministry of Science and Higher Education score: 30 points
My contribution to the invention consisted of developing the original principle of the invention, leading the conceptual and design work. In addition, I was involved in the state-of-the-art review and in the drafting of patent claims. ***My percentage share was 65%***		
P2	**Wieczorek B.**, Zabłocki M.: Piasta przekładniowa wielobiegowa do ręcznych wózków inwalidzkich, Patent at the Patent Office of the Republic of Poland, no. of exclusive right PL 223142, 2016	Ministry of Science and Higher Education score: 30 points
My contribution to the invention consisted of developing the original principle of the invention, leading the conceptual and design work. In addition, I was involved in the state-of-the-art review and in the drafting of patent claims. ***My percentage share was 65%***		
P3	**Wieczorek B.**, Kukla M.: Stabilizator osi koła wózka inwalidzkiego, Patent at the Patent Office of the Republic of Poland, no. of exclusive right PL 239438, 2021	Ministry of Science and Higher Education score: 70 points
My contribution to the invention consisted of developing the original principle of the invention and leading the conceptual and design work. In addition, I was involved in the state-of-the-art review and in the drafting of patent claims. ***My percentage share was 50%***		
P4	Warguła Ł. **Wieczorek B.**: Ciąg do koła wózka inwalidzkiego, Patent at the Patent Office of the Republic of Poland, no. of exclusive right PL 239411, 2021	Ministry of Science and Higher

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<tr><td></td><td></td><td>Education score: 70 points</td></tr>
<tr><td colspan="3"><i>My contribution to the invention consisted of verification of the correctness of the invention and substantive consultation. In addition, I was involved in the state-of-the-art review and in the drafting of patent claims. My percentage share was 25%</i></td></tr>
<tr><td>P5</td><td>Wieczorek B., Warguła Ł., Kukla M.: Moduł do uniwersalnego hamulca dźwigniowego koła wózka inwalidzkiego, Patent at the Patent Office of the Republic of Poland, no. of exclusive right PL 239693, 2021</td><td>Ministry of Science and Higher Education score: 70 points</td></tr>
<tr><td colspan="3"><i>My contribution to the invention consisted of developing the original principle of the invention, leading the conceptual and design work. In addition, I was involved in the state-of-the-art review and in the drafting of patent claims. My percentage share was 70%</i></td></tr>
<tr><td>P6</td><td>Wieczorek B., Warguła Ł., Kukla M.: Zestaw modyfikacyjny układu napędu do hybrydowego elektryczno-ręcznego wózka inwalidzkiego, Patent at the Patent Office of the Republic of Poland, no. of exclusive right PL 239350, 2021</td><td>Ministry of Science and Higher Education score: 70 points</td></tr>
<tr><td colspan="3"><i>My contribution to the invention consisted of developing the original principle of the invention and leading the conceptual and design work. In addition, I was involved in the state-of-the-art review and in the drafting of patent claims. My percentage share was 45%</i></td></tr>
<tr><td>P7</td><td>Wieczorek B., Warguła Ł., Giedrowicz M.: Karoseria wózka inwalidzkiego z zespołem mocowania, Patent at the Patent Office of the Republic of Poland, no. of exclusive right PL 239351, 2021</td><td>Ministry of Science and Higher Education score: 70 points</td></tr>
<tr><td colspan="3"><i>My contribution to the invention was to develop the original functional structure, analyse the need of the users of the invention and lead the conceptual and design work. In addition, I was involved in the state-of-the-art review and in the drafting of patent claims. My percentage share was 30%</i></td></tr>
<tr><td>P8</td><td>Wieczorek B., Rybarczyk D., Kubacki A.: System kontroli gestem wózka inwalidzkiego z napędem elektrycznym, Patent at the Patent Office of the Republic of Poland, no. of exclusive right PL 239351, 2021</td><td>Ministry of Science and Higher Education score: 70 points</td></tr>
<tr><td colspan="3"><i>My contribution to the invention consisted of developing the original principle of the invention and leading the conceptual and design work. In addition, I was involved in the state-of-the-art review and in the drafting of patent claims. My percentage share was 33%</i></td></tr>
<tr><td>P9</td><td>Wieczorek B., Branowski B., Głowala S., Zabłocki M.: Pojazd transportowy lub rehabilitacyjny dla osób z niepełnosprawnością ruchu, Patent at the Patent Office of the Republic of Poland, no. of exclusive right PL 228166, 2018</td><td>Ministry of Science and Higher Education score: 70 points</td></tr>
<tr><td colspan="3"><i>My contribution to the invention consisted of developing the original principle of the invention and participating in the conceptual and design work. In addition, I was involved in the state-of-the-art review and in the drafting of patent claims. My percentage share was 30%</i></td></tr>
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P10	**Wieczorek B.**, Warguła Ł., Kukla M., Berdychowski M.: Moduł do uniwersalnego hamulca dźwigniowego koła wózka inwalidzkiego, Patent at the Patent Office of the Republic of Poland, no. of exclusive right PL 239410, 2021	Ministry of Science and Higher Education score: 70 points
*My contribution to the invention consisted of developing the original principle of the invention, leading the conceptual and design work. In addition, I was involved in the state-of-the-art review and in the drafting of patent claims. **My percentage share was 40%***		
P11	**Wieczorek B.**, Warguła Ł., Waluś K.J., Kukla M.: Urządzenie do pomiaru siły oporów toczenia obiektów wyposażonych w układ jezdny, Patent at the Patent Office of the Republic of Poland, no. of exclusive right PL 239410, 2021	Ministry of Science and Higher Education score: 70 points
*My contribution to the invention consisted of developing the original functional concept of the invention and participating in the conceptual and design work. In addition, I was involved in the state-of-the-art review and in the drafting of patent claims. **My percentage share was 40%***		
P12	Górecki J., **Wieczorek B.**, Kukla M., Wilczyński D., Wojtkowiak D.: Urządzenie do symulacji warunków eksploatacji i pomiaru parametrów dynamicznych wózka inwalidzkiego, Patent at the Patent Office of the Republic of Poland, application No. P.424482, 2021	Ministry of Science and Higher Education score: 70 points
*My contribution to the invention consisted of developing the original functional concept of the invention and participating in the conceptual and design work. In addition, I was involved in the state-of-the-art review and in the drafting of patent claims. **My percentage share was 30%***		

3.3 Summary table of achieved indicators from the scientific output included in the scientific achievement

Type of scientific output	***Summary score of the Ministry of Science and Higher Schooling***	***Summary Impact factor***
Scientific articles and monograph chapters	1190 points	33.902
Patents	760 points	---
TOTAL	***1950 points***	***33.902***
Total deductible on the basis of the declared percentage	***936.1***	***15.449***

3.4. Outline of ongoing research topic

The scientific achievement I have presented is a response to the problem of increasing the accessibility of manual wheelchairs for people with mobility impairments whose degree of physical fitness prevented continuous operation of the manual propulsion. In my research and development work, I have placed great emphasis on the applicability of the results achieved. Therefore, most of the publications presented are supported by a patented and built real prototype. I have focused my research activities in the area of wheelchair propulsion systems because it performs the main function of the human-wheelchair anthropotechnical system, which is to satisfy the need for locomotion. The realisation of this function by the user using a classic wheelchair is in most cases limited by the design and geometrical features of the propulsion system and the individual physical characteristics of the user. The main advantage of using a manual propulsion is that physical activity is an important component of the rehabilitation process. Therefore, the problem of the mismatch between manual propulsions and the varying physical capabilities of humans has been noted, which can disqualify the operation of a manual propulsion due to its mismatch with the physical capabilities of the user and the place of operation.

The genesis for starting research work on the development of manual propulsion systems was an analysis of the current population of people with mobility disabilities. During this analysis, it was noted that there is a wide variation in the degree of disability, which translates into varying physical capabilities of the wheelchair user. The physical capabilities of the wheelchair user determine the type of propulsion system they use.

Currently, wheelchair users have electric and manual (e.g. pushrim) propulsion systems. The electric propulsion provides locomotion functions regardless of the wheelchair user's physical capabilities. With this propulsion system, the upper limbs are not involved in generating drive torque, only in controlling the wheelchair. The disadvantage of such propulsion is the lack of physical activity on the part of the user, as his participation in propelling the wheelchair is limited to the manipulation of the control system controller. In addition, electric propulsion wheelchairs are large structures with little mobility when transported and when moving indoors.

A different group are manual wheelchairs, which are the oldest technical solution and are also the most popular. The first known wheelchair solution that could be self-propelled by the user was developed in England in 1795. The designer of this wheelchair, John Dawson, fitted it with two drive wheels fitted with pushrims to allow them to be propelled by the upper limb. The solution of such a propulsion system being two independent wheels equipped with pushrims is an obsolete solution that is still in use today.

The main advantage of wheelchairs equipped with a manual pushrim propulsion system is the realisation of the locomotion function while at the same time realising the rehabilitation function. In addition, the design of such a wheelchair is simple and reliable. Its small size and weight allow it to be transported and make it easy to move indoors. Driving a manual wheelchair requires the upper limb to generate muscular force, which naturally forces the user to be physically active, essential for rehabilitation and keeping the body in good health. Despite these advantages, this type of propulsion system has a fundamental disadvantage, which is their adaptation to a small group of people with mobility impairments. Regardless of its type, the manual propulsion is dedicated to patients with a high degree of physical fitness.

On the basis of observation and cooperation with the wheelchair user community ("Jedna Chwila" Association), a problem was noticed in the mismatch between manual propulsion systems and the degree of disability and the individual physical capabilities of the user. This inadequacy allows wheelchair users to operate the wheelchair to a limited extent that does not reflect their social and personal needs. The mismatch between the wheelchair and the user translates into a reduction in the possible lifetime of the manual propulsion in the field and the value of the propulsion force generated by the muscles making it impossible to overcome certain off-road obstacles. The mismatch between the manual wheelchair propulsion systems currently in use and the individual characteristics of the user means that a significant proportion of people with disabilities choose not to use this type of propulsion. The reason for this decision stems from individual physical limitations and the fear of losing independence in extreme and rare operating scenarios. As a result, through technological limitations, they are at risk of further loss of mobility due to the lack of physical activity that could be provided by propelling a wheelchair using the upper limbs. At the same time, such a wheelchair should be individualised and adapted to the user and the place of use.

With the above outline of problems in wheelchair operation in mind, a research and design problem was formulated, defined as: **increasing the accessibility of manual wheelchairs and their adaptation to the individual physical capabilities of the user**. The problem thus defined initiated a series of research and development activities that included research grants, scientific articles, patents and awards at international invention fairs (Figure 1).

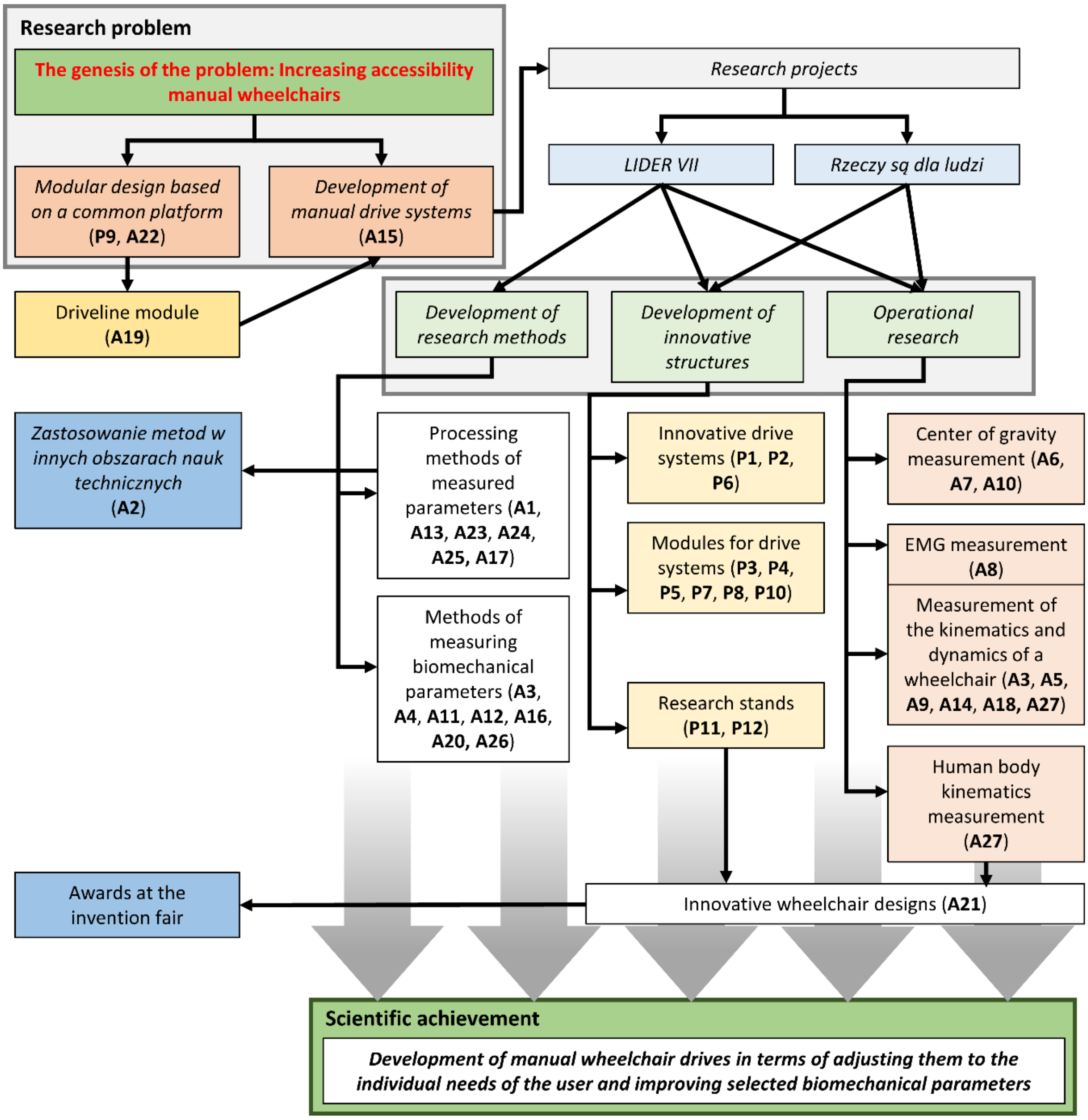


Fig. 1 Graphical representation of the scope of the research and development work carried out as part of the scientific achievement, taking into account the scientific output in accordance with sections 3.1 and 3.2.

The basic requirement that had to be met within the scope of the research and development problem posed was the adaptation of the manual propulsion in the wheelchair to the individualised physical capabilities of the user. The main rationale for addressing this problem was the simultaneous implementation of locomotion and rehabilitation functions by the manual propulsion system. The first concept to adapt the manual propulsion system to the individual physical capabilities of the user was the design of a modular wheelchair built on a common base platform. This work resulted in a patent (**P9**) (Figure 2) and a publication describing a methodology for developing a functional structure and assigning individual functions to modules (**A22**) enabling the construction of a functionally individualised wheelchair.

P9	***Wieczorek B.**, Branowski B., Głowala S., Zabłocki M.: Pojazd transportowy lub rehabilitacyjny dla osób z niepełnosprawnością ruchu, Patent at the Patent Office of the Republic of Poland, no. of exclusive right PL 228166, 2018*		*Ministry of Science and Higher Education score: 70 points*
A22	*Branowski B., Zabłocki M., **Wieczorek B.**, Kurczewski P, Torzyński D. (2017): Projektowanie rodziny konstrukcji elektrycznych pojazdów transportowych lub rehabilitacyjnych o wspólnej platformie bazowej, In: Wprowadzenie do inżynierii rehabilitacyjnej : collective work, ed. Marek Zabłocki, Wydział Maszyn Roboczych i Transportu, Politechnika Poznańska, - pp. 187-207*	*Ministry of Science and Higher Education score: 20 points*	---

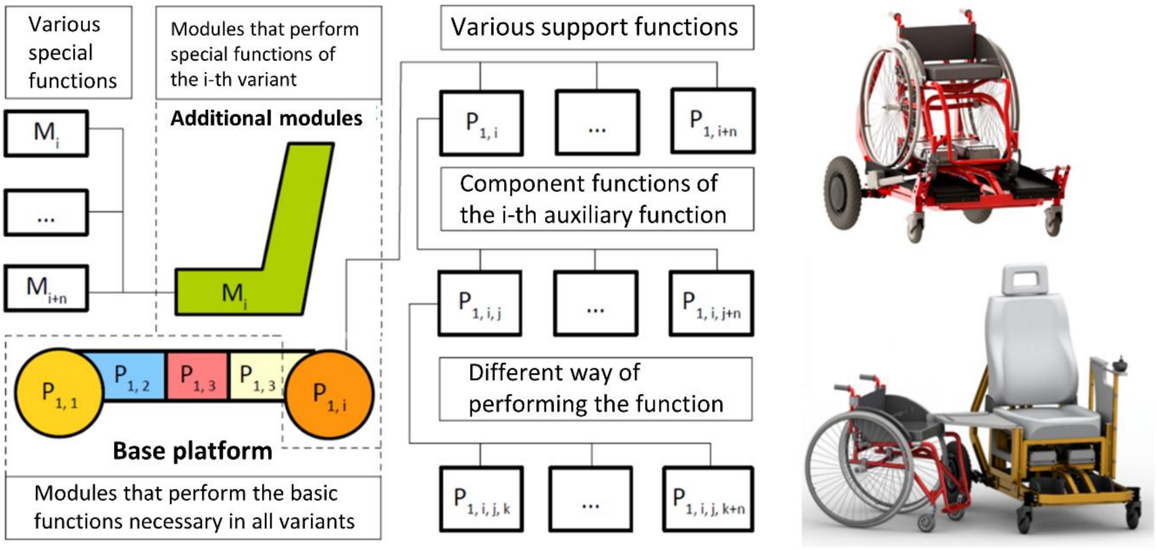


Fig. 2. Module structure for the i-th variant of the design family based on a common base platform with implementation examples.

The ongoing work on a modular family of wheelchair designs led me to separate the propulsion system from the wheelchair as a separate module that is part of a system called the wheelchair (**A19**). This approach made it possible to assume that this module can be freely modified and replaced even in classic manual wheelchairs. The separation of the manual propulsion as a single module allowed the research and development problem to be more specific and to focus on the study and analysis of only those biomechanical parameters that are related to the propulsion of the manual wheelchair.

A19	***Wieczorek B.** (2019): Adaptive modes supporting propulsion of a manual wheelchair, In: Research on the biomechanics of manual wheelchair drive for*	*Ministry of Science and Higher*	---

	*innovative manual and hybrid drives, **ed. Bartosz Wieczorek**, Publishing House Kazimierz Pulaski University of Technology and Humanities in Radom, pp. 135-145*	*Education score: 20 points*	

In my research and development of manual propulsion systems, I was guided by the principles of the Human Center Design method according to which the human being as user is at the centre and the technical device must meet his or her individual needs. In order to apply this methodological approach, it was necessary to produce real and functional prototypes. These prototypes were tested under real or simulated operating conditions. Based on these tests, biomechanical parameters were measured to assess the fit of the technical measure to the user.

Realisation of the defined R&D problem was facilitated by the implementation of two grants funded by the National Centre for Research and Development. The first of these, of which I was the manager, was a LIDER VII grant entitled "Research into the biomechanics of manual wheelchair propulsion for innovative manual and hybrid propulsions". The second one in which I acted as Principal Investigator was the Things Are For People grant entitled "Innovative Wheelchair Propulsion Systems – Design, Prototype, Research". A substantive summary of the work carried out as part of these projects is contained in the monograph "Biomechanical research on designing wheelchair propulsion systems" (A15), written under my editorship.

A15	***Wieczorek B.** (2019): Biomechanical research on designing wheelchair propulsion systems, In: Research on the biomechanics of manual wheelchair drive for innovative manual and hybrid drives, **ed. Bartosz Wieczorek**, Publishing House Kazimierz Pulaski University of Technology and Humanities in Radom, pp. 11-24.*	*Ministry of Science and Higher Education score: 20 points*	---

The realisation of the scientific achievement entitled: ***The development of manual wheelchair propulsions in terms of adapting them to the individual user's needs and improving selected biomechanical parameters*** required the implementation of three thematically related and overlapping stages:

- *the stage of development of test methods* enabling the measurement of biomechanical parameters affecting the operation of a manual wheelchair propulsion system,
- *the stage of development of innovative designs* in the form of functional prototypes of manual wheelchair propulsions,
- *the in-service test stage* consisting of tests to verify the effect of the propulsion system used on the biomechanical parameters of the entire anthropotechnical system.

3.5. Technical description of the scientific achievement

3.5.1 Research methods and analytical models developed

The basis of the scientific achievement developed was the development of a research methodology consisting of ***the development of proprietary methods for the measurement of biomechanical parameters related to the operation of the propulsion system***. The realisation of this objective consisted of parallel work on methods of realising the measurement of biomechanical parameters, methods of analysing and processing the measured measurement signals and the construction of original test benches. The development of the test method was closely linked to the construction of test benches, the most significant of which was the wheelchair dynamometer (Figure

3) and its additional modules. The methods developed determined the design features of this test bench.

