Engineering Transactions, **73**(4): 659–685, 2025, https://doi.org/10.24423/engtrans.3485.2025
Institute of Fundamental Technological Research Polish Academy of Sciences (IPPT PAN)
Université de Lorraine • Poznan University of Technology

SolMech 2024

Comparison of Gantry Drive and Crankset: A Pilot Study Across a Broad Power Spectrum

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The gantry drive was originally invented in 1948 in England and was "rediscovered" in Poland in 2019 while working on lightweight, personal, compact vehicles. In this study, the gantry drive is subjected to dynamic tests against the background of the commonly known crankset. The aim of the dynamic tests is to develop power curves and measure efficiency for various human-mechanism systems, i.e., the hand-driven crankset, the leg-driven crankset, and the gantry drive. Pilot dynamic tests have shown many advantages of the gantry over the crankset; in general, test participants were much less tired when using the gantry drive.

Keywords: gantry; crankset; drive; power; vehicle.

1. Introduction

The gantry drive (also referred to as "the gantry") was originally invented in 1948 in England (Shaftesbury) [1], but it was not implemented for unknown reasons. Then, this drive was rediscovered in Ropczyce (Poland) in 2019 [2] during the development of lightweight, compact vehicles. The gantry drive takes up less space than the commonly used crankset. It was observed that a user in a gantry-based system lifts a much larger mass (as in leg press or Smith machine). It was primarily these two premises that initiated work on the gantry drive.

The gantry drive is an alternative solution to the traditional crankset. The hand crank mechanism was discovered in China before A.D. 200 [3]. Another turning point for the cranking mechanism was when cranking was used to power a bicycle discovered by Pierre Lallement [4, 5]. After this event, a number of inventions appeared to improve bicycle cranking, including the use of a chain to transmit power to the wheel used by James Starley [6], which was crucial in the development of the bicycle industry and contributed to the creation of the so-called "safety bicycle" created, among others, by John Kemp Starley [7, 8].

The gantry was initially subjected to theoretical analyses [9, 10] and then improved through considerations and optimization research on the human-mechanism-environment system. These theoretical analyses greatly contributed to the understanding of the gantry drive. Still, it turned out that without tests it was impossible to determine the dynamic characteristics, mainly due to the fact that it was not possible to determine cadences (shaft rotational speeds) and timing of duty cycles. During theoretical considerations of various techniques for receiving energy from a human, it was noticed that a complete understanding of the gantry problem in the context of cranking requires considering the human connected to the mechanism in a specific environment. This environment should be understood as the movement of limbs under gravity, ambient temperature, humidity, air composition, nutrition, amount of rest before exercise, training level, and other factors affecting both the person and the mechanism. This insight let to the conclusion that the human-mechanism-environment system should be treated as a type of engine (drive unit), which significantly simplifies the analysis of this multidimensional issue. When it comes to engines, each engine can be described by typical characteristics designed to represent its performance, as is the case with combustion engines and electric motors. This approach significantly facilitates the analysis, mainly because the methods for describing engines are well known in mechanical engineering. Even small changes, such as a different person in the system, the time of day, slightly different design of the mechanism, or different environmental conditions, can result in significantly different characteristics at the power take-off shaft. For these reasons, the examined issue is complex, though testing is possible since many factors can be controlled to remain consistent. Unfortunately, it is not possible to perform parallel tests on the same person using two different mechanisms, so some caution is necessary when planning tests, particularly regarding long rest periods, which in turn significantly extends the duration of the research. When comparing the gantry and the crankset, in the conducted study, the environmental aspect is understood mainly as the operation of human limbs within the gravitational field, as other factors were kept at similar levels.

The gantry drive consists of a movable pressure plate, designed to support the user's feet, mounted opposite a seat that is stationary in relation to the vehicle frame, and this pressure plate is mounted on a guided system connected to an energy-receiving element. Moreover, it is crucial that the pressure plate is pushed with both legs simultaneously.

Basically, the gantry drive can be implemented in four ways:

- a gantry with a non-rotatable plate mounted on a trolley moving along straight guides [1, 2, 11, 12], as shown in Fig. 1,

– a gantry with a swinging plate mounted on a trolley moving along straight guides [13]; this invention extends the stroke of the gantry because of limitations caused by the locking of the musculoskeletal system, particularly in the area of the ankle joint (see Fig. 2a),
– a gantry with a swinging plate mounted on a swinging lever [14]; this invention allows the human foot to follow the so-called maximum force curve and also enables a simple way to implement the plate guidance system (see Fig. 2b),

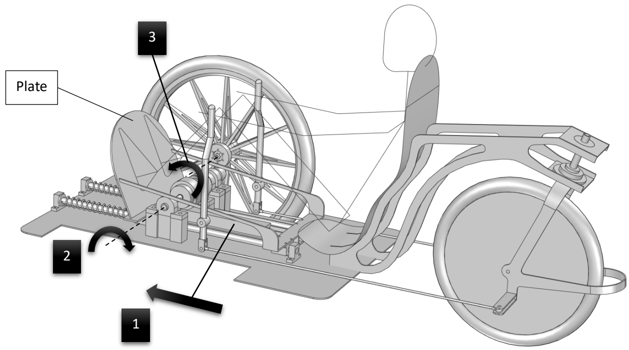

Fig. 1. Examples of gantry drives with a stationary pressure plate: 1 – linear movement of the trolley; 2 – rotary movement of the power take-off shaft; 3 – rotary movement of the drive wheel.