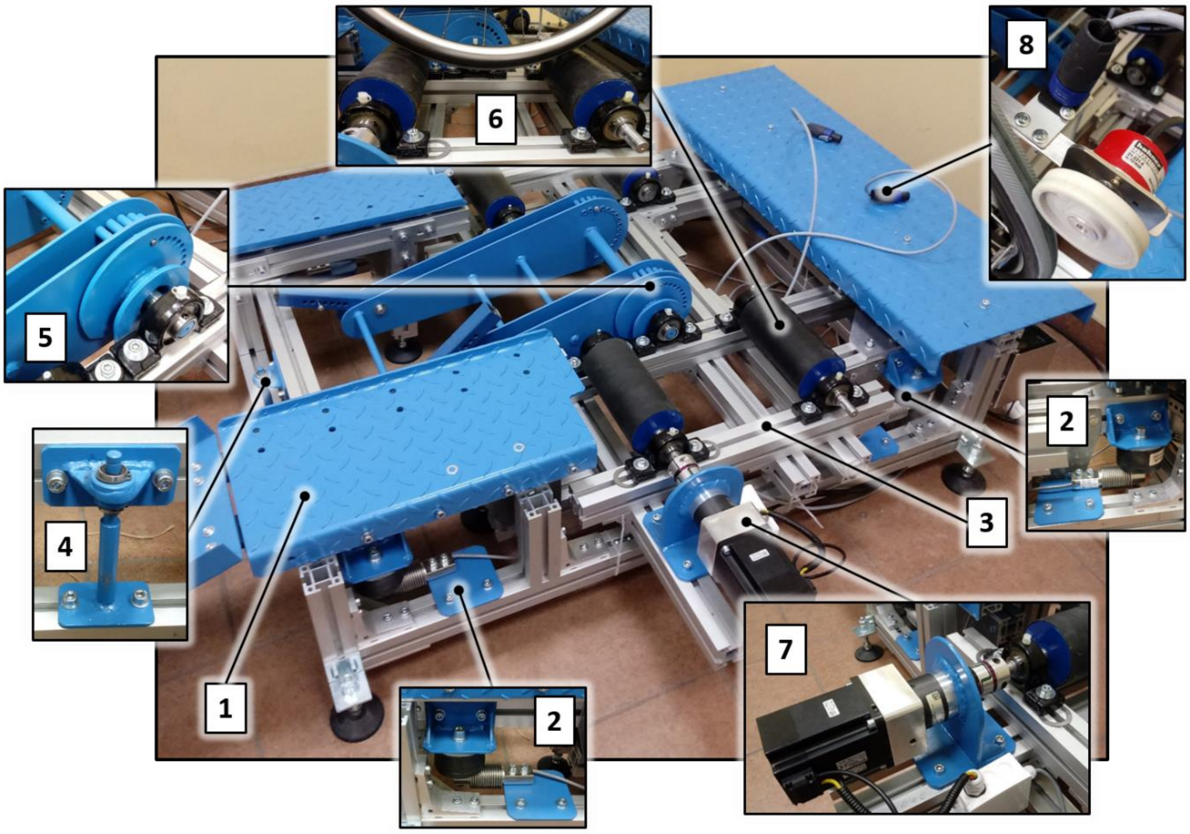


Fig. 3. View of the designed bench detailing the most important elements

The design of the wheelchair dynamometer and its use in research is described in the publication „Design and engineering of a test stand for testing human wheelchair anthropotechnical systems" (**A20**). The main component of the bench is the support frame (1) to which the weighing pan (3) is attached by means of strain gauge scales (2). Strain gauge scales measure the pressures induced by the wheelchair with the operator on the four points of the weighing pan (3). On this basis, the position of the centre of gravity of the man-wheelchair system is determined. Due to the sensitivity of the strain gauge scales to longitudinal loads, linear guides (4) were used to allow only vertical movement of the weighing pan relative to the support frame. The weighing pan were equipped with a wheelchair frame mounting system (5) and two traction roller systems (6). The wheelchair frame attachment system consists of a lever that allows the wheelchair to incline in the sagittal plane. The traction roller system consists of two rubber-coated rollers with a truncated cone shape tapering to the centre of the bench. The rollers receive drive torque from the drive wheels, but can also generate forced movements. The rear roller of the system is a passive roller whose function is only to support the wheelchair. A BLCD motor is attached to the front roller as a result of which it is the active roller. With its help, internal rolling resistance is reduced in the system and forced movements can be generated. In order to be able to record the distance and speed, two encoders (8) were mounted in the test bench member to allow independent measurement of the left and right wheels.

A20	***Wieczorek B.**, Górecki J. (2019): Design and engineering of a test stand for testing human wheelchair anthropotechnical systems, In: Research on the biomechanics of manual wheelchair drive for innovative manual and hybrid*	*Ministry of Science and Higher*	---

*drives, **ed. Bartosz Wieczorek**, Publishing House Kazimierz Pulaski University of Technology and Humanities in Radom, pp 41-52*	*Education score: 20 points*

The principle of the bench and its functional capabilities are shown in the diagram of Figure 4. The developed bench is a simulation and measurement device. With its help, it is possible to simulate the angle of inclination of the wheelchair and motion resistance associated with the type of terrain conditions simulated. Important for the simulation of field conditions was their translation into a motion resistance torque, which affects the entire anthropotechnical system. An analytical model of the driving torque used in the control of the bench is presented in the paper entitled „An analytical model of the demand for propulsion torque during manual wheelchair propelling" (**A4)**. The results of this work were also used in the work on adapting the drive torque model for wheelchairs equipped with a manual-electric hybrid propulsion (**A3**). For the work on this model, the original version was modernised to take into account the impact of the position of the power system. The position of the batteries translated into a change in the wheelchair's wheel load distribution. This, in turn, generated changes in the motion resistance value, which is the main factor determining the value of the driving torque of the wheelchair.

A3	*Kukla, M., **Wieczorek, B.**, Warguła, Ł., Górecki, J., & Giedrowicz, M. (2021). An Analytical Modelling of Demand for Driving Torque of a Wheelchair with Electromechanical Drive. Energies, 14(21), 7315*	*Ministry of Science and Higher Education score: 140 points*	*Impact factor: 3.004*
A4	*Kukla, M., **Wieczorek, B.**, Warguła, Ł., & Berdychowski, M. (2021). An analytical model of the demand for propulsion torque during manual wheelchair propelling. Disability and Rehabilitation: Assistive Technology, 16(1), 9-16*	*Ministry of Science and Higher Education score: 70 points*	*Impact factor: 2.500*

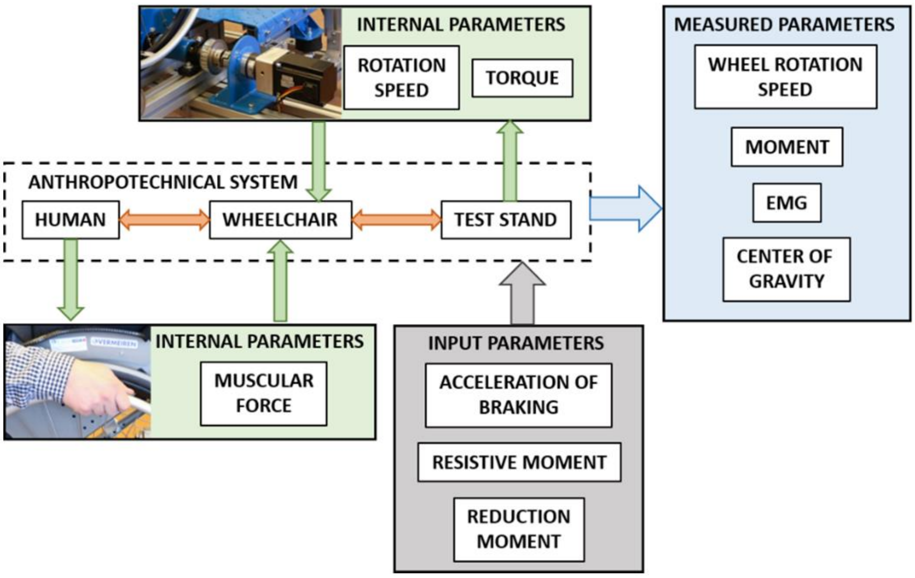


Fig. 4. Chart of the transmission of dynamic and biomechanical parameters within the system of the manual wheelchair propulsion biomechanics test bench [A20]

The dynamometer described is equipped with encoders, whose signal was used to determine the trajectory of the wheelchair. The method of determining the trajectory is described in paper „Methods of Determining Trajectory for Wheelchair with Manual Pushrims Drive" (**A11)** and was called the trapezoid method. The name derives from the way the method worked, which divided the movement of the wheelchair into trapeziums. The method developed uses differential wheelchair control consisting of varying the speed of the independently driven rear wheels v_L i v_P. According to the differential control principle, the turning radius *R* depends on the difference in the speed vectors of the drive wheels (Figure 5).

A11	***Wieczorek, B.*** *(2021). Methods of Determining Trajectory for Wheelchair with Manual Pushrims Drive. In IOP Conference Series: Materials Science and Engineering (Vol. 1016, No. 1, p. 012004). IOP Publishing*	*Ministry of Science and Higher Education score: 5 points*	---

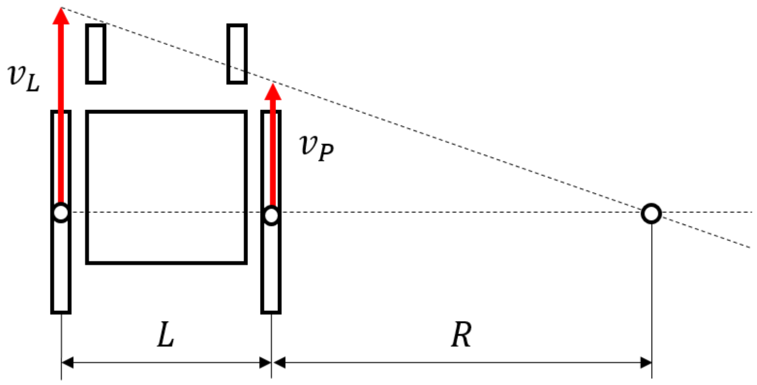


Fig. 5 Determination of the turning radius R using a geometric method based on known values of left wheel speed v_L, right wheel speed v_P and wheelbase L [A11]

When measuring the kinematic parameters of the wheelchair, the path of the left wheel s_L and the right wheel s_P were measured independently in the same time unit *t*. By dividing the whole wheelchair movement into equal time intervals, the wheelchair can be divided into trapezoids, in which the base is equal to the wheel base *L* and the sides are equal to the length of the path travelled by the left wheel s_L and the right wheel s_P (Figure 6 A, B).

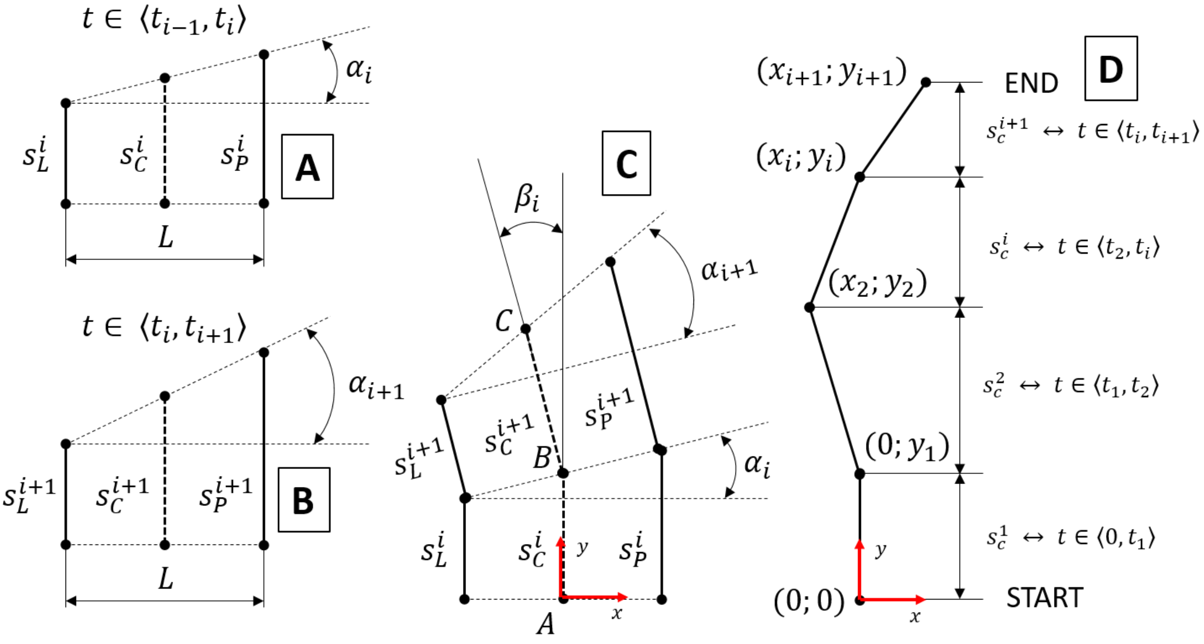


Fig. 6 Diagram of the distribution of wheelchair movement trajectories into trapezoids (description in text) [A11]

According to the trapezoid method, the entire movement must 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 (Fig. 6 A, B). Then the angle inclination *α* must be calculated relative to the horizontal of the straight line joining the path ends of the left wheel s_L and the right wheel s_P (1).

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

The trajectory of a wheelchair can be described as the change in position in space of a point which is the centre of the rear axle of the drive wheels. Therefore, for each trapezoid describing the path at equal time intervals *t*, the path of the centre of the axis s_C should be determined as the average of the paths travelled by the left-hand wheel s_L and the right-hand wheel s_P (2).

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

Determining the wheelchair's trajectory according to the trapezoid method involves assembling the entire wheelchair path from individual trapezoids according to several principles (Figure 6 C, B). The first trapezoid enveloping the path of the wheels and the centre of the axis always has a base *L* parallel to the x-axis and the point describing the centre of the axis for time *t=0* is the origin of the coordinate system. Each successive trapezoid should be drawn so that its base L lies on a line inclined at an angle α connecting the ends of the paths of the left wheel s_L and the right wheel s_P from the previous propulsion cycle. In addition, the centre points of the driving wheel axles from the end of the previous interval and the beginning of the new interval should coincide, as is the case with point B (Figure 6 C).

To determine the wheelchair trajectory, it is sufficient to determine the coordinates of the position of the centre point of the drive wheel axle for the end of each of the separated drive compartments (Figure 6 D). The coordinates $x_0=0$ and $y_0=0$ are taken as the first point. The coordinates of point two are $x_1=0$ $y_1=s_C^1$. The coordinates of each successive point are determined using equations (3):

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

Where the angle β is described by an equation that is the sum of all preceding angles α of the line connecting the ends of the paths of the left-hand wheel s_L and the right-hand wheel s_P (4).

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

The development of this method was necessary because, using the test bench (Figure 3), the wheelchair did not move relative to the bench. Therefore, the patient under study had no feedback to inform the direction of movement of the wheelchair he was driving.

The trajectory measurement was one of several kinematic parameters tested with the wheelchair dynamometer. A detailed description of all the kinematic parameters investigated is contained in the publication entitled „Methodology for determination of kinematic-dynamic parameters of the human-wheelchair anthropotechnical system" (**A16)**

A16	***Wieczorek B.*** *(2019): Methodology for determination of kinematic-dynamic parameters of the human-wheelchair anthropotechnical system, In: Research on the biomechanics of manual wheelchair drive for innovative manual and hybrid drives,* ***ed. Bartosz Wieczorek****, Publishing House Kazimierz Pulaski University of Technology and Humanities in Radom, pp. 93-107. Ministry of Science and Higher Education score: 20 points*	*Ministry of Science and Higher Education score: 20 points*	---

This publication also describes how the wheelchair speed measurement signal is processed and combined with analytical data (Figure 7). As a result of this combination, an overall histogram of the wheelchair speed waveform was determined. The main idea of the processing method was to measure the speed of the wheelchair on a dynamometer in which the propulsion phase (B) and the return phase (C) were extracted from the entire propulsion phase (A). Since different resistances were acting on the dynamometer than in real conditions, the measured wheelchair speed for the return phase (C) was replaced by an analytical model. The model could have taken into account, for example, a constant value for the deceleration acceleration a_h.

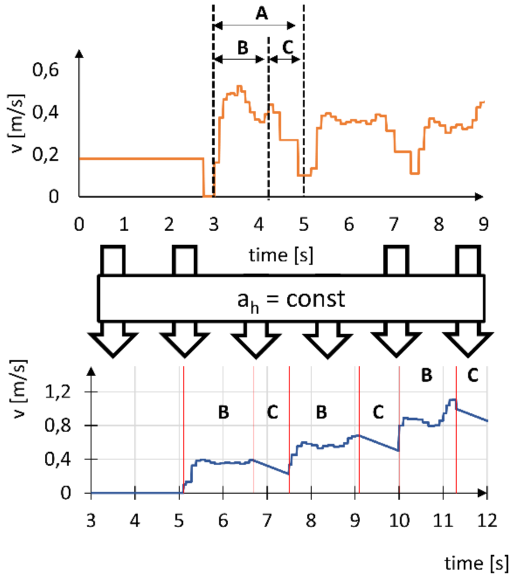


Fig. 7 Diagram of the transformation of wheelchair speed measured on a dynamometer to a signal modified by an analytical model of constant deceleration acceleration

The signal processing method presented was driven by the need to simulate on the dynamometer the free rolling of the wheelchair under the action of the inertial force accumulated during the propulsion phase (B). When using the method, the resistance force in the propulsion phase (B) was simulated by means of a torque generated by electric motors coupled to wheelchair dynamometer traction rollers.

Another method developed for processing data measured with wheelchair dynamometers was for determining the position of the centre of gravity of the human body under dynamic conditions. This method is described in the article entitled „Methods for measuring the position of the centre of gravity of an anthropotechnic human-wheelchair system in dynamic conditions." (**A12**). The essence of the entire method, and its novelty, was the possibility of determining the position of the centre of gravity under dynamic conditions. That is, those in which the human body moves by propelling a wheelchair. The method developed made it possible to visualise the variation in the position of a man's centre of gravity on his transverse plane.

Measuring the position of the centre of gravity uses signals from four strain gauge scales supporting a weighing pan on which the wheelchair is placed with the user (Figure 8). W_i scales measure the vertical reaction forces R_i at each of the four support points of the weighing pan. Assuming that a plane parallel to the Z-axis runs through each pair of strain gauge scales, the system of reaction and gravity forces is analysed in four planes π_1, π_2, π_3 and π_4. The position of the projection of the centre of gravity on the individual planes is determined as the distance between the points of application of forces R_i and R_{i+1} (Fig. 9). These distances were designated as f_{12}, f_{23}, f_{43} and f_{14}. Their values are determined from the equations of the torques of force occurring in the plane under consideration π_i. For each plane, one equation of torques relative to an arbitrary pole is assigned (5-8). The reactions of the supports in the x- and y-axis directions were neglected in these equations. Their negligible contribution and the effect of the vertical reaction forces only were assumed.

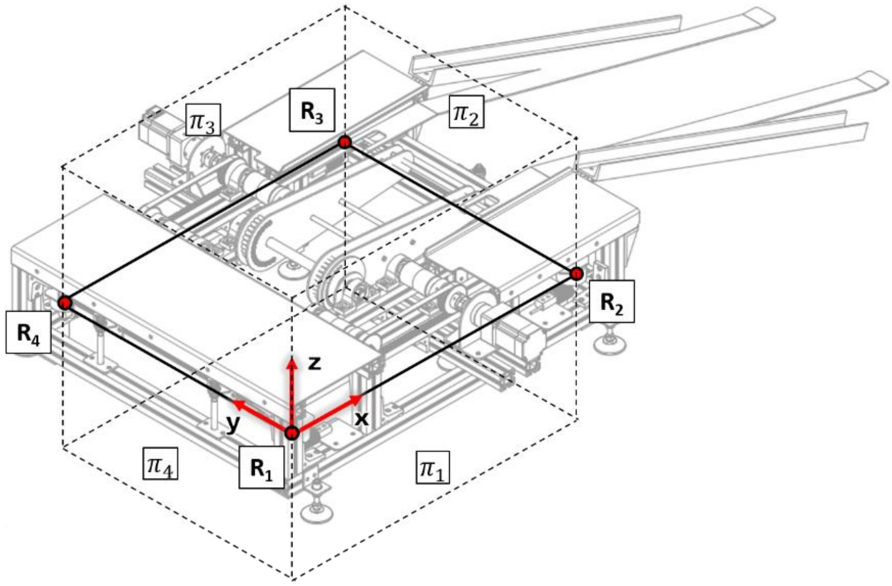


Fig. 8 Diagram of the bench with responses determined using strain gauge scales in four measuring planes [A10]

$$\sum M_{R_1} = 0: -(R_1 + R_2) \cdot f_{12} + R_2 \cdot L_1 = 0 \;\rightarrow\; f_{12} = \frac{R_2 \cdot L_1}{(R_1+R_2)}, \tag{5}$$

$$\sum M_{R_2} = 0: -(R_2 + R_3) \cdot f_{23} + R_3 \cdot L_2 = 0 \;\rightarrow\; f_{23} = \frac{R_3 \cdot L_2}{(R_2+R_3)}, \tag{6}$$

$$\sum M_{R_4} = 0: -(R_3 + R_4) \cdot f_{43} + R_3 \cdot L_1 = 0 \;\rightarrow\; f_{43} = \frac{R_3 \cdot L_1}{(R_3+R_4)}, \tag{7}$$

$$\sum M_{R_1} = 0: -(R_1 + R_4) \cdot f_{14} + R_4 \cdot L_2 = 0 \;\rightarrow\; f_{14} = \frac{R_4 \cdot L_2}{(R_1+R_4)}. \tag{8}$$

Where: Q – weight of a person including wheelchair, f_{12}, f_{23}, f_{43}, f_{14} – distances of the centre of gravity relative to the origin of the coordinate system on each of the measuring planes, R_1, R_2, R_3, R_4 – reactions at the points of attachment of the strain gauge scales, L_1 – distance between the strain gauge scales W_1 and W_2 and W_4 and W_3, L_2 – distance between the strain gauge scales W_2 and W_3 and W_1 and W_4.

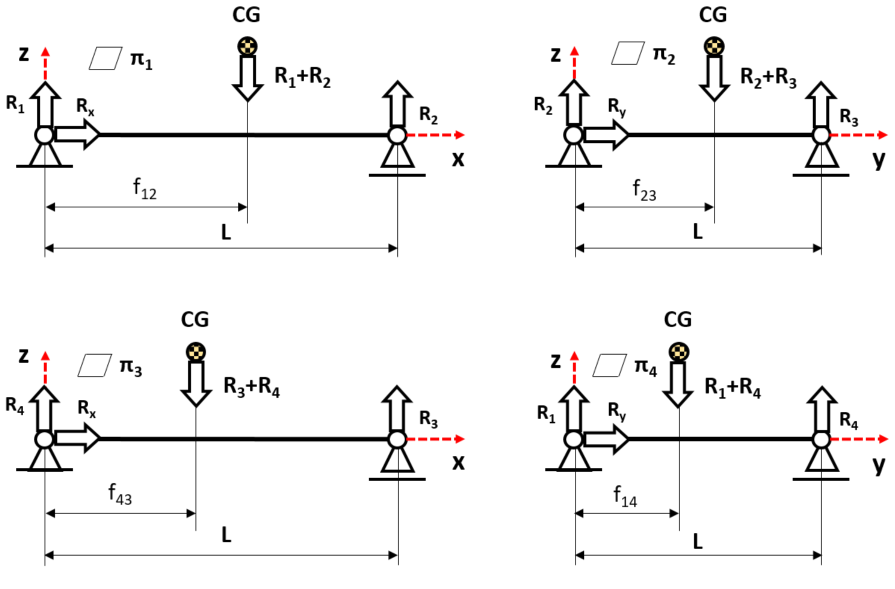


Fig. 9. Diagrams of beams showing the position of the centre of gravity of a person in a wheelchair on each of the four measuring planes [A10]

Using the determined distances f_i (Fig. 10), these were marked on the sides of the rectangle plotted on the points of application of the reaction forces R_i. Two lines can then be drawn through the P_i points marked on the sides of the rectangle. These lines intersect at a single point in the XY plane (Figure 10). The coordinates of this point (9, 10) are at the same time the coordinates describing the position of the centre of gravity of the human-wheelchair system for one measurement of the strain gauge scales in the XY plane.

$$x = \frac{-\frac{L_2 f_{12}}{f_{43} - f_{12}} - f_{14}}{\left(\frac{f_{23} - f_{14}}{L_1}\right) - \left(\frac{L_2}{f_{43} - f_{12}}\right)} \tag{9}$$

$$y = \frac{\left(\frac{f_{23} - f_{14}}{L_1}\right)\left(\frac{L_2 f_{12}}{f_{43} - f_{12}}\right) - \left(\frac{f_{23} - f_{14}}{L_1}\right) f_{14}}{\left(\frac{f_{23} - f_{14}}{L_1}\right) - \left(\frac{L_2}{f_{43} - f_{12}}\right)} + f_{14} \tag{10}$$

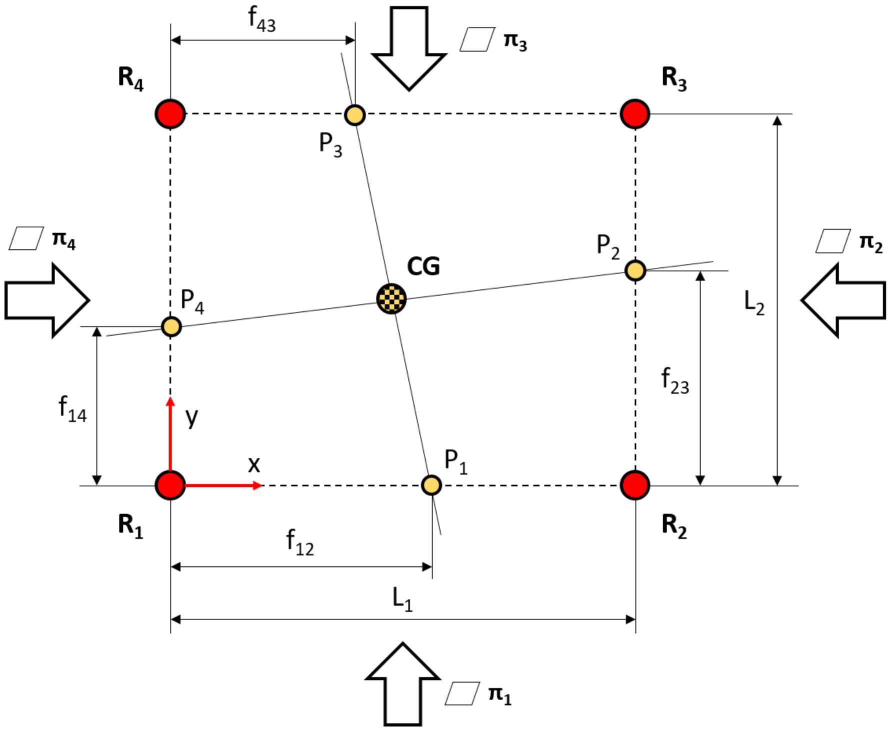


Fig. 10 Diagram of the method for determining the position of the centre of gravity in the XY plane [A10]

The variation in the position of the centre of gravity determined by the above method is represented by a point cloud that is difficult to interpret statistically and implement in mathematical models. Therefore, I have additionally developed a method of describing a set of points with elliptical areas. The exact algorithm of the method and its application to the analysis of selected experiments are described in the publication „Describing a Set of Points with Elliptical Areas: Mathematical Description and Verification on Operational Tests of Technical Devices" (**A1**). The method of describing a set of points with elliptical areas allows any number of points to be replaced by an ellipse depicting their area in the plane (Figure 11). The described method should be applied to sets of points in which the number of leading vectors of points R_i (11) greater than the average length of the leading vector $\overline{R}$ (12) is close to the number of vectors smaller than the average length of the leading vector. This relationship can be checked by determining the value of the distribution uniformity coefficient Δ_P (13) of the analysed points $P_i(x_i;y_i)$ with respect to the geometric centre of gravity of the analysed set $\overline{P}(\overline{x};\overline{y})$ (14, 15). For the method described, the value of Δ_P coefficient should be close to 0.5.

A1	***Wieczorek, B**, Kukla, M., & Warguła, Ł. (2022). Describing a Set of Points with Elliptical Areas: Mathematical Description and Verification on Operational Tests of Technical Devices. Applied Sciences, 12(1), 445*	*Ministry of Science and Higher Education score: 100 points*	*Impact factor: 2.679*

$$R_i = \sqrt{x_i^2 + y_i^2} \tag{11}$$

$$\bar{R} = \frac{\sum_{i=1}^{n} R_i}{n} \tag{12}$$

$$\Delta_P = \frac{n_{min}}{n} \tag{13}$$

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n} \tag{14}$$

$$\bar{y} = \frac{\sum_{i=1}^{n} y_i}{n} \tag{15}$$

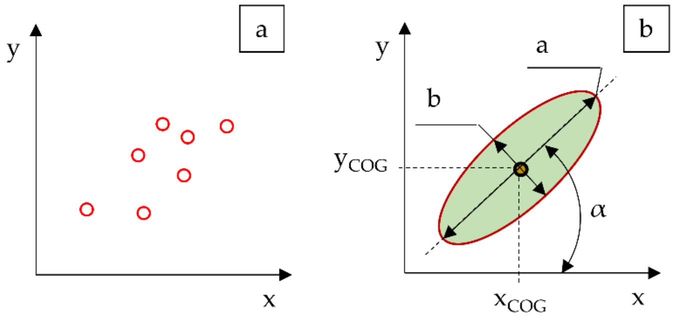


Fig. 11 Graphical illustration of the method of replacing an arbitrary set of points (a) with an ellipse defining the area of points in the plane under analysis (b) [A1]

Applying the method to a set of points satisfying the properties discussed above results in its replacement by an ellipse defined by the five parameters of the position of the centre of the ellipse x_{COG} (16) and y_{COG} (17), the angle of inclination of the directional line α (18), the length of the axle shaft a (19) parallel to the directional line and the length of the axle shaft b (20) perpendicular to the directional line.

$$x_{COG} = \frac{\sum_{i=1}^{n} x_i}{n} \tag{16}$$

$$y_{COG} = \frac{\sum_{i=1}^{n} y_i}{n} \tag{17}$$

$$\alpha = \tan^{-1}\left(\frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^{n}(x_i - \bar{x})^2}\right) \tag{18}$$

$$a = 2\sigma_x = 2\sqrt{\frac{\sum_{i=1}^{n}\left(x_i' - \bar{x'}\right)^2}{n}} \tag{19}$$

$$b = 2\sigma_y = 2\sqrt{\frac{\sum_{i=1}^{n}\left(y_i' - \bar{y'}\right)^2}{n}} \tag{20}$$

The wheelchair dynamometer used in my study, due to the way the wheelchair was used, only allowed the centre of gravity to be measured in the horizontal plane. In order to fill the gap left by the location of the centre of gravity on the vertical axis, I developed an analytical method for determining the position of the centre of gravity based on dividing the human body into fourteen segments (Figure 12).

The method is described in a publication entitled "The analytical method of determining the center of gravity of a person propelling a manual wheelchair." (**A25**) in which I derived equations defining the position of the center of gravity of the entire human body in a three-dimensional reference system. In the mathematical model derived, the position of the centre of gravity of the human body depended on the position of a kinematic member consisting of any number of segments.

A25	***Wieczorek, B.**, Górecki, J., Kukla, M., & Wojtkowiak, D. (2017). The analytical method of determining the center of gravity of a person propelling a manual wheelchair. Procedia Engineering, 177, 405-410*	*Ministry of Science and Higher Education score: 15 points*

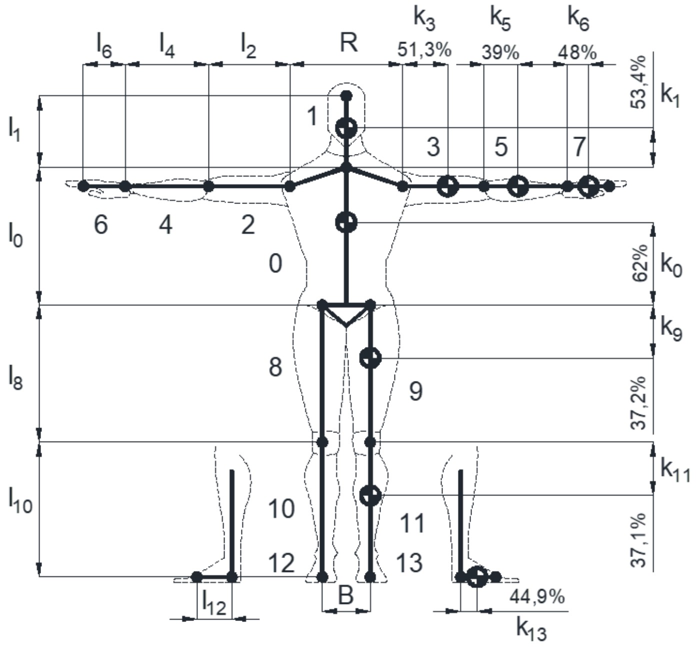


Fig. 12. Diagram of the segmented model. 0 – torso, 1 – head, 2 and 3 – forearms, 4 and 5 – shoulders, 6 and 7 – hands, 8 and 9 – thighs, 10 and 11 – shins, 12 and 13 – feet [A25] (Description in text)

According to the method adopted, each segment was defined by: the length l_i, the angle of inclination of the segment α_i between OY_i and the projection of the segment on the X_iY_i plane, the angle β_i between OY_i and the projection of the segment on the Z_iY_i plane and the angle δ_i between OX_i and the projection of the segment on the X_iZ_i plane (Fig. 13).

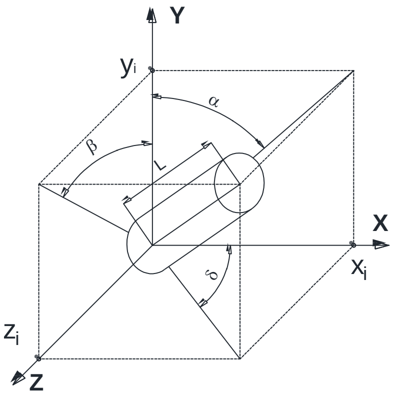


Fig 13. Diagram of the angles between the segment projections and the X, Y and Z axes [A25]

The representation of the length l_i of the i-th body segment in Cartesian coordinates (x_i, y_i, z_i) consists of projecting it (21-25). Using the coordinates of the end of the i-th segment and the position coefficients of the centre of gravity of the segment k_i, the human segment model can be described by a Pi matrix containing the position coordinates of the end (x_i, y_i, z_i) and centre of gravity (k_ix_i, k_iy_i, k_iz_i) of the i-th segment relative to its local reference system.

$$x_i = \begin{cases} \dfrac{l_i \tan \alpha_i}{\sqrt{(\tan \alpha_1)^2 + 1 + (\tan \beta_i)^2}} \vec{\imath}, & \leftrightarrow \alpha_i \neq \left|\dfrac{\pi}{2}\right| \vee \beta_i \neq \left|\dfrac{\pi}{2}\right| \\ l_1 \cos \delta_i \vec{\imath}, & \leftrightarrow \alpha_i = \left|\dfrac{\pi}{2}\right| \vee \beta_i = \left|\dfrac{\pi}{2}\right| \end{cases} \tag{21}$$

$$y_i = \begin{cases} \dfrac{l_i}{\sqrt{(\tan \alpha_1)^2 + 1 + (\tan \beta_i)^2}} \vec{\jmath}, & \leftrightarrow \alpha_i \neq \left|\dfrac{\pi}{2}\right| \vee \beta_i \neq \left|\dfrac{\pi}{2}\right| \\ 0, & \leftrightarrow \alpha_i = \left|\dfrac{\pi}{2}\right| \vee \beta_i = \left|\dfrac{\pi}{2}\right| \end{cases} \tag{22}$$

$$z_i = \begin{cases} \dfrac{l_i \tan \beta_i}{\sqrt{(\tan \alpha_1)^2 + 1 + (\tan \beta_i)^2}} \vec{k}, & \leftrightarrow \alpha_i \neq \left|\dfrac{\pi}{2}\right| \vee \beta_i \neq \left|\dfrac{\pi}{2}\right| \\ l_i \sin \delta_i \vec{k}\,, & \leftrightarrow \alpha_i = \left|\dfrac{\pi}{2}\right| \vee \beta_i = \left|\dfrac{\pi}{2}\right| \end{cases} \tag{23}$$

$$P_i = \begin{bmatrix} x_i \; k_i \cdot x_i \\ y_i \; k_i \cdot y_i \\ z_i \; k_i \cdot z_i \end{bmatrix} \tag{24}$$

$$CG = \left(\frac{\sum\left(e_{xi} + P_{i_{12}}\right) k_{mi} m_{cz}}{m_{cz}} ; \frac{\sum\left(e_{yi} + P_{i_{22}}\right) k_{mi} m_{cz}}{m_{cz}} ; \frac{\sum\left(e_{zi} + P_{i_{32}}\right) k_{mi} m_{cz}}{m_{cz}} \right) \tag{25}$$

The method developed for the analytical determination of the position of the centre of gravity of the human body requires knowledge of the angles between the analysed segments. To acquire such data, I developed a method to capture the position of human body segments under dynamic conditions. The method is described in a publication entitled „The method of measuring motion capture in wheelchairs during actual use–description of the method and model of measuring signal processing." (**A26**). Noteworthy is the implementation of an OpenCV algorithm in the method that locates the positions of AruCo markers popularly known as QR codes. The use of these ready algorithms allowed the construction of a low-cost instrument that is a wheelchair-attachable module easy to use during real-world testing. This module consisted of a GoPro HERO 7 camera (a) and a floodlight (b) attached on a boom (c) permanently connected to the wheelchair frame (Figure 14). The human body was equipped with markers (d), and additionally the use of electrodes measuring the EMG signal (e) is possible. The instruments designed in this way allowed the measurement of muscle activity to be linked to human body kinematics.

A26	***Wieczorek, B.**, & Kukla, M. (2021, November). The method of measuring motion capture in wheelchairs during actual use–description of the method and model of measuring signal processing. In IOP Conference Series: Materials Science and Engineering (Vol. 1199, No. 1, p. 012084). IOP Publishing.*	*Ministry of Science and Higher Education score: 5 points*

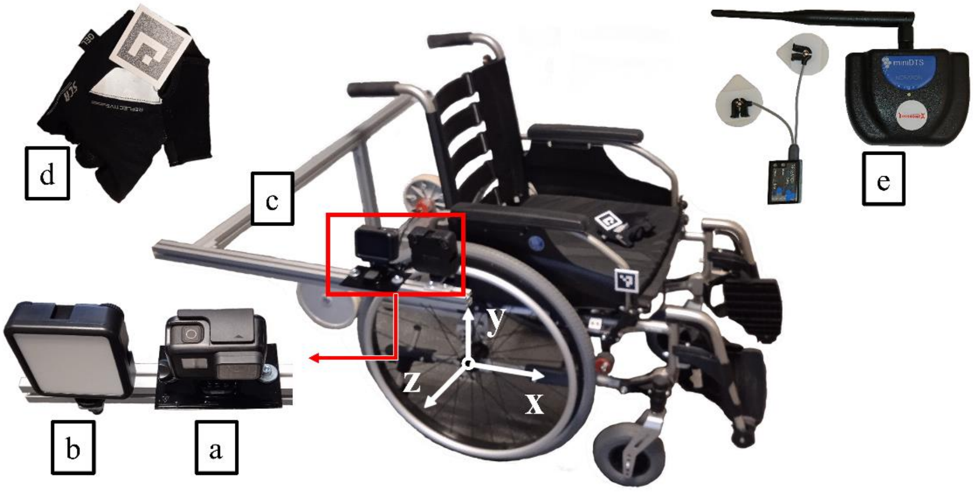


Fig. 14. Measurement instrument used in the study, where: a – camera, b – floodlamp, c – boom, d – ArUco marker, e – EMG camera [A26]

Due to the implementation of openCV algorithms in a new application and the prototype nature of the test instruments, I first decided to verify the method's performance and determine its accuracy. The results of this research have been published in a paper entitled „The effects of ArUco marker velocity and size on motion capture detection and accuracy in the context of human body kinematics analysis" (**A13**). In this study, it was found that marker detection error and probability of detection are related to camera quality and marker movement velocity. The dominant influence is the marker movement velocity (Figure 15).

_A13_	_**Wieczorek, B.**, Warguła, Ł., Kukla, M., Kubacki, A., & Górecki, J. (2020). The effects of ArUco marker velocity and size on motion capture detection and accuracy in the context of human body kinematics analysis. Technical Transactions, 117(1)_	_Ministry of Science and Higher Education score: 20 points_	---

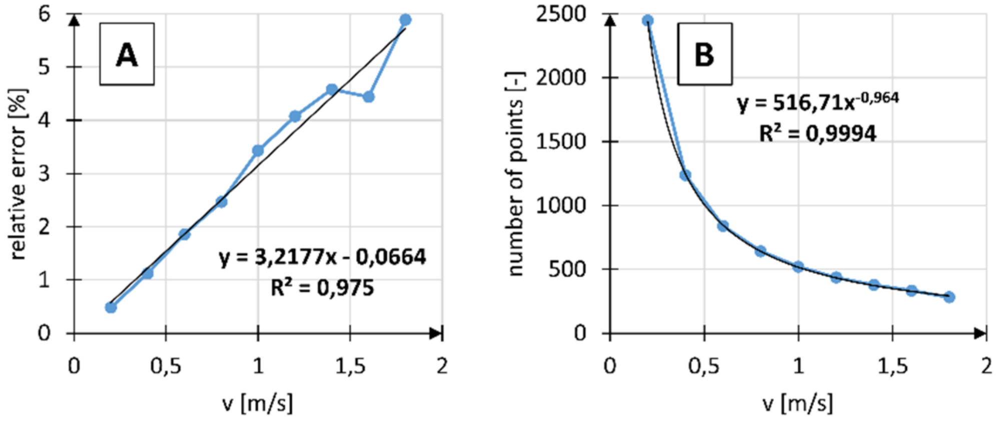


Fig. 15. Relative error (A) and number of detection points (B) versus marker velocity [A13]

Based on the results obtained, the measurement method was approved for further testing as the relative error for the velocities observed in the hand and wheelchair kinematics did not exceed 6%.

An important element of the research procedures being developed was the development of a method for converting the EMG signal expressed in mV into muscle effort expressed in percentage use of the muscle group being analysed. The relevance came from the ability to link the activity of propelling the wheelchair with the consumption of the patient's available energy resources.

A fundamental element in determining muscle activity is the determination of the maximum voluntary contraction MVC of the muscle. As such, as part of the National Centre for Research and Development's LIDER VII project, I led a team and participated in research into the methodology of conducting a static test of the maximum voluntary contraction MVC of muscle, the results of which are described in the publication entitled „Development of methods for performing the maximum voluntary contraction (MVC) test" (**A24**). The research carried out made it possible to select a set of exercises to determine the MVC for the muscle groups most active during wheelchair propulsion. This methodology was used by me in all subsequent work addressing the issue of MA muscle effort, which was calculated from the MVC measured during the wheelchair propulsion test and the maximum MVC measured during the static test (26). This preliminary research was essential and produced results that can be compared with those of other researchers. Hence, in the literature, the procedure for determining the maximum MVC is also called the normalisation procedure.

A24	*Kukla, M., **Wieczorek, B.**, & Warguła, Ł. (2018). Development of methods for performing the maximum voluntary contraction (MVC) test. In MATEC Web of Conferences (Vol. 157, p. 05015). EDP Sciences.*	*Ministry of Science and Higher Education score: 15 points*	---

$$MA = \frac{MVC}{MVC_{max}} \; [-] \tag{26}$$

Using all of the above procedures, methods and test benches, a complete measurement test of the biomechanical parameters associated with the operation of manual wheelchair propulsions was developed on a wheelchair dynamometer. The course of this test is described in the publication entitled „Procedure for measuring the biomechanical parameters of the wheelchair propulsion process with the use of a wheelchair dynamometer" (**A17**). The correct implementation of the measurement test (Figure 16) requires the adoption of a specific test procedure that is constant for each test object. Any measurement test carried out should be preceded by an appropriate preparation and calibration process. A human-wheelchair system is being prepared and a test bench is being calibrated as a device that simulates movement and measures biomechanical parameters at the same time. With regard to the measurement test itself, it is characterised by a fixed sequence of activities carried out by the testing team and the subject.

A17	***Wieczorek B.**, Kukla M. (2019): Procedure for measuring the biomechanical parameters of the wheelchair propulsion process with the use of a wheelchair dynamometer, In: Research on the biomechanics of manual wheelchair drive for innovative manual and hybrid drives, **ed. Bartosz Wieczorek**, Publishing House Kazimierz Pulaski University of Technology and Humanities in Radom, pp. 53-63*	*Ministry of Science and Higher Education score: 20 points*	---

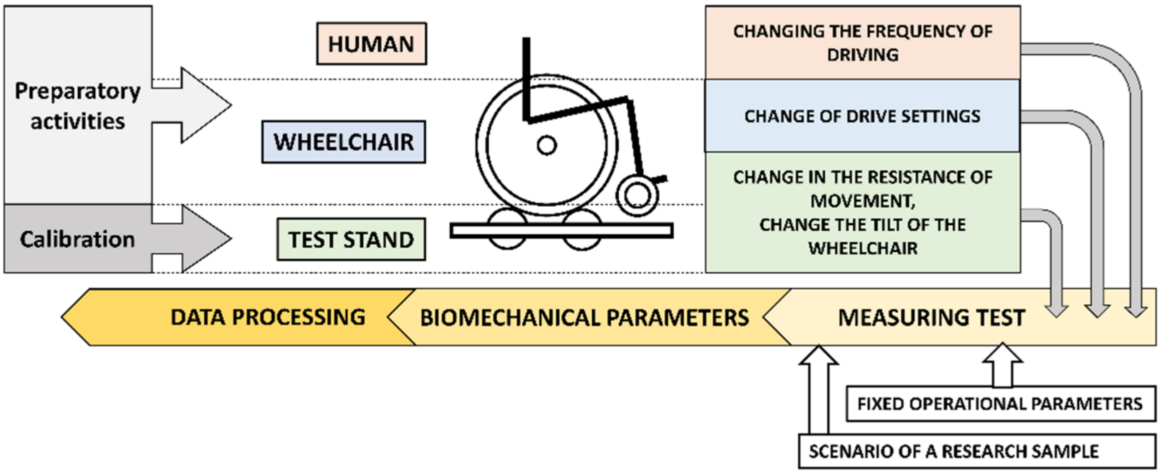


Fig. 16. Diagram of the measurement test adopted during the tests [A17]

It should be noted that the developed test procedure for biomechanical parameters consisted of several sub-procedures using in-house measurement instruments. Taken as a whole, all of these instruments constituted the additional modules of the wheelchair dynamometer. These modules could also be separated and operated independently of the dynamometer (e.g. EMG, Motion Capture). This approach makes it possible to perform selected tests under real conditions, which allows laboratory tests to be supplemented with data that cannot be measured under simulated conditions.