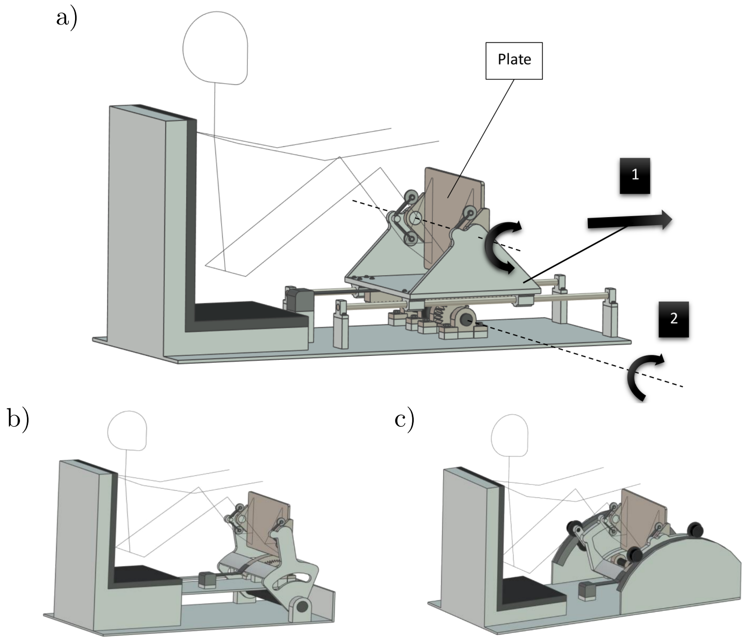

Fig. 2. Examples of gantry drives with a swinging pressure plate: 1 – linear movement of the trolley, 2 – rotary movement of the power take-off shaft and drive wheel.

– a gantry with a swinging plate mounted on a trolley moving along curved guides [15]; this invention allows the human foot to follow the so-called maximum force curve (see Fig. 2c).

In the case of a road vehicle, the final element receiving energy from the gantry is the wheel; in the case of a boat, it is a water turbine. Of course, a vehicle with a gantry drive can be equipped with any transmission type that improves its driving performance. A gantry-driven vehicle may also have a drive-support system powered by any type of engine, thus creating a hybrid drive configurations [16].

The aim of this research was to learn the dynamic properties of various techniques for extracting mechanical energy from humans. The main goal was to test a gantry with a swinging plate mounted on a trolley moving along straight guides, as in the original invention [13], and to compare this drive with the widely used leg-driven crankset. Moreover, in order to facilitate the interpretation of the test results, tests were also conducted using a hand-powered crankset. The research was designed to cover a wide spectrum of power outputs, and was mainly aimed at experimentally determining the power-time and efficiency-power graphs. Figure 3 shows the three human-mechanism-environment systems studied.

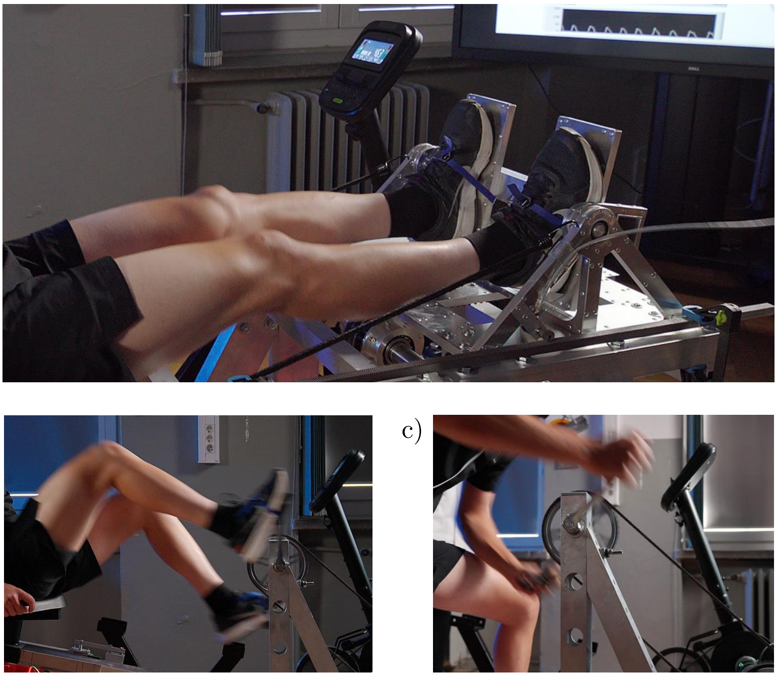

Fig. 3. Examined human-mechanism-environment systems: a) gantry drive, b) crankset powered by legs, c) crankset powered by hands.

The research was conducted to obtain the performance characteristics and compare them with the ones from the gantry drive with the commonly known crankset mechanism. The gantry drive, patented in late 2023, remains largely unstudied in terms of its mechanical characteristics. In addition, this research will enable a better understanding of human mechanics and mechanical energy generation processes. Plotting the previously mentioned graphs will allow further optimization of techniques for capturing mechanical energy from humans. The gantry drive is particularly suitable for ultra-light, three-wheeled vehicles (see Fig. 4), and can also be successfully used in four-wheeled vehicles, potentially revolutionizing the currently known passenger transport.

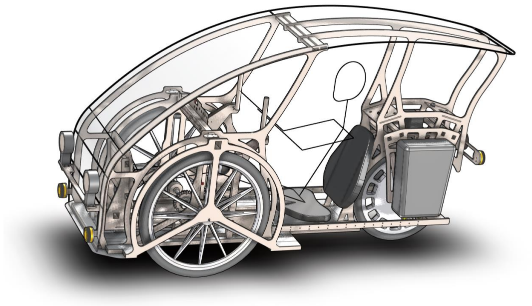

Fig. 4. Computer-aided design (CAD) model of a prototype personal vehicle equipped with a gantry drive [17].