Two test benches were designed, patented and built. Wheelchair dynamometer (P12) and wheelchair motion resistance measuring station (P11). In my further research activities, the main test bench was a wheelchair dynamometer, which in its basic version allowed the measurement of the position of the centre of gravity of the human body, path, speed and acceleration measured independently for each wheel of the wheelchair. When the bench was retrofitted with additional measurement modules, it additionally enabled the measurement of surface EMG electromyography and the displacement of human body segments (Motion Capture). It is worth mentioning that the wheelchair dynamometer is being further developed (Figure 17). It has now been rebuilt and functionally improved. This work was carried out as part of the National Centre for Research and Development's project "Things are for People", in which I participate as principal investigator. In the new version of the dynamometer, torque measurement directly at the wheelchair propulsion wheel has been added, and the module simulating off-road conditions and the coupling of wheelchair wheels to traction rollers has been improved.

P11	***Wieczorek B.**, Warguła Ł., Waluś K.J., Kukla M.: Urządzenie do pomiaru siły oporów toczenia obiektów wyposażonych w układ jezdny, Patent at the Patent Office of the Republic of Poland, no. of exclusive right PL 239410, 2021*	*Ministry of Science and Higher Education score: 70 points*
P12	*Górecki J., **Wieczorek B.**, Kukla M., Wilczyński D., Wojtkowiak D.: Urządzenie do symulacji warunków eksploatacji i pomiaru parametrów dynamicznych wózka inwalidzkiego, Patent at the Patent Office of the Republic of Poland, application No. P.424482, 2021*	*Ministry of Science and Higher Education score: 70 points*

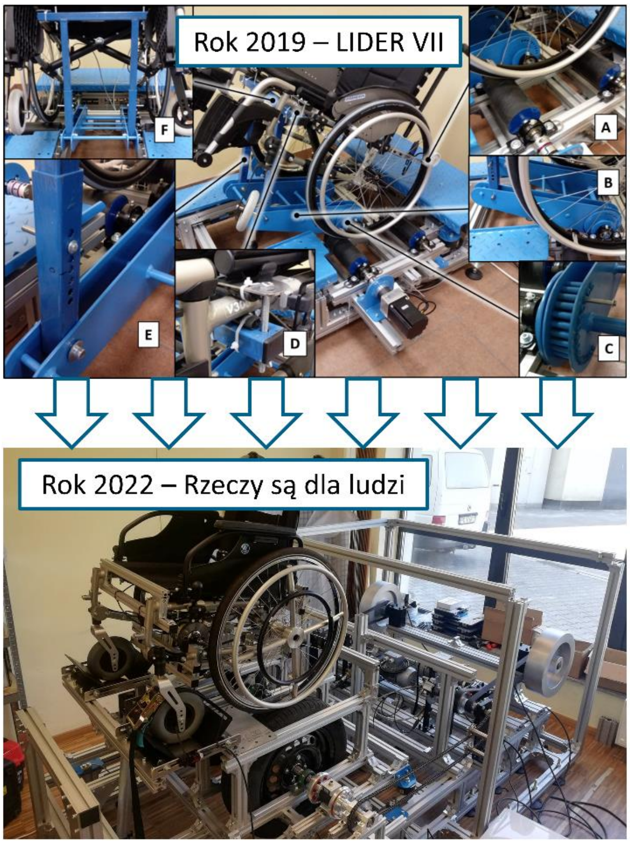


Fig. 17. Development of wheelchair dynamometers across two research grants LIDER VII and "Things are for People" observed between 2019 and 2022

3.7.2 Development and construction of test prototypes

The methodical stage was followed by construction and design work, which included the development of functional prototypes of innovative wheelchairs and propulsion systems. The realisation of this phase of my scientific activity was essential, as it provided research facilities that made it possible to carry out operational research under real conditions. The use of functional prototypes made it possible to modify them on the basis of clues collected from in-service testing. As a result, the biomechanical parameters defining the human-wheelchair interaction during propulsion were improved.

The conceptualisation and design of the innovative manual wheelchair propulsions was guided by the principles of Human Centred Design methodology. As part of my scientific achievement, I have designed and manufactured prototypes of devices that can be divided into new manual propulsions replacing the classic pushrim propulsion system and modules modifying the pushrim propulsion system. The new propulsion systems developed include: a lever propulsion system for wheelchairs (**P1**), a multi-speed gear hub for manual wheelchairs (**P2**) (Figure 18), and a modification kit for a hybrid electric/manual propulsion system (**P6**) (Figure 19).

P1	***Wieczorek B.**, Zabłocki M.: Dźwigniowy system napędowy wózka inwalidzkiego, Patent at the Patent Office of the Republic of Poland, no. of exclusive right PL 223141, 2016*	*Ministry of Science and Higher Education score: 30 points*

P2	***Wieczorek B.**, Zabłocki M.: Piasta przekładniowa wielobiegowa do ręcznych wózków inwalidzkich, Patent at the Patent Office of the Republic of Poland, no. of exclusive right PL 223142, 2016*	*Ministry of Science and Higher Education score: 30 points*
P6	***Wieczorek B.**, Warguła Ł., Kukla M.: Zestaw modyfikacyjny układu napędu do hybrydowego elektryczno-ręcznego wózka inwalidzkiego, Patent at the Patent Office of the Republic of Poland, no. of exclusive right PL 239350, 2021*	*Ministry of Science and Higher Education score: 70 points*

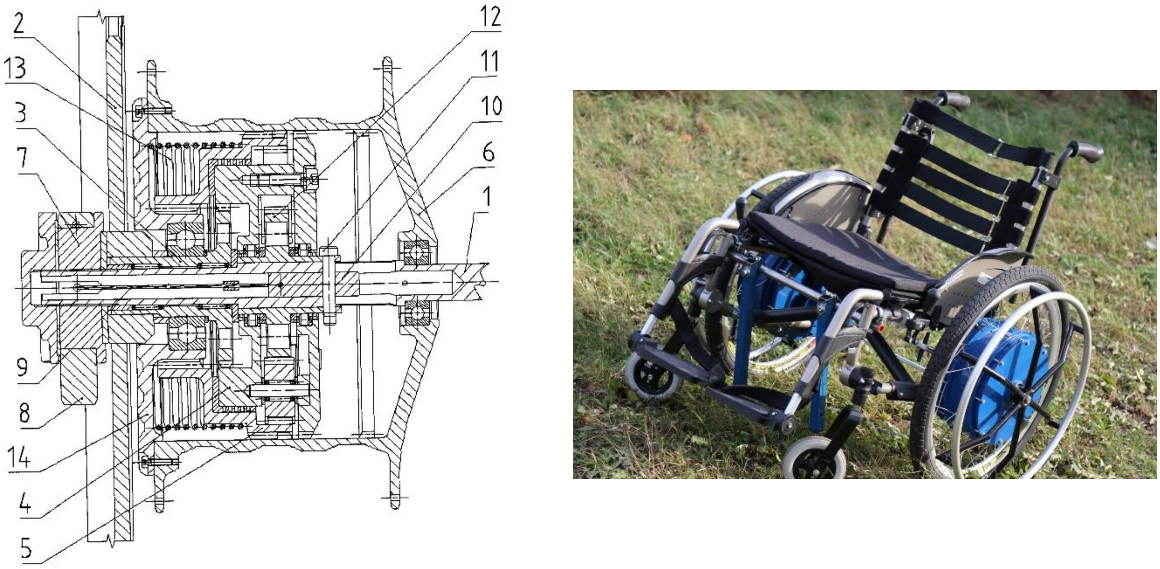


Fig 18. Prototype of a wheelchair-mounted multi-speed gear hub used in biomechanical research [P1]

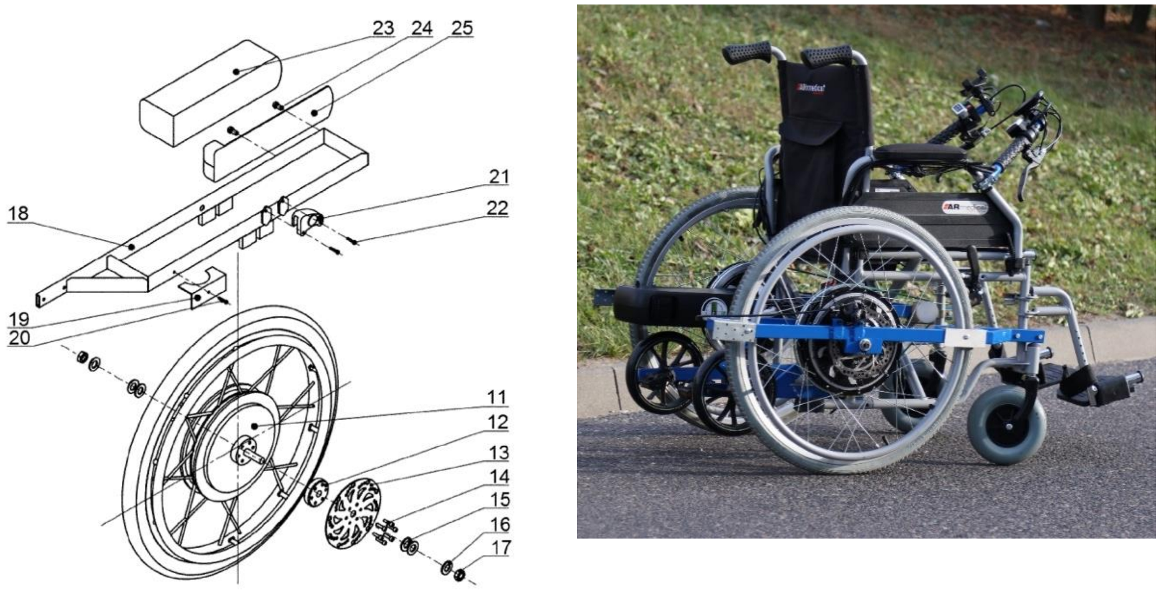


Fig. 19. Prototype of a wheelchair-mounted hybrid manual-electric propulsion system used in biomechanical research [P2]

Of the aforementioned innovative propulsion systems, the hybrid propulsion is particularly advantageous, the success of which is evidenced by a number of awards won at rehabilitation equipment and invention fairs. The propulsion has four modes of operation: manual propulsion mode, all-electric propulsion mode, hill assist mode, drive assist mode and cruise control mode.

Manual and electric propulsion modes use only one energy source - muscle power or energy stored in the battery. In these modes, the wheelchair is propelled as in a classic manual wheelchair or as in a classic electric wheelchair.

The hill assist mode recognises the slope of the terrain and, based on this, delivers the drive torque generated by the drive motors to the system. In its operation, this mode should reduce the resistance resulting from a change in the incline of the path on which the wheelchair travels.

The idea for the hill assist modes was based on the recognition, by sensors on the wheelchair, of the angle of the terrain on which the wheelchair is moving. On this basis, the electric motor control system was intended to reduce any variation in the motion resistance torque deviating from the torque of resistance associated with driving on a level and smooth road surface. This idea is shown in the diagram of Figure 20, according to which a wheelchair moving on a horizontal surface is approximately loaded with a constant external resistance torque M_0. When the wheelchair is on the driveway, the value of this torque is increased by the uphill resistance force torque F_w resulting from the wheelchair mass Q and the angle of inclination α (27).

$$M_i = M_0 + \frac{Q\sin(\alpha)D}{2} \tag{27}$$

Where:

M_i – external resistance force torque at the i-th section of the road,

M_0 – external resistance force torque on a horizontal road section,

Q – force of gravity of the wheelchair,

D – drive wheel diameter,

α – inclination angle.

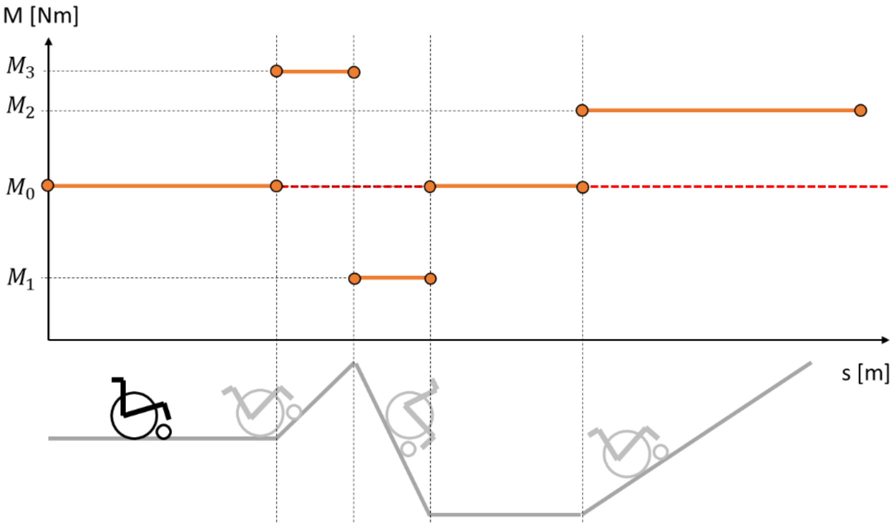


Fig. 20. Diagram of the variation of the external resistance torque (own elaboration)

In the case of manual propulsion assist mode, the aim of the electric motor control system is to maintain a constant assisting torque set individually by the user. The important thing about this mode is that the torque of the electric motors is only generated when the user initiates movement by pushing the pushrims.

The last mode of assisted acceleration is designed to keep the wheelchair at a constant speed by nullifying its deceleration resulting from the effect of the motion resistance force during the hand return phase on the initial position on the pushrims (Figure 21).

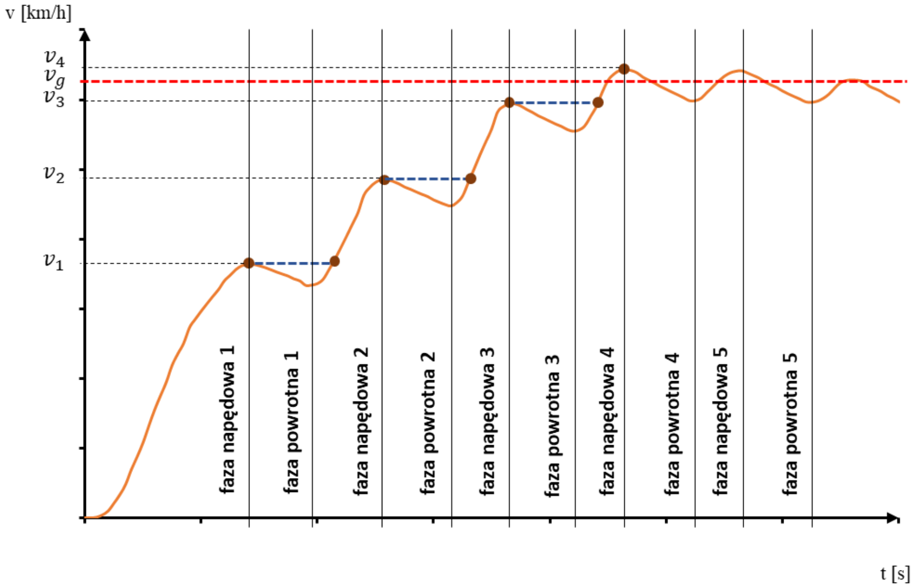


Fig. 21. Graph of the change of wheelchair speed with the speeds resulting from the acceleration assistance plotted (own elaboration)

In order to avoid triggering the acceleration assistance while manoeuvring, two logical conditions are checked whose fulfilment triggers the start of the support programme. The first condition checks whether the limiting speed $v\ g$ has been reached and the second condition checks whether the user is manoeuvring the wheelchair or accelerating it.

Figure 21 shows a graphical interpretation demonstrating the difference between the movement during manoeuvring, where the propulsion phase ends with a speed v_r, and the movement during propulsion where the propulsion phase ends with a speed v_i. Checking that the v_r speed does not exceed the speed limit allows the user to assess whether he or she is making low-speed manoeuvring movements. Checking the angle α of inclination of the line of increase in velocity makes it possible to determine whether we are dealing with gentle acceleration, in which acceleration assistance is not required.

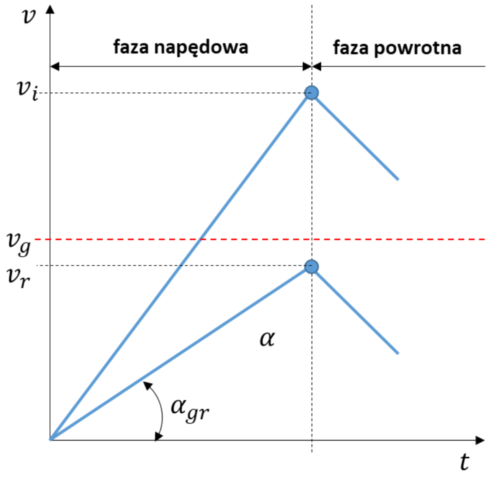


Fig. 21. Graph of the speed change in the propulsion and return phases for the acceleration of wheelchair vi and manoeuvring of the wheelchair (own elaboration)

Given the high level of adaptation of the hybrid propulsion (**P6**) to the individual physical capabilities of a person with a mobility disability, it was decided to enhance the propulsion with two modules to increase its functionality. The first is the wheelchair body with the attachment assembly (**P7**) (Figure 22). In addition to its aesthetic qualities, the body performs a protective function protecting the propulsion system from mechanical damage. In addition, the body is equipped with brushes to clean the wheelchair pushrims. The second module dedicated to hybrid propulsion is the gesture control system for the electric wheelchair (**P8**). This module allows the wheelchair to be controlled by flexing the index and middle finger. Each finger controls one drive wheel. The angle of deflection of the finger translates into the speed of the electric motor included in the hybrid propulsion (**P6**).

P6	***Wieczorek B.**, Warguła Ł., Kukla M.: Zestaw modyfikacyjny układu napędu do hybrydowego elektryczno-ręcznego wózka inwalidzkiego, Patent at the Patent Office of the Republic of Poland, no. of exclusive right PL 239350, 2021*	*Ministry of Science and Higher Education score: 70 points*
P7	***Wieczorek B.**, Warguła Ł., Giedrowicz M.: Karoseria wózka inwalidzkiego z zespołem mocowania, Patent at the Patent Office of the Republic of Poland, no. of exclusive right PL 239351, 2021*	*Ministry of Science and Higher Education score: 70 points*
P8	***Wieczorek B.**, Rybarczyk D., Kubacki A.: System kontroli gestem wózka inwalidzkiego z napędem elektrycznym, Patent at the Patent Office of the Republic of Poland, no. of exclusive right PL 239351, 2021*	*Ministry of Science and Higher Education score: 70 points*

Fig. 22. Visualisation of the patented wheelchair body with attachment unit

The propulsion systems presented so far are characterised by the need to significantly interfere with the wheelchair's base structure. This made it necessary to develop them as modules that completely replace the classic wheelchair propulsion wheel. This necessitated the development of adapters to fit the connections on the frame to the new propulsion modules. An example of such an adapter is the wheelchair wheel axle stabiliser (**P3**), which was designed to attach the main axle of a multi-speed hub (**P2**). In addition, this adapter performed the function of locking the rotation of the main hub axle.

P2	***Wieczorek B.**, Zabłocki M.: Piasta przekładniowa wielobiegowa do ręcznych wózków inwalidzkich, Patent at the Patent Office of the Republic of Poland, no. of exclusive right PL 223142, 2016*	*Ministry of Science and Higher Education score: 30 points*
P3	***Wieczorek B.**, Kukla M.: Stabilizator osi koła wózka inwalidzkiego, Patent at the Patent Office of the Republic of Poland, no. of exclusive right PL 239438, 2021*	*Ministry of Science and Higher Education score: 70 points*

Considering the economic and technical aspects of such a wheelchair modification, I also decided to develop, together with a collaborating team, modules to enhance the classic pushrim propulsion system without having to replace the drive wheel and use adapters. One such module that enhances the classic propulsion system is the wheelchair pushrim module (**P4**). The essence of this invention is the use of a one-way clutch in the pushrim (Figure 23). This clutch ensures that the wheelchair is propelled as in a classic pushrim propulsion system and allows the hand to return to the starting position without having to let go of the pushrim. In addition to improving the propulsion of the wheelchair, the clutch used also protects the upper limb from epidermal abrasion.

P4	*Warguła Ł. **Wieczorek B.**: Ciąg do koła wózka inwalidzkiego, Patent at the Patent Office of the Republic of Poland, no. of exclusive right PL 239411, 2021*	*Ministry of Science and Higher Education score: 70 points*

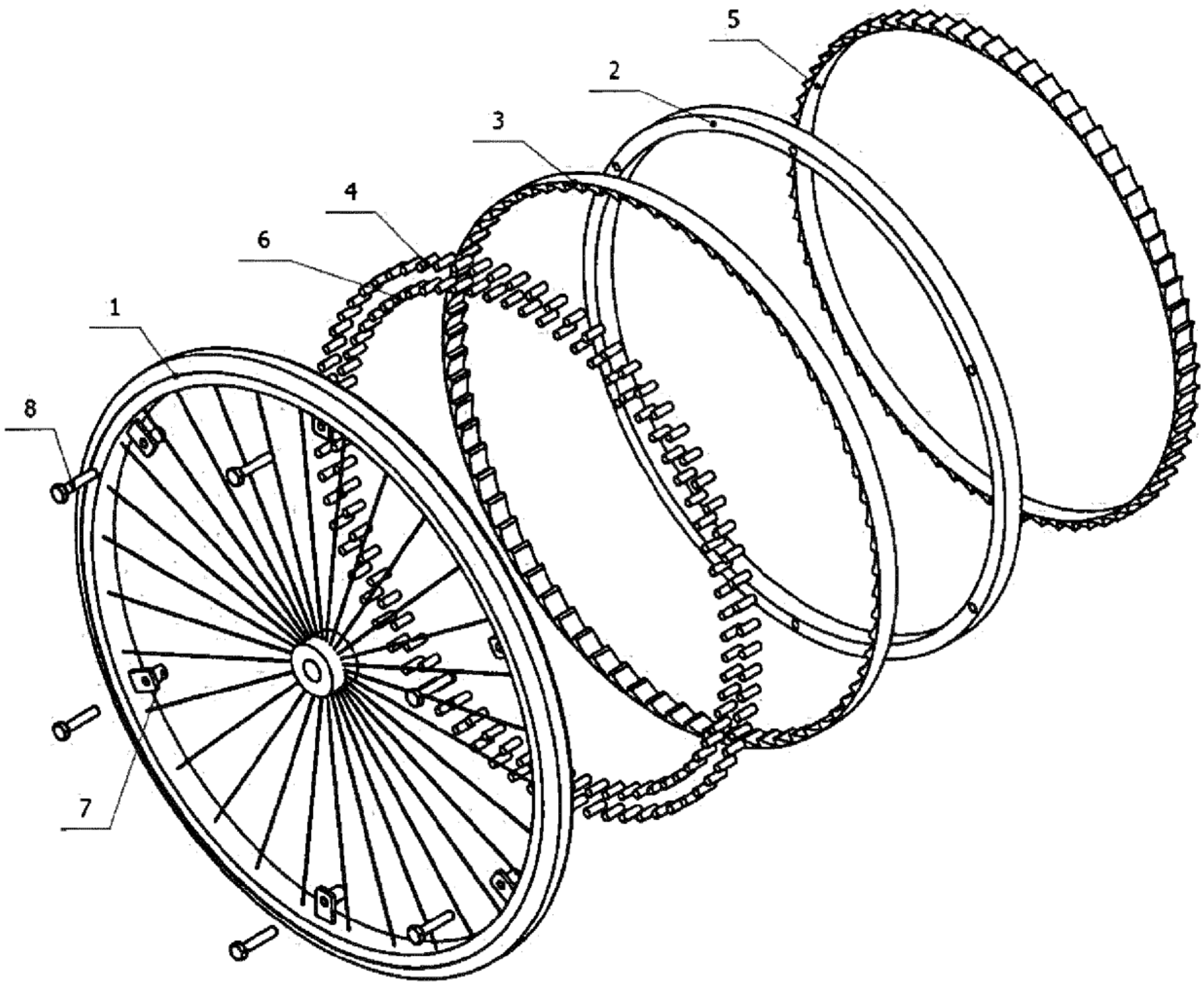


Fig. 23. Diagram illustrating the design of one-way coupling pushrim modules [P4]

Another add-on module developed during the scientific achievement that can be used in any wheelchair without modifying its propulsion system is the module for the universal lever brake. This module was developed in two variants (**P5**, **P10**). Regardless of the variant, the essence of this module is to assist when going uphill. When going uphill, the motion resistance increases significantly. The increase in motion resistance can reach such a level that wheelchair rolldown can occur during the return phase of the hand driving the pushrims. The answer to this problem is the use of a module (Figure 24) that blocks the reverse movement of a wheelchair on an incline.

P5	***Wieczorek B.**, Warguła Ł., Kukla M.: Moduł do uniwersalnego hamulca dźwigniowego koła wózka inwalidzkiego, Patent at the Patent Office of the Republic of Poland, no. of exclusive right PL 239693, 2021*	*Ministry of Science and Higher Education score: 70 points*
P10	***Wieczorek B.**, Warguła Ł., Kukla M., Berdychowski M.: Moduł do uniwersalnego hamulca dźwigniowego koła wózka inwalidzkiego, Patent at the Patent Office of the Republic of Poland, no. of exclusive right PL 239410, 2021*	*Ministry of Science and Higher Education score: 70 points*

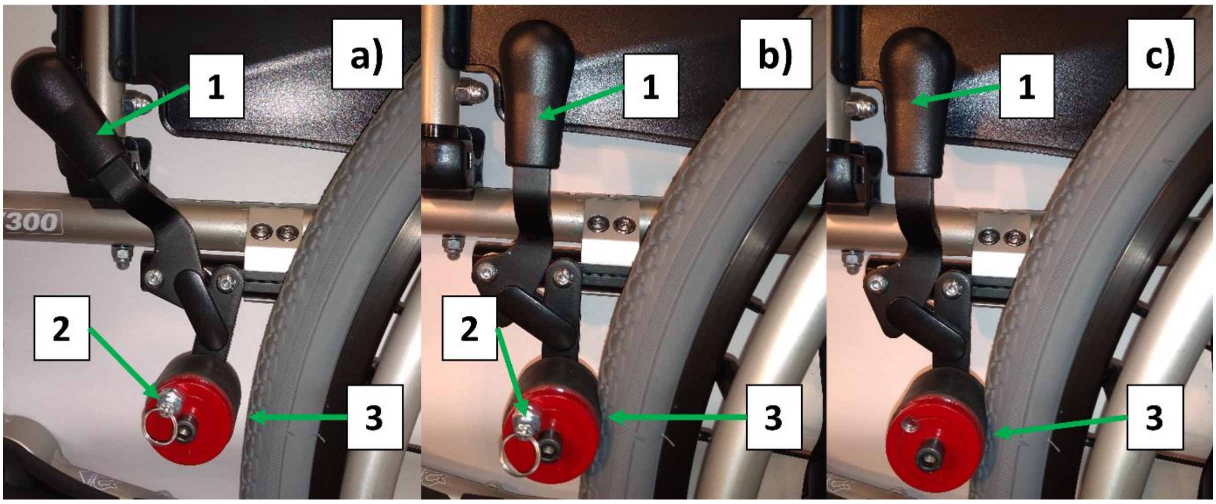


Fig. 22. Prototype of anti-rollback mechanism (a) in disengaged position, (b) in parking brake function, (c) in reversing lock function where: 1 – lever of standard wheelchair brake, 2 – latch safety device, 3 – anti-rollback roller [own elaboration]

3.7.3 Performance tests on manual propulsion systems

The core of the scientific achievement described was the operational testing of actual prototypes, which made it possible to verify their functionality, set new directions for the development of innovative propulsion systems and develop links between selected biomechanical parameters. The implementation of this research in feedback with all the propulsion system prototypes being developed all the time has helped to influence the development of propulsion systems for manual wheelchairs. This development involved increasing the functionality of the manual wheelchair propulsion and adapting it to the individual needs and physical capabilities of the user. During the performance tests carried out, I analysed biomechanical parameters such as the position of the centre of gravity of the human body under dynamic conditions, muscular activity, the kinematics and dynamics of wheelchair movement and the kinematics of the human body.

When analysing the variation of the position of the centre of gravity of the human body under dynamic conditions, I examined how the propulsion of a wheelchair affects the distribution of the centre of gravity position. The analysis of this parameter under dynamic conditions is a novelty as it is common to measure the position of the centre of gravity under static conditions. Tests on the change in the centre of gravity under dynamic conditions were performed on a wheelchair dynamometer (**P12**). However, the method of describing a set of points with elliptical areas (**A1**) was used to analyse and process the measured data

A1	***Wieczorek, B**, Kukla, M., & Warguła, Ł. (2022). Describing a Set of Points with Elliptical Areas: Mathematical Description and Verification on Operational Tests of Technical Devices. Applied Sciences, 12(1), 445*	*Ministry of Science and Higher Education score: 100 points*	*Impact factor: 2.679*
P12	*Górecki J., **Wieczorek B.**, Kukla M., Wilczyński D., Wojtkowiak D.: Urządzenie do symulacji warunków eksploatacji i pomiaru parametrów dynamicznych wózka inwalidzkiego, Patent at the Patent Office of the Republic of Poland, application No. P.424482, 2021*	*Ministry of Science and Higher Education score: 70 points*	

The main study on the variation of the centre of gravity of the human body was to see what effect the type of propulsion system used has. This study was published in paper entitled „The symmetric nature of the position distribution of the human body center of gravity during propelling manual wheelchairs with innovative propulsion systems" (**A6**). The research involved the analysis of three wheelchairs: classic pushrim propulsion, multi-speed hub (**P2**) and manual-electric hybrid propulsion (**P6**). The study analysed the variation of the centre of gravity distribution by describing it with elliptical areas (Figure 23) located on the horizontal plane.

A6	***Wieczorek, B.**, Kukla, M., & Warguła, Ł. (2021). The symmetric nature of the position distribution of the human body center of gravity during propelling manual wheelchairs with innovative propulsion systems. Symmetry, 13(1), 154. Ministry of Science and Higher Education score: 70 points, Impact factor: 2.713*	*Ministry of Science and Higher Education score: 70 points*	*Impact factor: 2.713*
P2	***Wieczorek B.**, Zabłocki M.: Piasta przekładniowa wielobiegowa do ręcznych wózków inwalidzkich, Patent at the Patent Office of the Republic of Poland, no. of exclusive right PL 223142, 2016*	*Ministry of Science and Higher Education score: 30 points*	
P6	***Wieczorek B.**, Warguła Ł., Kukla M.: Zestaw modyfikacyjny układu napędu do hybrydowego elektryczno-ręcznego wózka inwalidzkiego, Patent at the Patent Office of the Republic of Poland, no. of exclusive right PL 239350, 2021*	*Ministry of Science and Higher Education score: 70 points*	

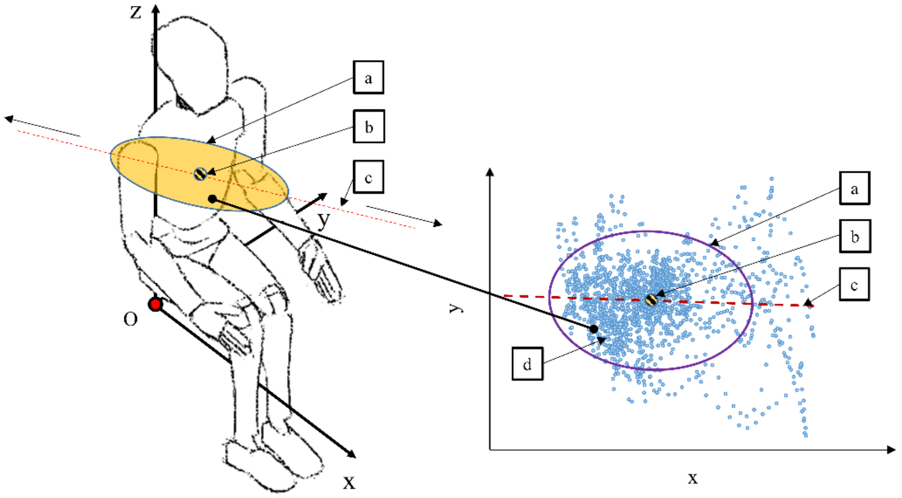
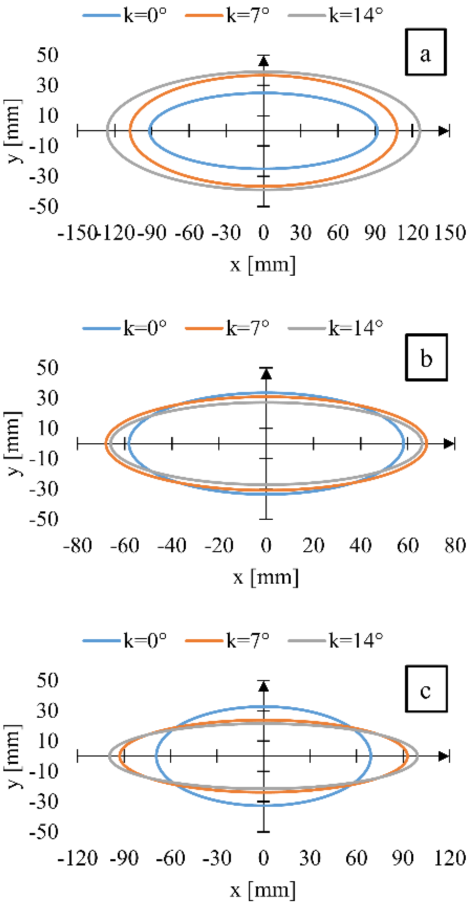


Fig. 23. Diagram of the location of the analysed ellipses in the body space of the tested patient, where: a – ellipse being the area of variation of the position of the human body's centre of gravity, b – centre of the ellipse, c – directional line, d – measured positions of the centre of gravity during the measurement test [own elaboration]

For each ellipse, a decomposition was performed extracting parameters such as the centre of the ellipse, the angle of inclination of the ellipse and its dimensions (Figures 24-26). Analysis of the dimensions of the ellipse (Figure 24) showed that, irrespective of the type of propulsion system used, the angle of inclination of the wheelchair has an effect on the geometric dimensions of the ellipses plotted. Differences in axle shaft lengths were observed in the propulsion systems tested, amounting to: 17.08 mm for axle shafts $a(\Delta a)$ and 4.63 mm for axle shaft $b(\Delta b)$ for multi-gear propulsion, 15.13 mm for axle shaft $a(\Delta a)$ and 5.63 mm for axle shaft $b(\Delta b)$ in conventional pushrim propulsion, and 5.89 mm for axle shaft $a(\Delta a)$ and 8.20 mm for axle shaft $b(\Delta b)$ in hybrid propulsion. Based on the determined dimensions of the ellipses, it was found that the largest area of variation in the position of the centre of gravity of the human body was measured for the multi-speed wheelchair. For this wheelchair, the average length of axle shaft$a(M\ a)$ was 108.53 mm, while for axle shaft $b(M\ b)$ it was 35.11 mm. The smallest area of variation in the centre of gravity was observed for the hybrid wheelchair, for which the average axle shaft length $a(M\ a)$ was 64.07 mm, while for axle shaft $b(M\ b)$ it was 33.85 mm.

This is an important observation, which may indicate that modification of the classical manual propulsion system translates into a change in the distribution of positions of the centre of gravity of the human body under dynamic conditions. The differences in the dimensions of the areas of variation of the centre of gravity are due to the kinematics of the human body propelling the wheelchair. The results presented for the dimensions of the ellipses show that it is advantageous to use systems that support the manual pushrim propulsion system. During their use, there are the smallest increases in the dimensions of the area of variation in the position of the centre of gravity of the human body as a result of changing wheelchair operating parameters.



$a_{k=0°} = 91.89$ mm $b_{k=0°} = 29.75$ mm
$a_{k=7°} = 107.65$ mm $b_{k=7°} = 36.57$ mm
$a_{k=14°} = 126.05$ mm $b_{k=14°} = 39.02$ mm

$a_{k=0°} = 58.22$ mm $b_{k=0°} = 43.52$ mm
$a_{k=7°} = 67.99$ mm $b_{k=7°} = 30.91$ mm
$a_{k=14°} = 65.99$ mm $b_{k=14°} = 27.12$ mm

$a_{k=0°} = 69.20$ mm $b_{k=0°} = 32.75$ mm
$a_{k=7°} = 92.91$ mm $b_{k=7°} = 23.88$ mm
$a_{k=14°} = 99.45$ mm $b_{k=14°} = 21.49$ mm

Fig. 24. Graphs of ellipses describing the variation in the position of the centre of gravity of the human body versus angle of inclination of the wheelchair k for (a) a manual multi-speed wheelchair, (b) hybrid propulsion, (c) classic manual wheelchair, where – length of the axle shaft lying on the directional axis when the wheelchair is propelled at 0°, – length of the axle shaft lying on the directional axis when the wheelchair is propelled at an inclination of 7°, – length of the axle shaft lying on the directional axis when driving a truck inclined at 14°, – length of the axle shaft perpendicular to the directional axis when driving a truck inclined at 0°, – length of the axle shaft perpendicular to the directional axis when driving a 7° inclined wheelchair°, – length of the axle shaft perpendicular to the directional axis when driving a truck inclined at 14° [A6]

In addition, the tests performed showed the symmetrical nature of the distribution of the centre of gravity position points. The axis of symmetry was a line that was also the trend line of the measured centre of gravity position points (Figure 25). It was observed that, irrespective of the case studied, the directional line was always inclined at a certain angle to the lying x-axis. The angle of inclination of the directional line oscillated between values ranging from -9.24° for the classic-propulsion wheelchair when going uphill with an inclination of k = 0° to 1.99° for the hybrid-propulsion wheelchair when going uphill with an inclination of k = 0°. The directional line, with its slope, depicted the direction in which the torso makes bends when propelling the wheelchair. The analysis of the results showed that the value of the angle of inclination of the trend line is closely related to the user's physical abilities and which upper limb is dominant in the user.

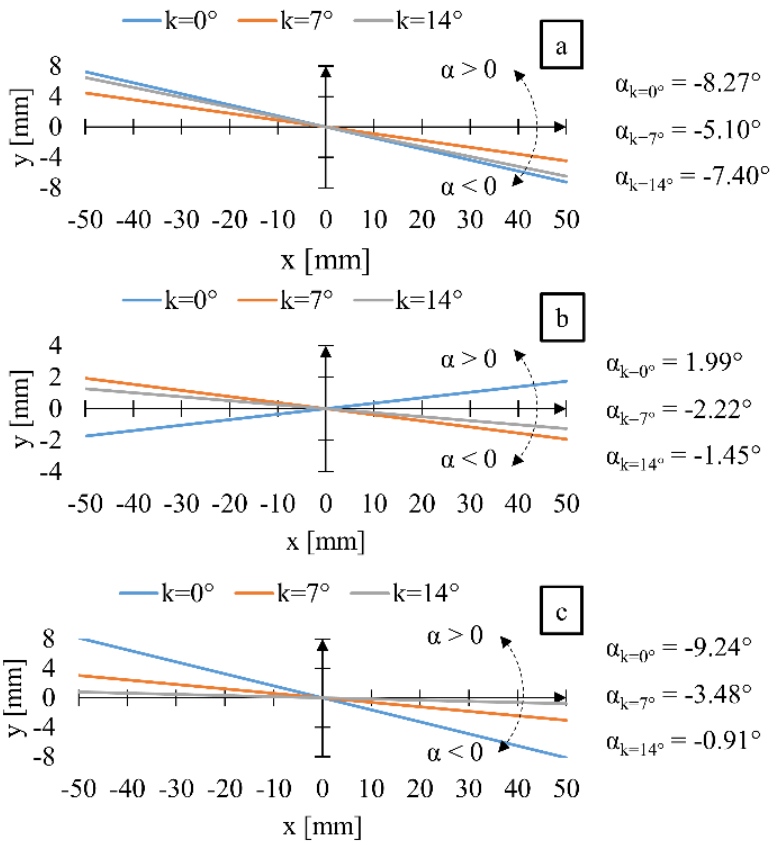


Fig. 25. Directional line graphs of ellipses versus wheelchair inclination angle k for (a) manual multi-speed, (b) hybrid propulsion, (c) classic manual wheelchair, where $\alpha_{\mathrm{k=0^\circ}}$ – directional line inclination angle when driving a wheelchair inclined at 0°, $\alpha_{\mathrm{k=7^\circ}}$ – directional line inclination angle when driving a wheelchair inclined at 7°, $\alpha_{\mathrm{k=13^\circ}}$ $\alpha_{\mathrm{k=7^\circ}}$ directional line inclination angle when driving a wheelchair inclined at 14° [A6]

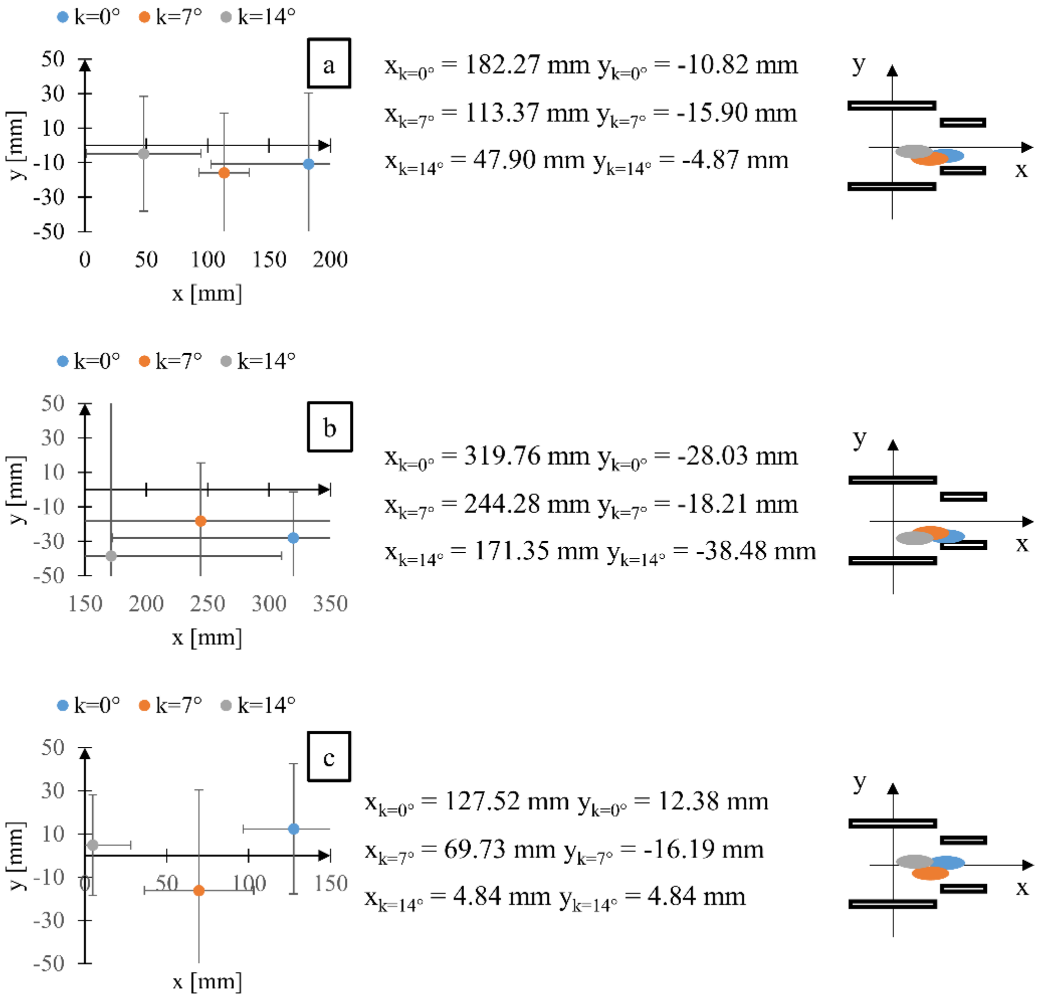


Fig. 26. Graphs of the position of the centre of ellipses describing the variation of the position of the centre of gravity of the human body versus the angle of inclination of the wheelchair k for (a) manual multi-speed wheelchair, (b) hybrid propulsion, (c) classic manual wheelchair, where $\square_{k=0°}$ and $\square_{k=0°}$ – coordinates of the position of the centre of the ellipse when driving the wheelchair inclined at 0°, where $\square_{k=7°}$ and $\square_{k=7°}$ – coordinates of the position of the centre of the ellipse when driving the wheelchair inclined at 7°, where $\square_{k=14°}$ and $\square_{k=14°}$ – coordinates of the position of the centre of the ellipse when driving the wheelchair inclined at 14° [a6]

The above studies have shown the influence of the design features and functions of the propulsion system on the variation of the centre of gravity position under dynamic conditions. Therefore, I decided to extend the research and analyse how the trajectory of wheelchair movement affects the positions of the centre of gravity of the human body. This research is described in a paper entitled „Between Manual Wheelchair Steering and the Position of the Human Body's Center of Gravity" (**A7**). The purpose of the research described in this publication was to analyse the deviation Δ between the function describing the wheelchair's trajectory and the function describing the position trajectory of the centre of gravity (Figure 27). During the test, the wheelchair's trajectory was plotted by the movement of a point that was the geometric centre of rotation of the rear wheels, and the trajectory of the centre of gravity of the human body was plotted by its position versus the wheelchair's displacement.