The gantry drive is a fundamentally new solution that may be widely used in everyday life within a few years. Considering that personal vehicles can help solve the problem of traffic jams in cities and improve mobility in small towns and villages [18], researching this technology is certainly worthwhile. Moreover, using a gantry drive may enable new records to be achieved for vehicles powered by humans, as recorded, among others, by the World Human Powered Vehicle Association [19].

2. Materials and methods

The aim of this research was to compare the gantry drive with the commonly known leg-driven crankset. Although a crankset mechanism driven by manual force was also investigated, its low efficiency and low comfort led to its exclusion from detailed analysis in this paper. The crankset mechanism has been the subject of many studies; however, to due variations in human factors and diverse research techniques, it is not possible to compare data from the literature with the research on the gantry that was planned to be carried out. Therefore, the leg-powered crankset and gantry drive were tested simultaneously by the same participants to increase the reliability of the comparison between these mechanisms. Additionally, hand-powered crankset tests were performed to aid in the interpretation of the results obtained.

As mentioned in Sec. 1, the research aimed to prepare two test graphs comparing the characteristics of the gantry drive with those of the crankset. The power-time graph for various techniques of extracting mechanical energy from a human shows for how long a person can maintain a predetermined constant power. In turn, the efficiency graph, which plots various techniques for receiving mechanical energy from a human as a function of power, shows the efficiency of the human-mechanism-environment system at a specific power level, which is kept essentially constant during the test.

The research methods were developed during the research team's work on crankset tests at a 50 W load conducted on a large study group [18] and taking into account literature related to similar types of research [20].

Dynamic tests were planned across the entire power spectrum to comprehensively and clearly illustrate the differences between techniques for receiving energy from humans. The research carried out was of a pilot nature. The researchers hypothesized that tests across a wide power spectrum would show significant differences between techniques for receiving mechanical energy from humans, which would be visible in the differences in the measured characteristics.

2.1. Participants

Two participants took part in the pilot tests:

- user A (amateur): male, age 33, height 177 cm, weight 76 kg (cycling enthusiast, spending about 1 hour per day cycling for recreation; time spent on the gantry drive prior to the experiment was about 1 hour),
- user P (professional): male, age 19, height 178 cm, weight 67 kg (professional cyclist, spending about 5 hours per day on a bicycle; time spent on the gantry drive before the experiment was about 3 minutes during an on-the-job training that took place a few days prior to the research).

Both participants were informed about the purpose of the study during the recruitment process and signed informed consent prior to the experiment. All methods were carried out in accordance with relevant guidelines and regulations. All procedures were approved by the Ethics Committee for Research with Human Subjects Team at Warsaw University of Technology, approval number 5/2023, dated June 28, 2023. This approval was obtained for conducting dynamic research titled "Pilot studies of dynamic properties of mechanisms for receiving mechanical energy from a human across a wide power spectrum". The tests were carried out over a broad power spectrum, and some tests were carried out reaching the limits of the test participants' physical strength; consequently, the presence of two qualified paramedics and an ambulance was required during the experiment. Before and after each examination, the participants' blood pressure and heart rate were checked. All planned research methods were non-invasive. Only healthy people participated in the study. They were subjected to various levels of physical exertions (different power outputs). Tests were generally conducted at low, medium, high, and maximum energy expenditure levels. During the tests, the limitations of the human-mechanism system were observed.

2.2. Test procedures

The tests took place over three consecutive days in July 2023. On the first day, the hand-powered crankset was tested; on the second day, the leg-powered crankset was tested; and on the third day, the gantry drive was tested. Testing began at the same time each day, and the same hourly schedule was maintained each day. A detailed research schedule, which was carried out on each subsequent day of research for subsequent human-mechanism-environment systems, is presented in Table 1.

TABLE 1. Detailed one-day research schedule.

Test No.	Description of the study	Test type	User
1	Maximum peak rotary speed and power	Rotary speed test and power test	A
2	Maximum peak rotary speed and power	Rotary speed test and power test	P
3	Average power: – hand-driven crankset (about 160 W) – leg-driven crankset (about 320 W) – gantry drive (about 320 W)	Time trial (Phases P1-P13)	A
4	Average power: – hand-driven crankset (about 160 W) – leg-driven crankset (about 320 W) – gantry drive (about 320 W)	Time trial (Phases P3-P13)	P
5	Low power: – hand-driven crankset (about 100 W) – leg-driven crankset (about 220 W) – gantry drive (about 220 W)	Time trial (Phases P3-P13)	A
6	Low power: – hand-driven crankset (about 100 W) – leg-driven crankset (about 220 W) – gantry drive (about 220 W)	Time trial (Phases P3-P13)	P
7	Power 50 W, 150 W, 250 W	Efficiency test (Phases Q3-Q17)	A
8	Power 50 W, 150 W, 250 W	Efficiency test (Phases Q3-Q17)	P
9	Power 50 W, 150 W, 350 W	Efficiency test (Phases Q3-Q17)	A
10	Power 50 W, 150 W, 350 W	Efficiency test (Phases Q3-Q17)	P
11	Power 50 W, 150 W, 450 W	Efficiency test (Phases Q3-Q17)	A
12	Power 50 W, 150 W, 450 W	Efficiency test (Phases Q3-Q17)	P

Two test procedures were necessary to generate the power and efficiency graphs.