_A7_	_**Wieczorek, B.**, & Kukla, M. (2020). Biomechanical Relationships Between Manual Wheelchair Steering and the Position of the Human Body's Center of Gravity. Journal of biomechanical engineering, 142(8), 081006_	_Ministry of Science and Higher Education score: 70 points_	_Impact factor: 2.097_

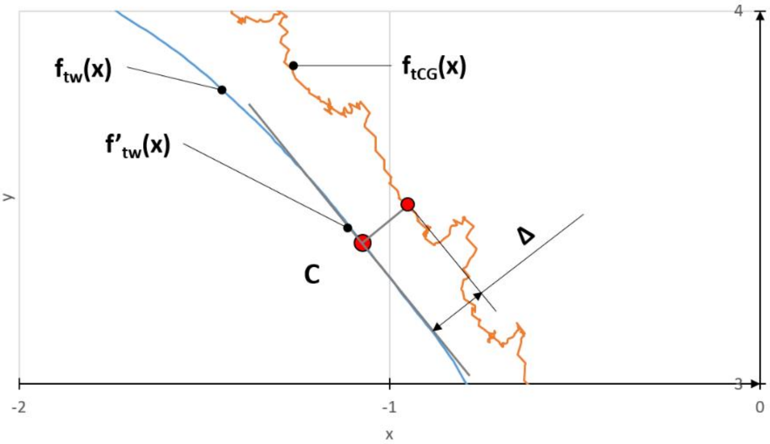


Fig. 27. Diagram for determining the deviation of the trajectory of the centre of gravity position Δ from the characteristic points on the wheelchair trajectory. Where $f_{tw}(x)$ – the wheelchair trajectory function, $f'_{tw}(x)$ – the derivative of the wheelchair trajectory function, $f_{tCG}(x)$ the trajectory function of the centre of gravity of the human body and Δ – the deviation of the centre of gravity trajectory relative to the considered point of the wheelchair trajectory [A7]

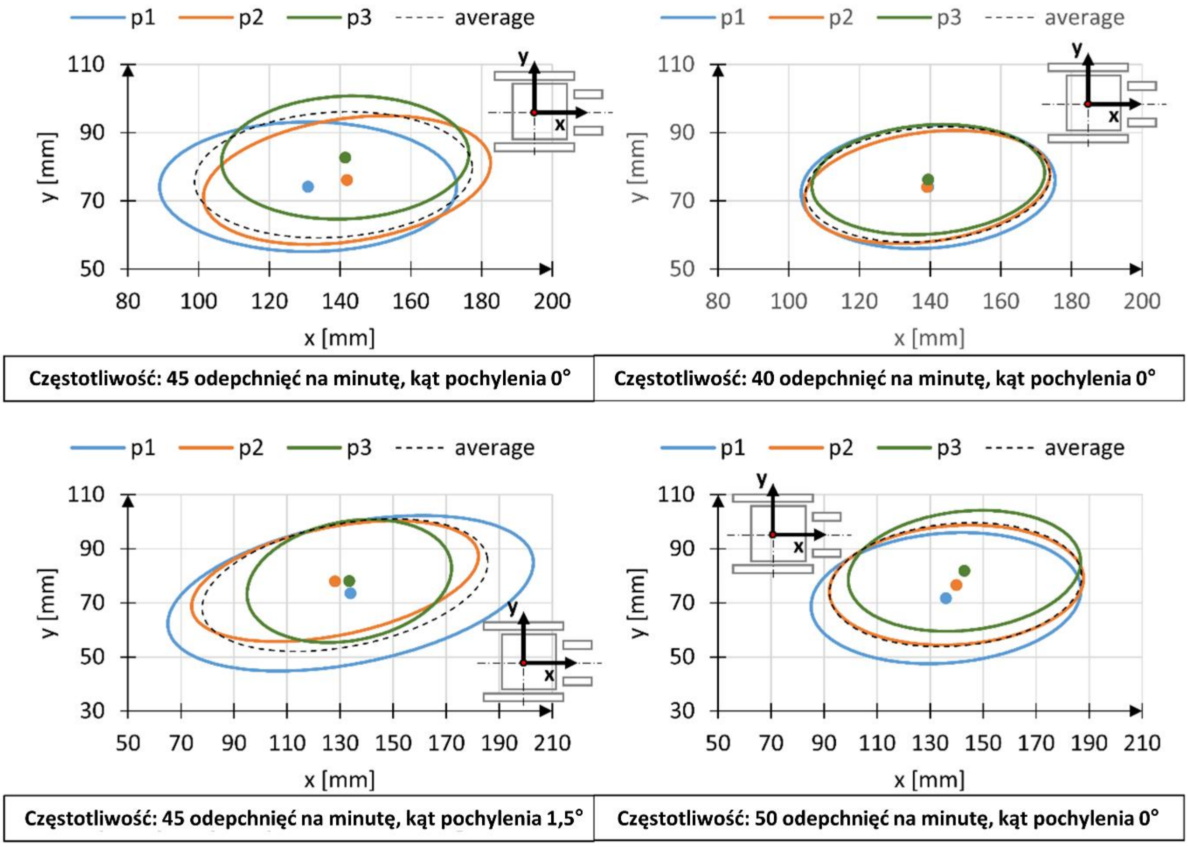
Analysing the measurement samples realised during this research, which represented different wheelchair trajectories, the following relationships were found:

- the trajectory of the centre of gravity is always on the outer side of the curve of the trajectory of the turning wheelchair,
- the absolute value of the trajectory distance coefficient increases as the turning radius of the wheelchair decreases,
- the course of the centre of gravity trajectory line depends on the current propulsion phase in the time interval under consideration.

Having analysed the effect of the type of manual propulsion and wheelchair control on the area of variation of the centre of gravity position, I carried out an analysis of the effect of the gear ratio of multi-speed propulsion on the dimensions and geometry of these areas. This research is described in a paper entitled „Effects of the performance parameters of a wheelchair on the changes in the position of the centre of gravity of the human body in dynamic condition” (**A10**). A multi-speed wheelchair (**P2**) was used as the test subject. The aim of the study was to determine the influence of wheelchair operating parameters such as its inclination, speed of movement and propulsion system ratio on the variation of the centre of gravity position under dynamic conditions. The results obtained depending on these three variables are shown as elliptical areas of variation in the position of the centre of gravity (Figure 28)

_A10_	_**Wieczorek, B.**, & Kukla, M. (2019). Effects of the performance parameters of a wheelchair on the changes in the position of the centre of gravity of the human body in dynamic condition. PloS one, 14(12), e0226013_	_Ministry of Science and Higher Education score: 100 points_	_Impact factor: 2.740_

P2	***Wieczorek B.**, Zabłocki M.: Piasta przekładniowa wielobiegowa do ręcznych wózków inwalidzkich, Patent at the Patent Office of the Republic of Poland, no. of exclusive right PL 223142, 2016*	*Ministry of Science and Higher Education score: 30 points*



Częstotliwość: 45 odepchnięć na minutę, kąt pochylenia 0°

Częstotliwość: 40 odepchnięć na minutę, kąt pochylenia 0°

Częstotliwość: 45 odepchnięć na minutę, kąt pochylenia 1,5°

Częstotliwość: 50 odepchnięć na minutę, kąt pochylenia 0°

Fig. 28 Summary of centre of gravity position areas for three gears with ratios: p1 – i = 1.96, p2 – i = 1 and p3 – i = 0.51 [A10]

In the tests, the propulsion system gear ratio, propulsion frequency and wheelchair angle were changed. The research carried out confirmed the results of previous studies and showed the influence of operating parameters such as inclination angle and propulsion frequency on the area of variation of the position of the centre of gravity of the human body. The study found that changing the gear ratio of the multi-speed propulsion system translated into a change in the effort the person propelling the wheelchair was subjected to. Multiplication ratios increased the effort and reduction ratios decreased it. Changes in the degree of loading on the muscular system (effort) translated into a change in the kinematics of movement of human body segments. As the strain on the muscular system increased, the man compensated with more intense trunk bends. Based on these observations, it was concluded that an increase in wheelchair motion resistance translates into an increase in the area of variation of the position of the centre of gravity of the human body.

During the research on the multi-gear wheelchair, a link was noted with the variation of the centre of gravity position with effort. In addition, the muscular effort analysis itself makes it possible to assess the match between the propulsion system and the user's physical capabilities. Therefore, my research activities also include the study of muscle activity in terms of the operation of innovative wheelchair propulsion systems. This type of research work uses the methodology described earlier for converting the muscle surface tension signal EMG into muscle activity MA. I performed muscle activity tests for each of the manual propulsion systems I designed. The aim of this research was to analyse their impact on the human muscular system, thus improving the designs under development.

One of the ongoing studies of muscle activity is described in paper "Evaluation of the biomechanical parameters of human-wheelchair systems during ramp climbing with the use of a manual wheelchair with anti-rollback devices" (**A8**). This study analysed the effect of using a module for a universal wheelchair lever brake (**P5**) on muscle effort and wheelchair speed. Muscle activity tests were realised for four muscles of the upper limb (Figure 29) analysed on eight patients.

A8	***Wieczorek, B.**, Kukla, M., Rybarczyk, D., & Warguła, Ł. (2020). Evaluation of the biomechanical parameters of human-wheelchair systems during ramp climbing with the use of a manual wheelchair with anti-rollback devices. Applied Sciences, 10(23), 8757*	*Ministry of Science and Higher Education score: 70 points*	*Impact factor: 2.679*
P5	***Wieczorek B.**, Warguła Ł., Kukla M.: Moduł do uniwersalnego hamulca dźwigniowego koła wózka inwalidzkiego, Patent at the Patent Office of the Republic of Poland, no. of exclusive right PL 239693, 2021*	*Ministry of Science and Higher Education score: 70 points*	

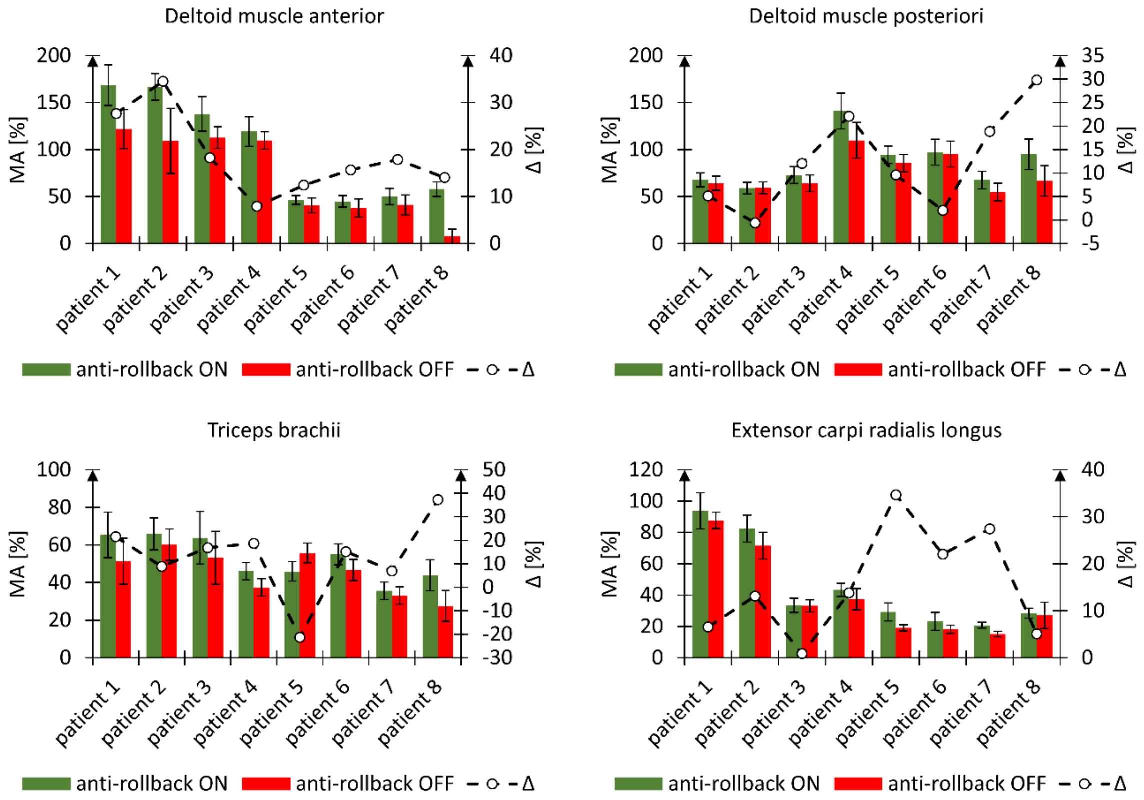


Fig. 29 Graphs of mean muscle activity for individual patients with the anti-rollback system ON and the anti-rollback system OFF. Where: Δ – percentage difference between the muscle activity measured with the anti-rollback system on and the anti-rollback system off [A8]

Analysis of muscle activity MA showed that the patient's muscular system was exposed to more physical effort during the use of the anti-rollback module (**P5**) during the uphill climb than during the uphill climb without its use. An exception to this observation was found for only two patients. During the MA deltoid muscle posteriori measurement for patient 2 where there was a 0.62% decrease when using the module, and the MA Triceps brachii measurement for patient 5 where there was a 21.27% decrease when using the module. During the uphill climb, the greatest increase in MA was found for the Deltoid muscle anterior. The average MA gain during the uphill climb with the module on was 18.56%. For all the muscles examined, the difference in muscle effort (MA) depending on the use of the module was at a similar level and amounted to the following muscles respectively: deltoid muscle anterior – 18.56%, deltoid muscle posteriori – 12.37%, triceps brachii – 13.00%, extensor carpi radialis longus – 15.44%. A significant increase in the percentage difference between the muscle activity measured with the anti-rollback module switched on versus off was observed for patients characterised by extensive experience of using a manual wheelchair. This phenomenon can be observed for patients 1 to 4 especially in muscle effort measured on the deltoid muscle anterior and triceps brachii muscles.

I also carried out similar tests for multi-speed propulsion (**P2**) and a hybrid propulsion (**P6**). In both of these cases, it was examined how the value of the resistance torque affects the average effort of the whole upper limb. In this analysis, mean whole limb effort was defined as the average muscle effort of all measured muscle groups. The results obtained for the pushrim propulsion system with multi-speed gear (**P2**) are included in Figure 30 and for the hybrid propulsion (**P6**) in Figure 31.

P2	***Wieczorek B.**, Zabłocki M.: Piasta przekładniowa wielobiegowa do ręcznych wózków inwalidzkich, Patent at the Patent Office of the Republic of Poland, no. of exclusive right PL 223142, 2016*	*Ministry of Science and Higher Education score: 30 points*
P6	***Wieczorek B.**, Warguła Ł., Kukla M.: Zestaw modyfikacyjny układu napędu do hybrydowego elektryczno-ręcznego wózka inwalidzkiego, Patent at the Patent Office of the Republic of Poland, no. of exclusive right PL 239350, 2021*	*Ministry of Science and Higher Education score: 70 points*

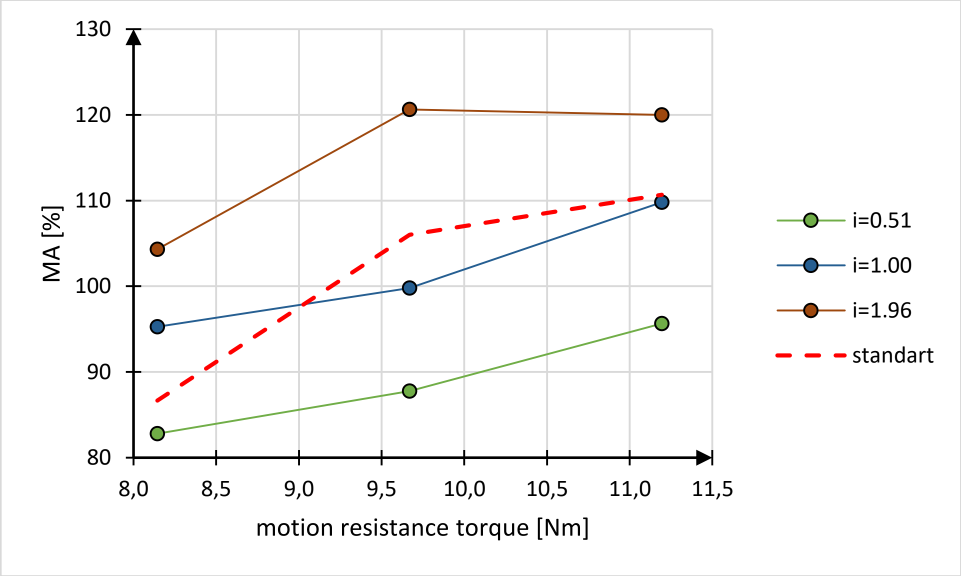


Fig. 30 Average muscular activity of the whole upper limb during propulsion of a multi-speed wheelchair with different gear ratios i, where the standard is a classical pushrod unmodified propulsion system [data not published]

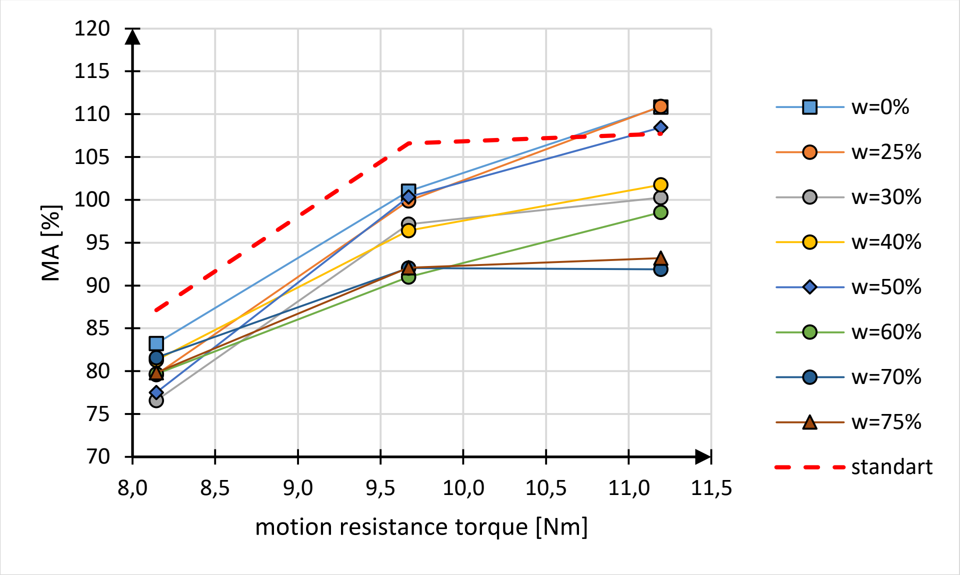


Fig. 31. Average muscular activity of the whole upper limb when propelling a hybrid powered wheelchair for different values of upper limb support by the torque generated by electric motor w, where the standard is classical traction unmodified propulsion system [unpublished data]

Analysing the quoted results, it can be concluded that the multi-speed propulsion and the hybrid propulsion have a positive effect on reducing the user's muscular effort. In the case of multi-speed propulsion, an effort value for neutral gear (i=1) was obtained at a level similar to a wheelchair with a classic pushrim propulsion system (Figure 30). Which is a good result confirming that the modification introduced does not introduce additional resistance to the anthropotechnical system. Examination of the other ratios confirmed a reduction in muscle activity for the reduction run and an increase in muscle activity for the multiplicative run. Such results were expected because, at a constant motion resistance force torque, the change in gear ratio was compensated for by the muscular system.

In the case of hybrid propulsion (Figure 31), a reduction in muscular activity was found with an increase in the value of the drive assist coefficient from the electric motors. Whereby, in this case. The reduction in muscular effort allows the manual wheelchair to also be operated by people with a reduced upper limb capacity. In addition, the ability to reduce effort means that the effectiveness of using a manual wheelchair is less dependent on the physical condition of the user. It has been noted that too high a value for the assist factor coefficient translates into interference with the natural propulsive movements performed by the upper limb. As a result, the hand movement is out of sync with the pushrims and there are jerks that generate extra effort. In addition, the value of the assist coefficient not disturbing the movement of the hand driving the wheelchair varied according to the motion resistance force torque of the wheelchair. For example, for a resistance torque of 8.1 Nm, the lowest effort was obtained for an assist factor of w = 30%. In contrast, for a resistance torque of 11.1 Nm, the lowest muscle activity was measured for an assist coefficient of w = 70%.

The muscle activity results for the multi-speed and hybrid wheelchair are part of the final report for the LIDER VII project I led titled "Research on the biomechanics of manual wheelchair propulsion for innovative manual and hybrid propulsion", funded by the National Centre for Research and Development. This report, together with the results, was submitted to the National Centre for Research and Development and received a positive formal and substantive opinion.

The main function of the propulsion system is that of locomotion, so the development of propulsion systems by tailoring them to the user should not deteriorate the kinematic and dynamic performance. A desirable feature of an innovative wheelchair propulsion system is the improvement of these parameters. In line with this, parameters such as propulsion torque, speed, acceleration and the distance the modified wheelchair travels during the propulsion phase were analysed during the research work on the prototypes built. One of the studies I took part in is described in a publication entitled „An Analytical Modelling of Demand for Driving Torque of a Wheelchair with Electromechanical Drive. Energies" (**A3**) investigated how the arrangement of the power system of a hybrid wheelchair (**P6**) influences changes in the motion resistance torque. This study used a previously developed analytical model that I was involved in developing (**A4**). The model considered all variables related to terrain and human body kinematics.

A3	*Kukla, M., **Wieczorek, B.**, Warguła, Ł., Górecki, J., & Giedrowicz, M. (2021). An Analytical Modelling of Demand for Driving Torque of a Wheelchair with Electromechanical Drive. Energies, 14(21), 7315*	*Ministry of Science and Higher Education score: 140 points*	*Impact factor: 3.004*
A4	*Kukla, M., **Wieczorek, B.**, Warguła, Ł., & Berdychowski, M. (2021). An analytical model of the demand for propulsion torque during manual wheelchair propelling. Disability and Rehabilitation: Assistive Technology, 16(1), 9-16*	*Ministry of Science and Higher Education score: 70 points*	*Impact factor: 2.500*
P6	***Wieczorek B.**, Warguła Ł., Kukla M.: Zestaw modyfikacyjny układu napędu do hybrydowego elektryczno-ręcznego wózka inwalidzkiego, Patent at the Patent Office of the Republic of Poland, no. of exclusive right PL 239350, 2021*	*Ministry of Science and Higher Education score: 70 points*	

Willing to assess the effect of a human driving a wheelchair on the value of the motion resistance torque, in subsequent research work I researched the motion resistance force. In a work that I was the prime mover of, entitled „The Impact of the Human Body Position Changes During Wheelchair Propelling on Motion Resistance Force: A Preliminary Study" (**A5**) analysed the effect of the movement of the body propelling the wheelchair on the value of motion resistance force. This study used a proprietary and patented test bench for testing the motion resistance force (**P11**) and a wheelchair dynamometer (**P12**). The research work carried out made it possible to determine the value of the motion resistance force versus the position of the centre of gravity (Figure 32).