The following procedure was used to develop the power graph (the procedure is schematically presented in Fig. 5):

P1. Presenting the participant with a detailed exercise schedule.

P2. Collecting data on the participant's age, height and weight.

P3. Entering the participant's data into the computer, controlling the magnetic brake, and activating the mode for maintaining a set power of 30 W.

P4. Seating the participant on the seat and determining the distance between the seat and the mechanism for receiving mechanical energy.

P5. Measuring heart rate and blood pressure using an external measuring device.

P6. Connecting the heart rate sensor to the subject (ECG measurement) and putting a mask equipped with a flow sensor on the participant.

P7. Allowing the participant to regulate their breathing for 3 minutes.

P8. Conducting a warm-up at a power of 30 W for 1 minute, while at the same time allowing the participant to adapt to the test stand.

P9. Allowing a 3-minute break for the participant. During this time, the load on the magnetic brake was increased to a pre-planned power (in the case of the maximum peak power test, the load was adjusted at the request of the test person, which is directly related to selecting the optimal cadence for maximum power output).

P10. Having the participant perform the exercise until they felt the need to stop.

P11. Measuring heart rate and blood pressure using an external measuring device.

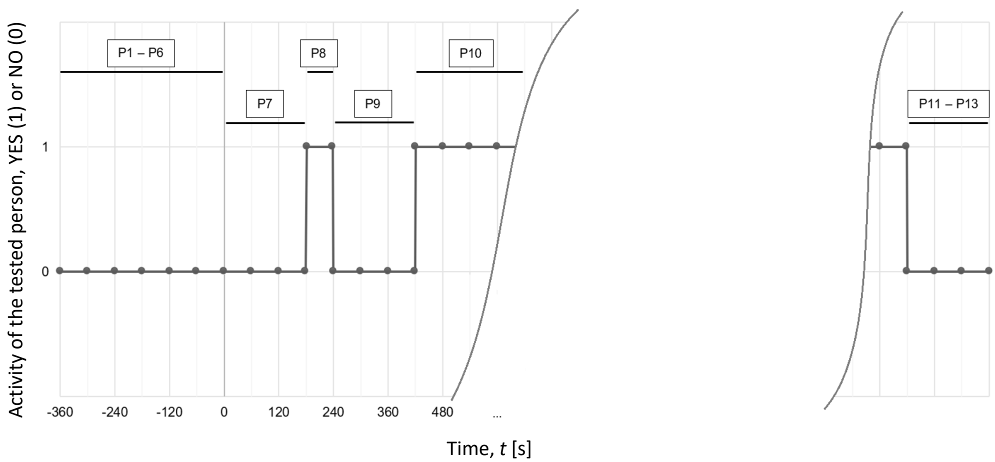

FIG. 5. Schematic of the test procedure aimed at developing the power graph.

P12. Disconnecting the measuring equipment from the participant.

P13. Conducting an interview with the participant to assess their feelings of fatigue during the exercise.

A series of tests aimed at determining the power characteristics were continued until the participant indicated that they were unable to continue the exercise. In this study, peak powers and successively lower powers were examined. There was a break of at least 30 minutes between the end of the P13 test and the start of the next test procedure if the participating person continued testing at subsequent power levels [21].

The following procedure was used to develop the efficiency graph (the procedure is schematically presented in Fig. 6):

Q1. Presenting the participant with a detailed exercise schedule.

Q2. Collecting data about the age, height and weight of the participant.

Q3. Entering data about the participant into the computer, controlling the magnetic brake, and activating the mode to maintain a set power of 30 W.

Q4. Seating the participant on the seat and determining the distance between the seat and the mechanism for receiving mechanical energy.

Q5. Measuring heart rate and blood pressure using an external measuring device.

Q6. Connecting the heart rate sensor to the participant (ECG measurement) and putting a mask equipped with a flow sensor on the participant.

Q7. Allowing a 3-minute brake for the participant to adapt their breathing.

Q8. Conducting a warm-up at a power of 30 W for 1 minute, while at the same time allowing the participant to adapt to the test stand.

Q9. Allowing a 3-minute break for the participant. During this time, the load on the magnetic brake was increased.

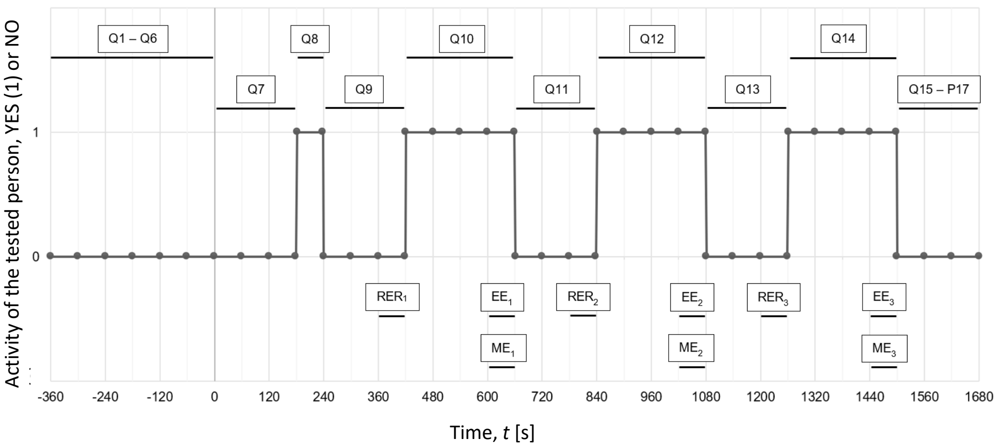

Fig. 6. Schematic of the test procedure used to develop an efficiency graph.

Q10. Having the participant perform the exercise for 4 minutes.

Q11. Allowing a 3-minute break for the participant. During this time, the load on the magnetic brake was increased.

Q12. Having the participant perform the exercise for 4 minutes.

Q13. Allowing a 3-minute break for the participant. The load on the magnetic brake was increased.

Q14. Having the participant perform the exercise for 4 minutes.

Q15. Measuring heart rate and blood pressure using an external measuring device.

Q16. Disconnecting the measuring equipment from the participant.

Q17. Conducting an interview with the participant to assess their feelings of fatigue during the exercise.

Figure 6 shows the areas from which data were collected to determine gross and net efficiency. RER represents resting energy used for life processes, EE represents the energy used for life processes and during exercise, while ME represents the mechanical energy transferred from the human-mechanism-environment system. Detailed definitions and formulas for determining RER, EE, and ME, which ultimately allow the calculation of gross and net efficiency, are described in the work preceding this study [18]. Areas Q10, Q12, and Q14 are where the main exercise took place.

There was a break of at least 30 minutes between the end of the Q17 test and the start of the subsequent testing procedure, in case the participant needed to continue testing at subsequent higher power levels after recovery.

Before starting the maximum power test (tests 1 and 2, see Table 1), the load on the magnetic brake was lowered to the minimum value to allow the participant performing mechanical work to adapt to the mechanism through several seconds of movement; then, the maximum peak cadence was checked. Additionally, tests 1 and 2 examined peak power, with each exercise lasting only a few seconds. The exercises was repeated 2–3 times to make sure that the peak power was achieved, with breaks of several minutes taken between maximum power tests. The load on the magnetic brake during this test was selected based on the participant's request and modified between subsequent maximum power trials.

The load in all tests was adjusted at the participant's personal request. Once the load was selected, it was maintained constant throughout the exercise.

The inclination of the seat backrest was equal to $\alpha = 17.5°$; in turn, the seat was positioned horizontally. The test stand (see Fig. 7) was attached to the floor so that it did not move under the influence of inertial forces generated by the motion of the participant's limbs.

The starting torque for the entire measurement path, when the drive belt to the magnetic brake was unfastened, was $0.8\ \mathrm{N \cdot m}$ for the crankset mecha-

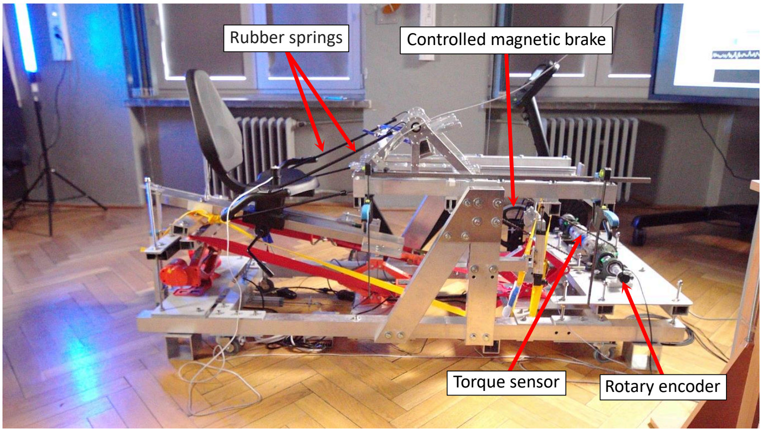

FIG. 7. General view of the test stand equipped with a gantry drive.

nism. This braking torque includes bearing resistance in the crankcase, chain movement resistance, bearing resistance in the measuring track and magnetic brake, and clutch movement resistance. In the analysis, the starting torque was not subtracted from the torque considered as the transferred mechanical energy because it was assumed that some braking torque in the personal vehicle would also be present. The length of one of the crankset arms was 0.175 m.

The tension force of the rubber springs pulling the trolley when the gantry was in its initial position was 21.9 N, and when the gantry was in the second extreme position, the force increased to 84.8 N. The total stroke of the gantry was 0.47 m. The force required to move the trolley, with the drive belt to the magnetic brake unfastened and the rubber springs removed, was 18.6 N. The pitch

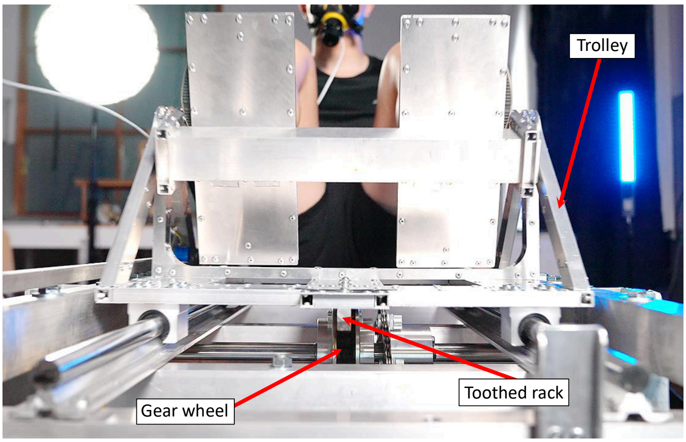

FIG. 8. Front view of the test stand equipped with a gantry drive.