A5	***Wieczorek, B.**, Kukla, M., Warguła, Ł., Rybarczyk, D., Giedrowicz, M., & Górecki, J. (2021). The Impact of the Human Body Position Changes During Wheelchair Propelling on Motion Resistance Force: A Preliminary Study. Journal of Biomechanical Engineering, 143(8), 081008*	*Ministry of Science and Higher Education score: 70 points*	*Impact factor: 2.097*
P11	***Wieczorek B.**, Warguła Ł., Waluś K.J., Kukla M.: Urządzenie do pomiaru siły oporów toczenia obiektów wyposażonych w układ jezdny, Patent at the Patent Office of the Republic of Poland, no. of exclusive right PL 239410, 2021*	*Ministry of Science and Higher Education score: 70 points*	
P12	*Górecki J., **Wieczorek B.**, Kukla M., Wilczyński D., Wojtkowiak D.: Urządzenie do symulacji warunków eksploatacji i pomiaru parametrów dynamicznych wózka inwalidzkiego, Patent at the Patent Office of the Republic of Poland, application No. P.424482, 2021*	*Ministry of Science and Higher Education score: 70 points*	

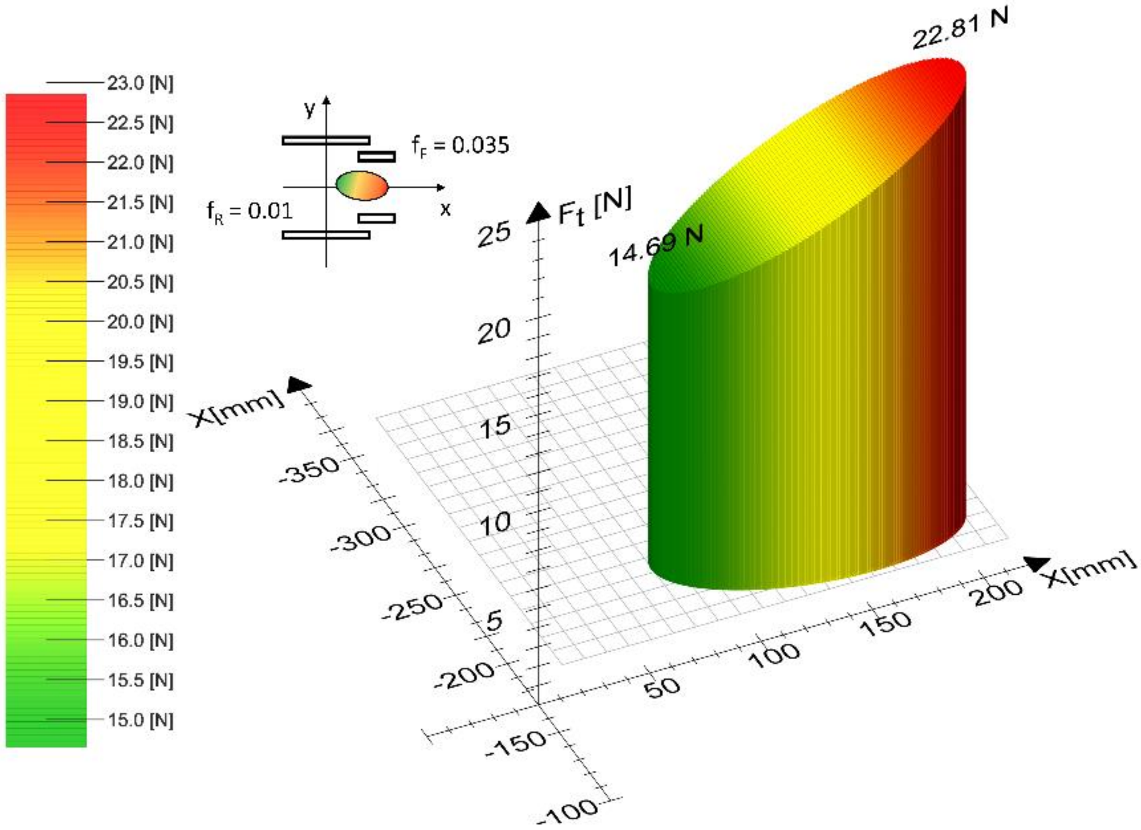


Fig. 32. Graph of the variation of the rolling resistance force versus the position of the centre of gravity of the human body when the wheelchair is inclined from the horizontal by an angle k = 0° [A5]

The research carried out showed a significant effect of changing the position of the human body on the value of the motion resistance force. It was found that the final stages of the propulsion phase had the highest motion resistance. This is due to the forward incline of the trunk and the increased load on the front castors. These wheels have a higher motion resistance coefficient than the rear wheels, which explains the variation in the motion resistance values.

On the basis of the research carried out, a model was developed to determine the value of the motion resistance of the wheelchair versus the angle of inclination of the terrain and the position of the centre of gravity on the longitudinal axis connecting the points of contact between the front and rear wheels and the road surface (29) (Figure 33)

$$\mathrm{F_r}(x_{CG}, \alpha) = 0.0613 \cdot x_{CG} + (9.818 + \mathrm{m} \cdot \mathrm{g} \cdot \sin\alpha) \tag{29}$$

Where:

F_r – motion resistance force,

x_{CG} – position of the centre of gravity of the human body on an axis running along the wheelchair,

m – weight of human,

g – ground acceleration,

α – angle of inclination of the wheelchair relative to the horizontal.

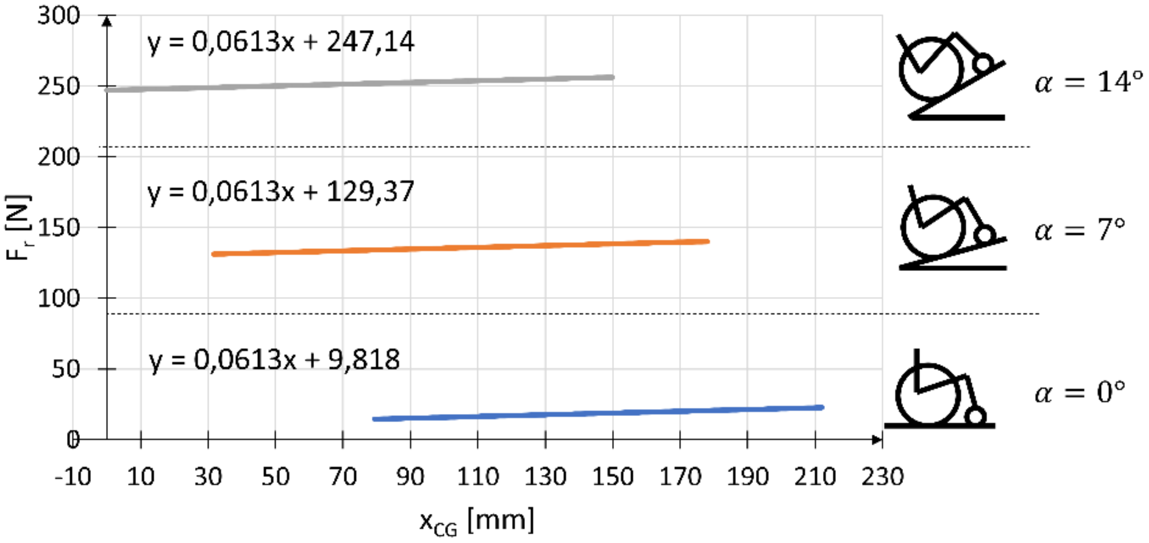


Fig. 33 Summary of the results of calculating the motion resistance force using the developed analytical model. Assumed human mass of 100 kg [A5]

During this research, the results developed during the studies described in the publications "The impact of wheelchairs driving support systems on the rolling resistance coefficient"(**A14**) and "The determination of the rolling resistance coefficient of objects equipped with the wheels and suspension system - results of preliminary tests"(**A18**) were relevant. This research determined the values of the motion resistance coefficient used in the motion resistance force model being developed.

A14	*Warguła, Ł., Kukla, M., &* ***Wieczorek, B.*** *(2020). The impact of wheelchairs driving support systems on the rolling resistance coefficient. In IOP Conference Series: Materials Science and Engineering (Vol. 776, No. 1, p. 012076). IOP Publishing*	*Ministry of Science and Higher Education score: 5 points*	---
A18	*Wargula, Ł.,* ***Wieczorek, B.****, & Kukla, M. (2019). The determination of the rolling resistance coefficient of objects equipped with the wheels and suspension system–results of preliminary tests. In MATEC Web of Conferences (Vol. 254, p. 01005). EDP Sciences.*	*Ministry of Science and Higher Education score: 5 points*	---

The functions of some of the propulsion systems I have developed went beyond the standard assist of muscle power by the torque generated by an electric motor. An example of this is the manual-electric hybrid propulsion (**P6**) discussed earlier. The functions that the control algorithm had were so wide-ranging that they also affected the kinematics of the entire anthropotechnical system. I have outlined this impact in a paper titled „Impact of a hybrid assisted wheelchair propulsion system on motion kinematics during climbing up a slope" (**A9**). This study examined how the use of a hybrid manual-electric propulsion system affects the speed of a wheelchair during the uphill climb. The main focus of the study was the analysis of the velocity amplitude Δv (Fig. 34). Two modes were tested in the performed research: hill assist (t3) and amplification of the torque generated (t4) by the upper limb.

A9	***Wieczorek, B.**, Warguła, Ł., & Rybarczyk, D. (2020). Impact of a hybrid assisted wheelchair propulsion system on motion kinematics during climbing up a slope. Applied Sciences, 10(3), 1025.*	*Ministry of Science and Higher Education score: 70 points*	*Impact factor: 2.679*
P6	***Wieczorek B.**, Warguła Ł., Kukla M.: Zestaw modyfikacyjny układu napędu do hybrydowego elektryczno-ręcznego wózka inwalidzkiego, Patent at the Patent Office of the Republic of Poland, no. of exclusive right PL 239350, 2021*	*Ministry of Science and Higher Education score: 70 points*	

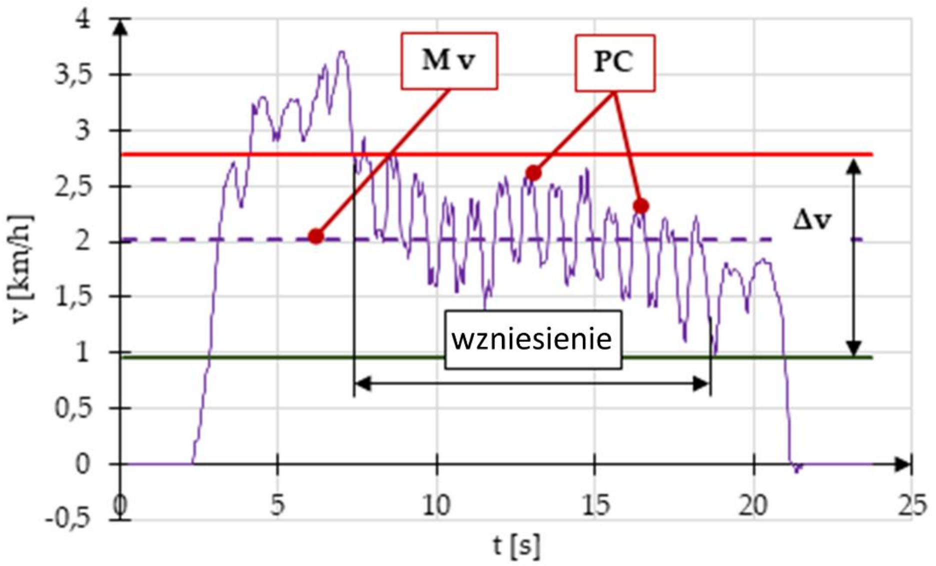


Fig. 34 Example of the analysed speed waveform of a wheelchair when going uphill, where PC – end point of the propulsion cycle, M v – average speed [A9]

A tabular summary of the mean results of the analysed parameters for the patients studied is included in Table 1 and 2. They include information on the total number of propulsion cycles CC, the number of propulsion cycles when going uphill, the average uphill speed M v, the amplitude of the uphill speed Δv and the average acceleration when going uphill M a.

Tab. 1. Summary of mean values of the analysed kinematic parameters for the hill assist mode (t3)

w		patient 1	patient 2	patient 3	average	SD
0%	CC *[-]*	19 ±1	22 ±1	19 ±0	19	1
	CH *[-]*	12 ±1	15 ±0	12 ±0	12	1
	M v *[km/h]*	2.03	1.31	1.51	1.85	0.26
	Δv *[km/h]*	1.70	1.95	1.87	1.76	0.14
	M a $[m/s^2]$	-0.004	-0.005	-0.003	-0.004	0.006
25%	CC *[-]*	16 ±1	22 ±2	18 ±1	17	1
	CH *[-]*	11 ±0	14 ±0	11 ±0	11	0
	M v *[km/h]*	2.34	2.25	2.32	2.33	0.10
	Δv *[km/h]*	0.81	0.88	0.86	0.83	0.08
	M a $[m/s^2]$	-0.010	0.009	0.008	-0.004	0.012
50%	CC *[-]*	14 ±1	20 ±1	17 ±2	15	2
	CH *[-]*	10 ±1	12 ±1	11 ±0	10	1
	M v *[km/h]*	2.77	2.56	2.64	2.73	0.08

	Δv *[km/h]*	0.70	0.71	0.88	0.76	0.16
	M a $[m/s^2]$	-0.008	-0.004	-0.003	-0.006	0.010
75%	CC *[-]*	13 ±0	18 ±0	16 ±0	14	1
	CH *[-]*	9 ±1	9 ±1	10 ±1	9	1
	M v *[km/h]*	2.88	2.78	2.94	2.90	0.06
	Δv *[km/h]*	0.71	0.98	0.85	0.75	0.16
	M a $[m/s^2]$	-0.001	0.008	-0.015	-0.006	0.010
100%	CC *[-]*	11 ±1	19 ±1	13 ±1	12	1
	CH *[-]*	7 ±2	9 ±0	9 ±1	7	2
	M v *[km/h]*	3.19	3.43	3.47	3.28	0.14
	Δv *[km/h]*	0.75	0.70	0.69	0.73	0.13
	M a $[m/s^2]$	-0.001	0.008	-0.002	-0.001	0.026

Tab. 2. Summary of mean values of the analysed kinematic parameters for the drive torque amplification mode (t4)

w		**patient 1**	**patient 2**	**patient 3**	**average**	**SD**
0%	CC *[-]*	19 ±1	22 ±1	19 ±1	20	2
	CH *[-]*	12 ±1	15 ±1	12 ±0	13	1
	M v *[km/h]*	2.01	1.31	1.51	1.61	0.31
	Δv *[km/h]*	1.70	1.95	1.87	1.84	0.18
	M a $[m/s^2]$	-0.006	-0.005	-0.003	-0.005	0.008
25%	CC *[-]*	19 ±2	17 ±0	18 ±0	18	1
	CH *[-]*	12 ±1	12 ±0	12 ±1	12	1
	M v *[km/h]*	1.66	1.41	1.63	1.57	0.19
	Δv *[km/h]*	1.61	1.95	1.84	1.80	0.21
	M a $[m/s^2]$	-0.007	0.006	-0.005	-0.002	0.024
50%	CC *[-]*	10 ±1	10 ±1	8 ±1	9	1
	CH *[-]*	5 ±0	6 ±0	6 ±1	6	1
	M v *[km/h]*	2.28	1.98	2.14	2.13	0.15
	Δv *[km/h]*	2.08	2.91	2.29	2.43	0.45
	M a $[m/s^2]$	-0.043	-0.017	0.011	-0.017	0.025
75%	CC *[-]*	5 ±1	5 ±0	6 ±1	5	1
	CH *[-]*	2 ±0	3 ±0	4 ±1	3	1
	M v *[km/h]*	3.02	2.07	2.62	2.57	0.49
	Δv *[km/h]*	2.81	4.28	3.15	3.41	0.79
	M a $[m/s^2]$	0.014	-0.120	0.017	-0.030	0.071
100%	CC *[-]*	4 ±0	n/a	4 ±1	4	1
	CH *[-]*	2 ±0	n/a	2 ±0	2	0
	M v *[km/h]*	3.13	n/a	3.37	3.25	0.16
	Δv *[km/h]*	3.83	n/a	4.23	4.03	0.30
	M a $[m/s^2]$	0.023	n/a	0.121	0.072	0.093

Based on the research carried out, it was concluded that the use of hybrid propulsion systems translates into positive changes in wheelchair kinematics. As the value of the assist factor w increased, the number of propulsion cycles decreased. Fewer propulsion cycles translate into a reduction in muscle effort, and maximum muscle activity values when propelling the wheelchair. This observation is confirmed by the results of the analysis of the amplitude of the wheelchair velocity determined by the maximum velocity in the propulsion phase and the minimum velocity value in the return phase of the hand (Figure 35).

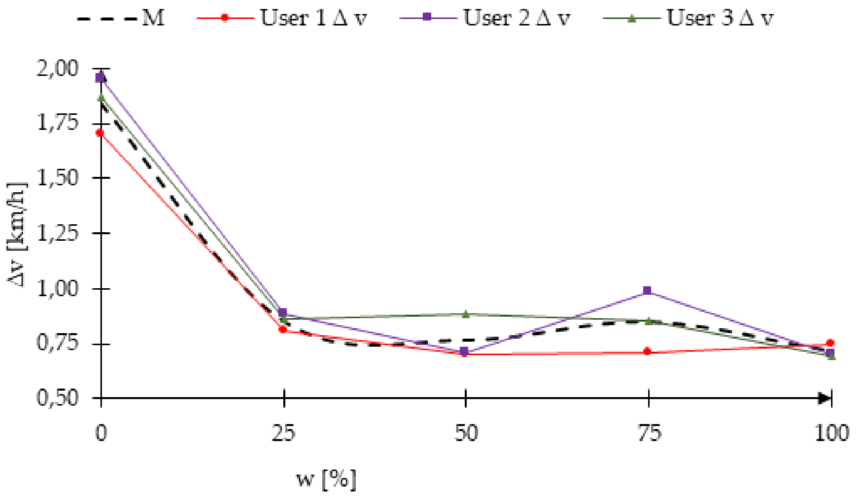


Fig. 35 Graphs of maximum speed amplitude versus assist gain coefficient during uphill climb versus assist gain coefficient for uphill climb assist mode [A9]

The movement kinematics were also analysed for the anti-rollback lock module. I have presented this research in a publication titled "Evaluation of the biomechanical parameters of human-wheelchair systems during ramp climbing with the use of a manual wheelchair with anti-rollback devices" (**A8**). In this study, in addition to the muscle activity tests discussed earlier, we also examined how the use of the wheelchair anti-rollback module (**P5**, **P10**) affected the uphill climb speed and the distance travelled by the wheelchair during a single drive wheel push-off (propulsion phase). Overall, this research had the objective of assessing the impact of the frictional coupling of the anti-rollback lock module to the drive wheel on the quality of operation of such a modified pushrim propulsion wheelchair. The study showed that in only 2 out of 10 patients did the use of the anti-rollback lock module negatively affect wheelchair speed (Figure 36). On the other hand, with regard to the distance covered by the wheelchair during a single push-off of the pushrims, no dependence of the effect on the module used was found (Figure 37).

A8	***Wieczorek, B.**, Kukla, M., Rybarczyk, D., & Warguła, Ł. (2020). Evaluation of the biomechanical parameters of human-wheelchair systems during ramp climbing with the use of a manual wheelchair with anti-rollback devices. Applied Sciences, 10(23), 8757*	*Ministry of Science and Higher Education score: 70 points*	*Impact factor: 2.679*
P5	***Wieczorek B.**, Warguła Ł., Kukla M.: Moduł do uniwersalnego hamulca dźwigniowego koła wózka inwalidzkiego, Patent at the Patent Office of the Republic of Poland, no. of exclusive right PL 239693, 2021*	*Ministry of Science and Higher Education score: 70 points*	
P10	***Wieczorek B.**, Warguła Ł., Kukla M., Berdychowski M.: Moduł do uniwersalnego hamulca dźwigniowego koła wózka inwalidzkiego, Patent at the Patent Office of the Republic of Poland, no. of exclusive right PL 239410, 2021*	*Ministry of Science and Higher Education score: 70 points*	

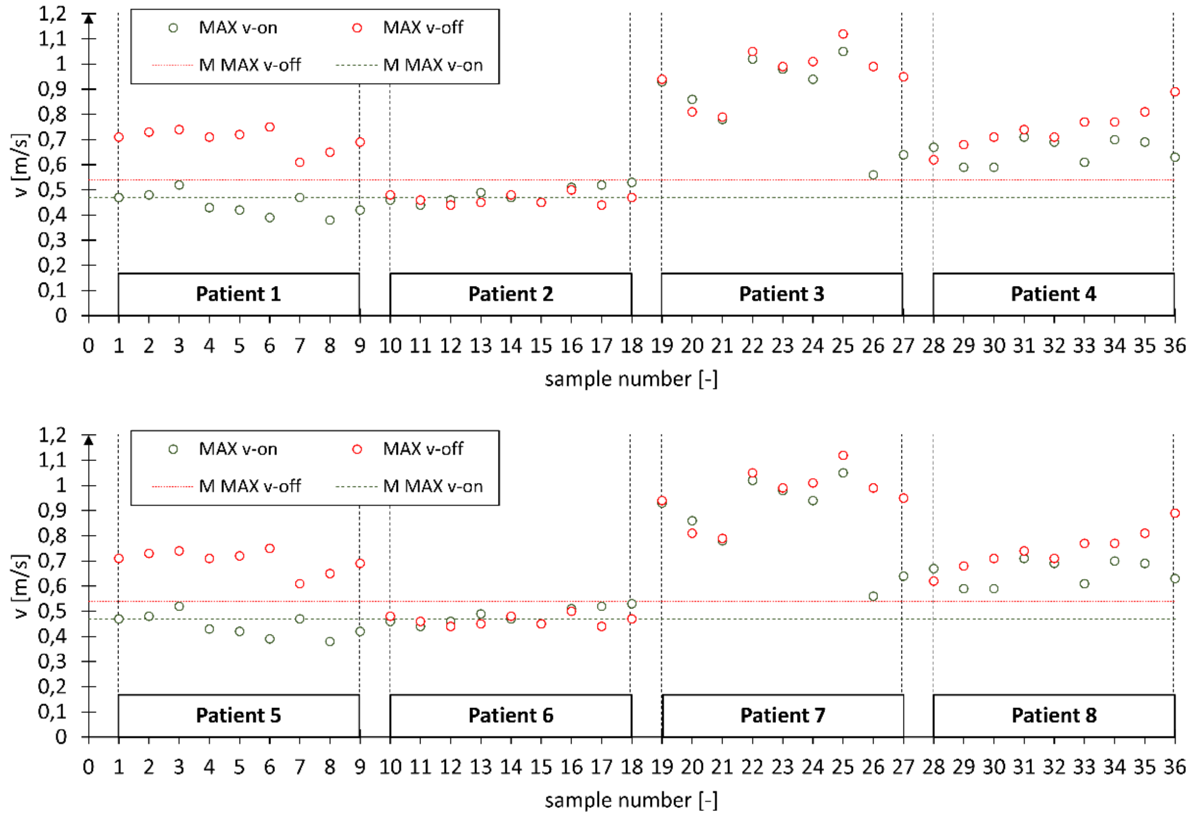


Fig. 36. Graph of maximum wheelchair speed for all measurement trials analysed, where MAX v-on – maximum wheelchair speed with anti-rollback system on, MAX v-off – maximum wheelchair speed with anti-rollback system off, M MAX v-on – average maximum wheelchair speed for all measurement trials with anti-rollback system on, M MAX v-off – average maximum wheelchair speed for all measurement trials with anti-rollback system off [A8]