radius of the gear wheel connected to the toothed rack attached to the trolley from the bottom was 0.064 m (see Fig. 8). Based on these data, it can be calculated that the braking torque for the gantry is $1.2\ \mathrm{N} \cdot \mathrm{m}$. This is higher than in the case of the crankset, but it should be kept in mind that the gantry drive allows the drive to be transferred directly to the vehicle wheel without using a chain, which is an essential feature of this drive system. The crucial advantage of the gantry drive is that it allows direct power transfer to the chassis wheels. In the case of traditional crankset, this is impossible because there will be a collision between the human leg and the shaft. Hence, a chain is necessary in the crankset mechanism to move the drive out of the collision zone. It should also be noted that there is a crankset mechanism based on the construction of a cranked shaft (a shaft with eccentric journals), which is commonly used in water bikes. However, with a cranked shaft in road vehicles, it is not possible to directly drive the driving wheel due to mismatched angular velocities. Therefore, it is necessary to increase the rotational speed, which forces the use of a transmission, e.g., one based on chain wheels and a chain.

A schematic diagram of the test stand is shown in Fig. 9. The human-mechanism system (a gantry drive or a crankset powered by legs or hands) is treated as a single object, which can be treated as an engine or motor. In this

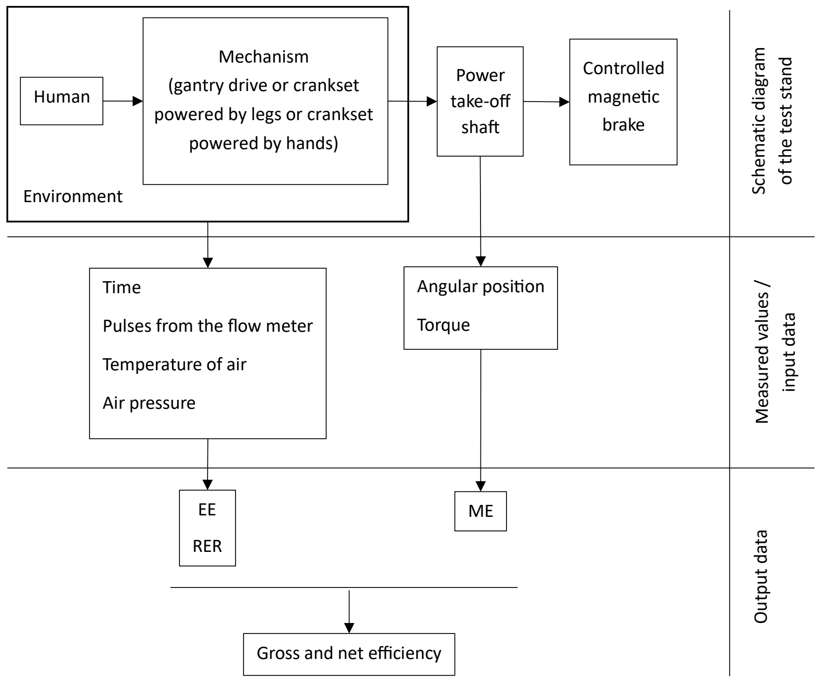

FIG. 9. Diagram of the test stand, including measured values and output data.

study, the comparison of the human-mechanism system to an engine was made because the operation of engines is well understood in technology, which significantly simplifies the description of the phenomenon being studied. The human-mechanism system is connected to the power take-off shaft. The values measured on the test stand, which serve as input data for calculations, are listed, along with output values obtained from the calculations.

Power was calculated as the amount of energy at the power take-off shaft over a given time. Input data such as time, angular position, and torque were used in the power calculation.

3. Theory and calculations

Human fatigue is a multidimensional problem [22]. It can be considered at various levels:

- respiratory load (amount of air absorbed),
- respiratory and cellular load (amount of oxygen consumed, difference between absorbed and consumed oxygen),
- cardiovascular load (heart rate, ECG signal measurement),
- thermal load (overheating of the body, especially during prolonged exercise),
- muscular load (calculation method based on recorded human reactions and geometry),
- skeletal load (calculation method based on recorded human reactions and geometry).

In this study, the efficiency of the human-mechanism-environment system was determined by the amount of air absorbed in accordance with a method described and validated in practice by the authors. All measured values at the test stand, together with the descriptions of the measuring devices and the equations for analyzing the collected results, were described in detail in the work preceding this study [18].

4. Results

The tests took place over three consecutive days, starting at 9:00 a.m. The basic environmental conditions in which the tests were carried out are presented below (the given values were recorded at the beginning of the day):

- day 1 – hand-powered crankset, temperature 27.8°C, air humidity 34%,
- day 2 – leg-powered crankset, temperature 26.8°C, air humidity 38%,
- day 3 – gantry drive, temperature 27.4°C, air humidity 32%.

Tables 2–5 were prepared based on the data collected from the first part of the research, i.e., tests 1 to 6, as described in Table 1. Power graphs were developed based on these data. Peak power values considered for times of 0.015 s are not presented in the graphs.

In Tables 2 and 3, one complete cycle is defined differently for the gantry and the crankset. In the case of the gantry drive, it starts from the moment when the torque began to increase and continues until the next work cycle. For the gantry, one full cycle consists of three phases: the torque's increase, the torque's drop to zero, and the phase where the torque is zero. During this time, the trolley is withdrawn, and the cycle is repeated. In the case of the crankset, one complete cycle is understood as a complete revolution of the shaft to which the cranks are mounted, i.e., a rotation of the shaft by 2π. In other words, in one complete crankset cycle, the work of both arms or legs is recorded.

TABLE 2. Data obtained to develop power graphs for user A.

Exercise number	Time considered [s]	Power [W]	Torque [N · m]	Angular velocity of the shaft [rad/s]
Hand-powered crankset				
1	0.015	2162.9*	32.2*	67.3*
2**	0.490	395.8***	29.0***	20.2***
3	4.602	305.1***	16.7***	29.0***
4	52.961	157.3***	14.5***	14.9***
5	106.952	98.7***	8.5***	18.5***
Leg-powered crankset				
1	0.015	3563.8*	47.0*	75.8*
2**	0.315	612.2***	27.4***	29.6***
3	7.801	486.8***	31.3***	19.6***
4	56.679	312.5***	24.0***	20.1***
5	118.720	200.7***	16.1***	20.0***
Gantry drive				
1	0.015	6634.1*	85.8*	77.3*
2**	0.667	605.6***	31.8***	20.1***
3	4.678	496.0***	27.3***	22.8***
4	46.800	320.5***	21.0***	20.0***
5	125.119	228.9***	15.8***	20.7***

* Peak instantaneous (values when maximum power was recorded).

** Values for one complete cycle of the mechanism.

*** Values averaged for the time considered.

Table 3. Data obtained to develop power graphs for user P.

Exercise number	Time considered [s]	Power [W]	Torque [N · m]	Angular velocity of the shaft [rad/s]
Hand-powered crankset				
1	0.015	3273.9*	34.5*	94.9*
2**	0.541	456.8***	36.5***	17.8***
3	12.085	202.6***	13.8***	19.3***
4	94.699	162.0***	14.9***	15.6***
5	245.686	96.7***	8.3***	17.8***
Leg-powered crankset				
1	0.015	4008.5*	63.5*	63.1*
2**	0.414	714.2***	43.8***	24.5***
3	5.179	575.9***	36.3***	24.9***
4	103.819	342.0***	27.3***	19.7***
5	309.102	232.8***	20.3***	17.4***
Gantry drive				
1	0.015	5650.1*	75.2*	75.1*
2**	0.659	483.1***	23.8***	27.3***
3	5.279	472.1***	25.4***	24.4***
4	78.240	307.0***	21.0***	20.1***
5	332.561	242.8***	16.5***	20.5***

* Peak instantaneous (values when maximum power was recorded).

** Values for one complete cycle of the mechanism.

*** Values averaged for the time considered.

In Tables 4 and 5, the peak instantaneous speed is not related to the corresponding peak instantaneous torque reading. The maximum speed was measured when the brake was set to its minimum load during the so-called test of the

Table 4. Peak instantaneous rotational speeds and peak instantaneous torques for user A.

Peak instantaneous rotation speed [rad/s]	Peak instantaneous torque [N · m]
Hand-powered crankset	
92.1	47.5
Leg-powered crankset	
88.0	69.9
Gantry drive	
127.7	92.3

TABLE 5. Peak instantaneous rotational speeds and peak instantaneous torques for user P.

Peak instantaneous rotation speed [rad/s]	Peak instantaneous torque [N · m]
Hand-powered crankset	
100.1	55.3
Leg-powered crankset	
81.4	71.5
Gantry drive	
153.2	81.2

maximum speed, to determine the highest speed a human can achieve. The peak torque was recorded when attempting to achieve maximum power (the load was selected at the participant's request), but this peak torque is not related to the instantaneous peak power reading for time 0.015 s (see Tables 2 and 3).

The power curves differ significantly for the two participants (see Figs. 10 and 11), but their trend is essentially identical. Taking into account that the maximization of muscle power, according to the Hill curve [23, 24], reaches its extreme when the muscle speed is correctly selected, when analyzing the power curve, it is important to note that the load on the magnetic brake, and, consequently the speed of muscle work, may not have been selected in an optimal way for power maximization. A surprising finding during the research was how high cadences could be developed on the gantry drive. After the tests, a conclusion emerged that the gantry drive should generally be operated at relatively high cadences. Before the tests, it seemed that the gantry drive was more like a "force"

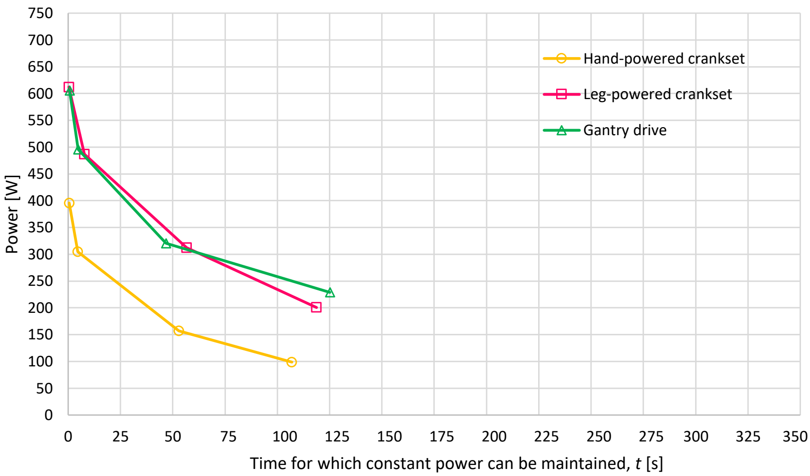

FIG. 10. Power graph for user A.