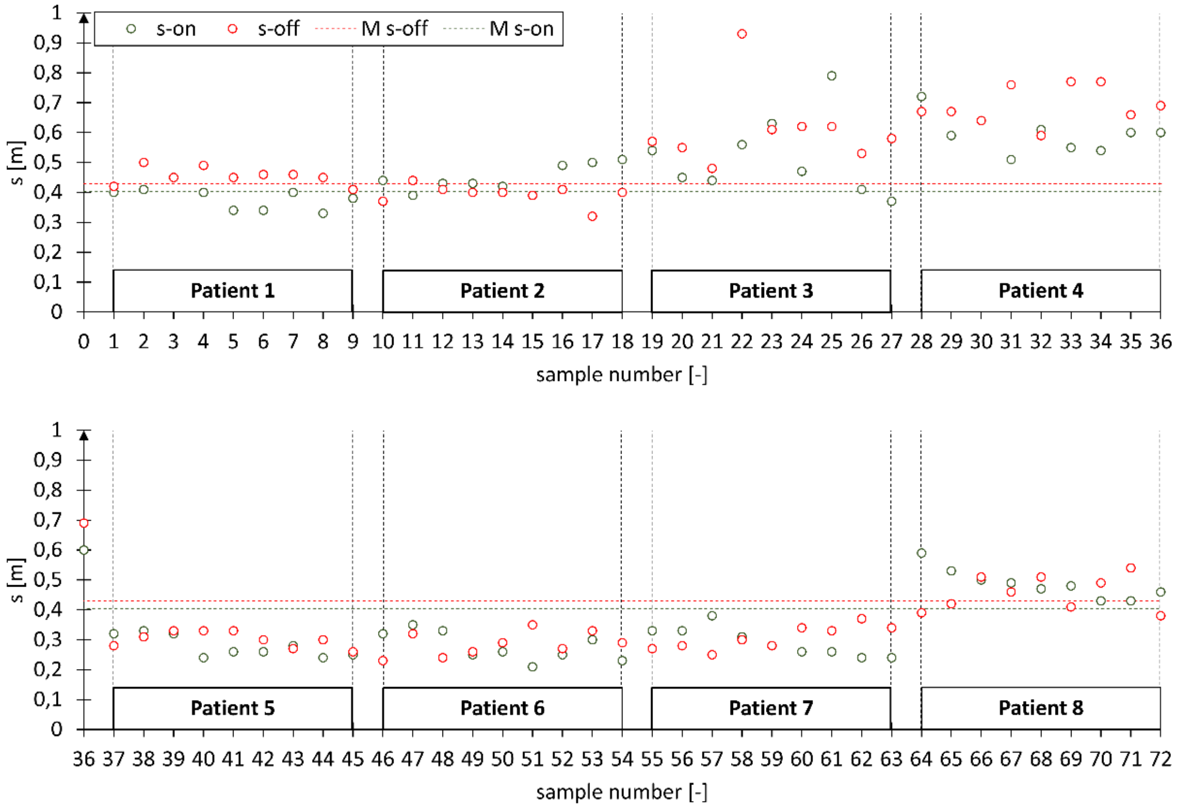


Fig. 37 Graph of the distance travelled in a single propulsion cycle for all the measurement tests analysed, where s-on – distance travelled during one propulsion cycle with the anti-rollback system switched on, s-off – distance travelled during one propulsion cycle with the anti-rollback system switched off, M s-on – average distance for all the measurement tests carried out with the anti-rollback system switched on, M s-off – average distance for all the measurement tests carried out with the anti-rollback system switched off [A8]

The method of operating the propulsion systems I designed required them to be driven by upper limb movements. Thus, the realisation of the scientific achievement required me to engage in the study of the kinematics of human body segments and their relationship to previously studied biomechanical parameters. Noteworthy results developed as part of this research problem are the development of a muscle effort map (results pending publication), map of recommended areas for mounting modules to enrich the functionality of the propulsion system (results pending publication) and a model of the rotation angle of the drive wheel during the propulsion phase (**A27**).

A27	***Wieczorek, B.*** *(2022). The Wheelchair Propulsion Wheel Rotation Angle Function Symmetry in the Propelling Phase: Motion Capture Research and a Mathematical Model. Symmetry, 14, p. 576*	*Ministry of Science and Higher Education score: 70 points*	*Impact factor: 2.713*

The muscle effort map is the result of a combination of motion capture and EMG muscle activity studies. The map is based on an experiment involving propelling a wheelchair up an incline of 4.57°, where the wheelchair was equipped with two types of anti-rollback lock module (Figure 38). The results of the experiment were published in an article entitled „Evaluation of anti-rollback systems in manual wheelchairs: muscular activity and upper limb kinematics during propulsion” [A28].

A28	***Wieczorek, B.**, Kukla, M., Warguła, Ł., Giedrowicz, M., & Rybarczyk, D. (2022). Evaluation of anti-rollback systems in manual wheelchairs: muscular activity and upper limb kinematics during propulsion. Scientific Reports, 12(1), 1-15.*	*Ministry of Science and Higher Education score: 140 points*	*Impact factor: 4.996*

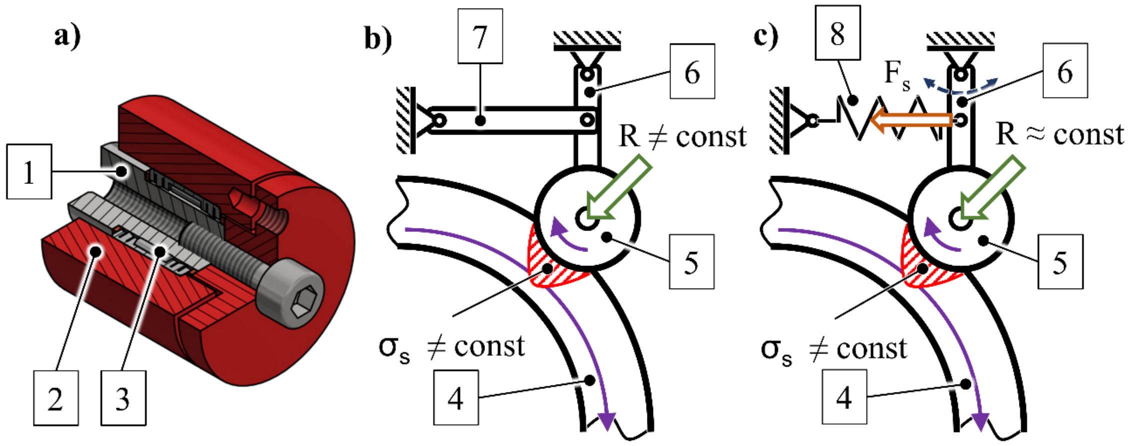


Fig. 38 Anti-rollback system (a) and the ways in which it is coupled to the drive wheel via a rigid element (b) and a spring element (c). Where: 1 – central axle, 2 – anti-rollback roller, 3 – one-way clutch, 4 – pneumatic wheelchair propulsion wheel, 5 – anti-rollback system, 6 – articulated link, 7 – rigid beam, 8 – tension spring [A28]

The map study performed (Fig. 39) shows the value of the muscle effort depending on the position of the hands on the pushrims during the propulsion phase. The results obtained can be used in the development of the control algorithm for the hybrid propulsion system (**P6**) or in the selection of gear ratios for mechanical transmissions with automatic shifting. Research related to the development of the map is currently being submitted for publication.

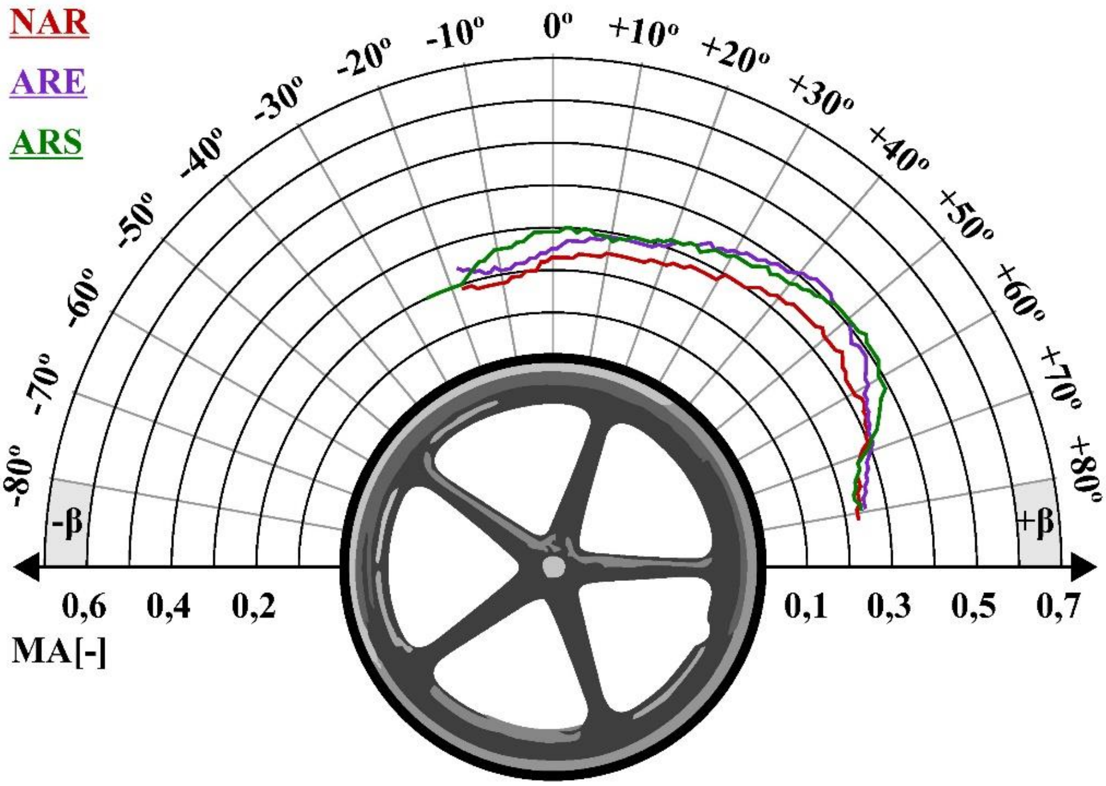


Fig. 39 Graphs of average total muscle effort of the upper limb versus its position on the pushrims. Where NAR – wheelchair without modification, ARS – wheelchair with rigid anti-rollback lock coupling module (**P5**), ARE – wheelchair with flexible anti-rollback lock coupling module (**P5**) [A28]

The map of recommended areas for the installation of additional modules is a tool used in the design process. It was developed on the basis of motion capture measurements in which three areas of hand reach dependent on the configuration of the kinematic chain used were determined.

- The first area called area of propulsion (AoP) described the position of the hand during wheelchair propulsion.
- The second area named area of comfort (AoC) described the free movement of the kinematic chain consisting of the forearm (FA) while the arm (AR) was stationary and pointing downwards parallel to the trunk (TR).
- The third area named area of approval (AoA) described the free movement of the kinematic chain consisting of the forearm (FA) and arm (AR) while keeping the torso (TR) supported by the wheelchair backrest stationary.
- The fourth area named area of risk (AoR) described the free movement of the kinematic chain consisting of the forearm (FA), arm (AR) and trunk (TR) while keeping the hip resting on the seat stationary.

The effect of combining these areas and taking into account the geometric features of the wheelchair is to produce a map showing the spaces on the wheelchair where it is possible to fit add-on modules. The separate areas (Figure 40) illustrate the three comfort zones for hand manipulation. These zones are located within three levels defined by the geometric features of the wheelchair. The area between the FUL and FDL level illustrates the space of the wheelchair support frame that does not change its position relative to the drive wheel. The area between the ARL and FUL levels marks the location of the armrests. This area is isolated because they are removed during wheelchair use, e.g. when transferring. Therefore, when planning to accommodate wheelchair accessories, it is important to bear in mind the need for periodic removal. The analysis performed showed that the area of the AoC that is most comfortable in terms of safety and effort reduction is significantly reduced by the area reserved for the spinning wheel and the area in which the AoP hand driving the pushrim propulsion system. After reduction, the AoC area is 194 mm wide and 227 mm high.

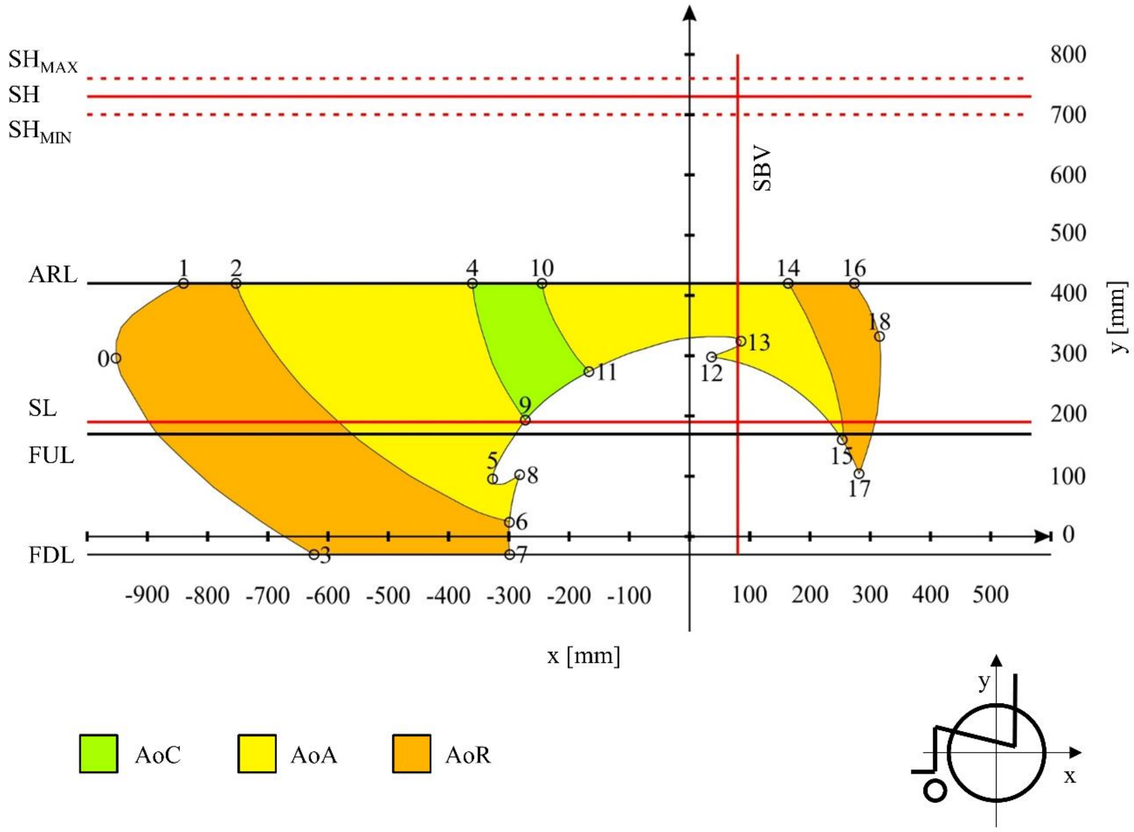


Fig. 40 Hand reach areas taking into account the geometric features of the wheelchair and areas reserved for manual pushrim propulsion operation. Where: SH – shoulder level for torso resting against wheelchair backrest, SHMIN – minimum shoulder level for torso resting against wheelchair backrest, SHMAX – maximum shoulder level for torso resting against wheelchair backrest, SBV – seat back riser, SL – seat level, ARL – armrest height, FUL – wheelchair upper frame height, FDL – wheelchair lower frame height, AoC – hand reach area comfortable, AoA – hand reach area allowed, AoR – hand reach area risky [data in publication]

Analysis of human body kinematics using motion capture measurement also allowed a model to be developed of the rotational function of the drive wheel during the propulsion phase. The model is described in a publication entitled „The Wheelchair Propulsion Wheel Rotation Angle Function Symmetry in the Propelling Phase: Motion Capture Research and a Mathematical Model" (**A27**). To obtain this model, the angle of rotation of the drive wheel depended on the percentage of the propulsion phase. This was to standardise the results of the measurements for all patients studied.

Standardisation was necessary because each patient realised the propulsion phase at different times. The procedure for converting the duration of the propulsion phase expressed in seconds into a percentage of the propulsion phase duration is formalised by the following equation (30):

$$PD = \frac{t_i}{t_{max}} * 100\% \tag{30}$$

Where: t_i – any time between $<0;t_{max}>$, t_{max} – duration of the propulsion phase and PD – percentage duration of the propulsion phase.

A27	***Wieczorek, B.*** *(2022). The Wheelchair Propulsion Wheel Rotation Angle Function Symmetry in the Propelling Phase: Motion Capture Research and a Mathematical Model. Symmetry, 14, p. 576*	*Ministry of Science and Higher Education score: 70 points*	*2.713*

On the basis of the experiments carried out and the analysis of the measurement signal, the occurrence of the phenomenon of central symmetry in the course of the drive wheel rotation angle function was observed (Figure 41). To analyse the phenomenon, two parameters describing the centre symmetry point (SP) and the symmetry lines (SL) were determined.

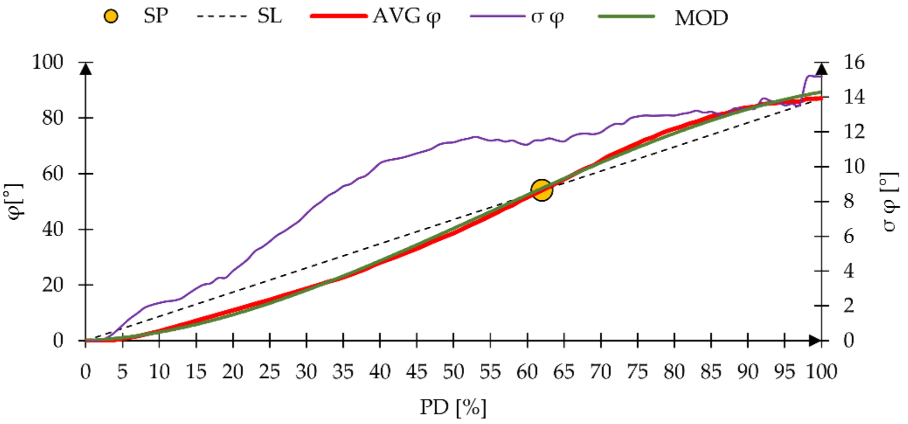


Fig. 41. Graph of the averaged function of change in drive wheel angle and standard deviation versus propulsion phase duration for wheelchair W2. Where: SP – point of symmetry, SL – line of symmetry, AVG ϕ – average for all patients function of driving wheel rotation angle, σ ϕ – standard deviation between tested patients, MOD – mathematical approximation function of the determined average function AVG ϕ, ϕ – driving wheel rotation angle, PD – percentage duration of propulsion phase

These observations and tests carried out on 10 patients and three models of a manual pushrim propulsion wheelchair allowed a generalised mathematical model to be developed to calculate the actual angle of rotation of the drive wheel ϕ(PD) versus the percentage duration of the PD propulsion phase (31).

$$\varphi(PD) = -0.0001PD^3 + 0.0192PD^2 + 0.1971PD \tag{31}$$

Describing the model in absolute terms, expressed as a percentage of the propulsion phase duration, gives it the ability to be adapted to different patients with different rates of wheelchair propulsion. This model, assuming the total duration of the propulsion phase expressed in seconds, makes it possible to generate a waveform of the drive wheel rotation angle function depending on the actual duration of the propulsion phase.

It should be noted that the research methods developed for the study of the biomechanics of manual wheelchair propulsion are also applicable to other areas of in-service testing of technical equipment. An example is the method of describing a set of points with elliptical areas, despite my work on it for use in describing the variation of the position of the centre of gravity it has also found application in other areas of exploitation research in which I have been involved. Among other things, the method was used in the definition of the energy intensity of the wood chipping process (**A2**).

A2	*Warguła, Ł., Kukla, M.,* ***Wieczorek, B.,*** *& Krawiec, P. (2022). Energy consumption of the wood size reduction processes with employment of a low-power machines with various cutting mechanisms. Renewable Energy, 181, 630-639*	*Ministry of Science and Higher Education score: 140 points*	*Impact factor: 8.001*

3.8. Summary

The research and development work carried out by me and with my participation has influenced the development of manual wheelchair propulsion systems. The presented research activity has developed new patented technical solutions to increase the accessibility of manual wheelchair propulsion. The innovative propulsion systems I have developed have significantly increased the possibility for a larger group of people with mobility disabilities to use manual propulsion, which has a positive impact on the aspect of promoting physical activity among people with mobility disabilities. The improved functionality and customisation of the propulsion systems demonstrated in the abstract are confirmed by published research work and also by a number of awards won at international invention fairs. The innovation of these solutions and their filling of a gap in the state of the art are confirmed by the patent rights granted.

The research procedures and data analysis methods developed in my work contribute to the design and construction process of wheelchairs. The research and procedure presented in the publications represent a new step in the design process to verify the structure in terms of its impact on the human-wheelchair anthropotechnical system. The values of the biomechanical parameters studied and their relationship to the specifics of manual wheelchair use constitute new data providing a set of information used in design as input to the design process.

The research problem I undertook was impossible for one person to carry out due to the complexity and amount of instruments handled during the research and the technical sophistication of the propulsion systems being designed. Therefore, when given the opportunity to lead the LIDER VII project, I assembled a permanent interdisciplinary team with whom I worked on the development of manual propulsion systems for wheelchairs. The research and work referenced in the abstract - and I am their first author - are my idea and are based on my vision of how to implement the research and engineering process. For the other work I mentioned, I was actively involved in the execution of the experiments, analysis of the measured data, verification of the methodology and verification of the design.

4. Additional scientific activities

My additional scientific activities are directed towards off-road grinding machines with low-power engines, inventive activities in the field of working equipment and machinery, and research into non-classical structural materials such as nickel and titanium alloys.

I have authored 20 reviews in 5 journals such as Applied Sciences, Sensors, Symmetry, Technologies and Disability and Rehabilitation. In addition, I am member of the regular review team for the journal Technologies and the academic editor of a special issue entitled "Symmetry and Asymmetry in Biomechanics" in the journal Symmetry.

My scientific activity is also expressed by membership in the Poznan Society of Friends of Science, Division V of Technical Sciences and the Association of Polish Inventors and Rationalisers. In addition, I am member of the Scientific Committee of the scientific conference entitled "False alarms generated by fire alarm systems" organised by the Józef Tuliszkowski Scientific and Research Centre for Fire Protection – National Research Institute.

I have presented the results of my research at eight international scientific conferences. Meanwhile, I have presented the physical results of my scientific activities in the form of functional prototypes in person at three international invention fairs.

5. List of academic achievements obtained before and after the award of the doctoral student in technical sciences

Post-doctoral research achievements	
Number of scientific articles	35
Number of chapters in the monograph	8
Number of patents granted	13

Scientific achievements **prior to** the award of the doctoral degree in technical sciences	
Number of scientific articles	1
Number of chapters in the monograph	4
Number of patents granted	0