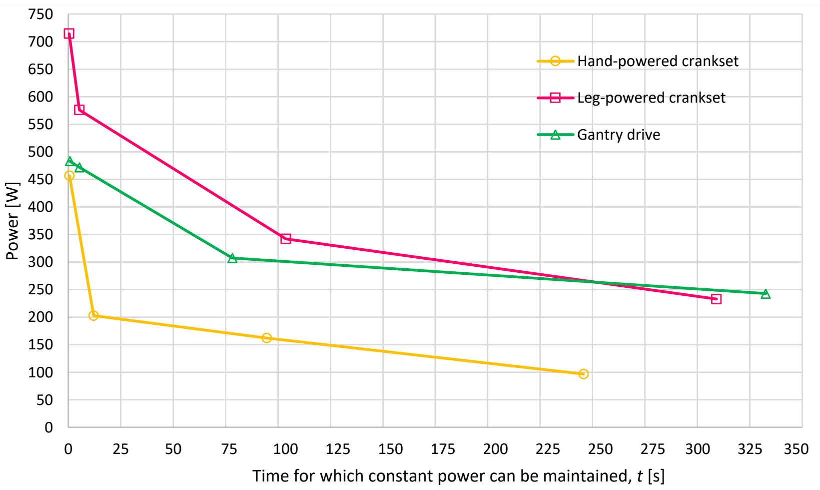

Fig. 11. Power graph for user P.

drive, where high-pressure force was perceived as a crucial advantage over the crankset. Additionally, it should be noted that a different cadence is optimal for different powers, making the topic even more complex and requiring further research.

The power peak shows a significant advantage of the gantry over the leg-driven crankset (see Tables 2 and 3).When short times are considered, in practice, it seems that this will manifest itself in an exceptionally high acceleration of the vehicle equipped with the gantry drive in the initial phase of movement. The power graphs indicate that there is a time range, from a few to 65 s in the case of user A, and up to 250 s for user P, where the crankset has an advantage over the gantry drive. It is suspected that, in practice, this advantage would be evident in the so-called "sprints", where a vehicle with the crankset can outperform a vehicle with the gantry drive. The next area of the graph beyond 65 s for user A and 250 s in the case of user P, shows where the gantry allows the user to generate much greater power than with the crankset. The characteristic curves for the hand-powered crankset, as expected, are significantly worse than those for the leg-powered crankset and the gantry drive, which aligns well with the authors' assumptions.

During peak power tests, it turned out that there was a high risk of breaking the bicycle chain, as it transmitted the drive from the gantry to the measuring track. The chain became significantly deformed while trying to measure peak power and went out of tune. Hence, slightly greater results in favor of the gantry can be expected in the area of short times on the power diagram. In future research, it would be advisable to use a chain from a moped to transmit the drive from the gantry drive.

Tables 6 and 7 present the calculated gross and net efficiencies.

Table 6. Gross and net efficiencies for user A.

Estimated power [W]	Gross efficiency [%]	Net efficiency [%]
Hand-powered crankset		
50	9.6	20.3
150	10.8	15.6
250	9.0	11.8
Leg-powered crankset		
50	10.6	21.6
150	14.1	22.1
250	18.1	25.3
350	15.6	18.9
450	13.4	15.2
Gantry drive		
50	10.2	30.8
150	14.8	28.8
250	17.4	26.3
350	19.1	28.7
450	16.0	19.1

Table 7. Gross and net efficiencies for user P.

Estimated power [W]	Gross efficiency [%]	Net efficiency [%]
Hand-powered crankset		
50	10.2	24.8
150	13.9	27.7
250	15.3	23.7
350	11.0	13.4
Leg-powered crankset		
50	12.2	29.4
150	17.2	32.4
250	24.2	38.9
350	32.1	50.7
450	33.2	44.8
550	24.1	27.4
Gantry drive		
50	11.6	30.0
150	16.5	29.4
250	18.2	27.2
350	20.7	29.0
450	24.1	33.5
600	16.9	19.1

The gross efficiency graphs (see Figs. 12a and 13a) show that the efficiency of the gantry drive and the leg-driven crankset drive is similar in low power areas. Significant differences become apparent when the power increases. While the efficiency of different users and powers levels vary greatly, the overall trend is identical.

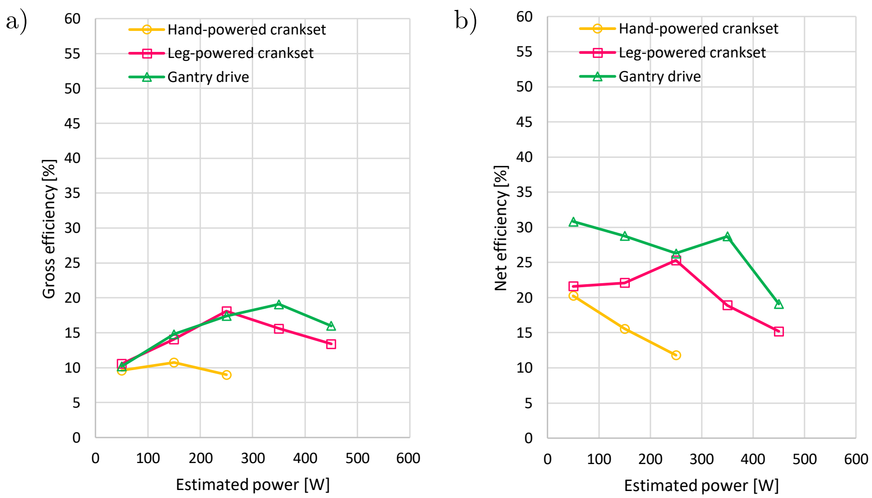

Fig. 12. Gross efficiency (a) and net efficiency (b) graphs for user A.

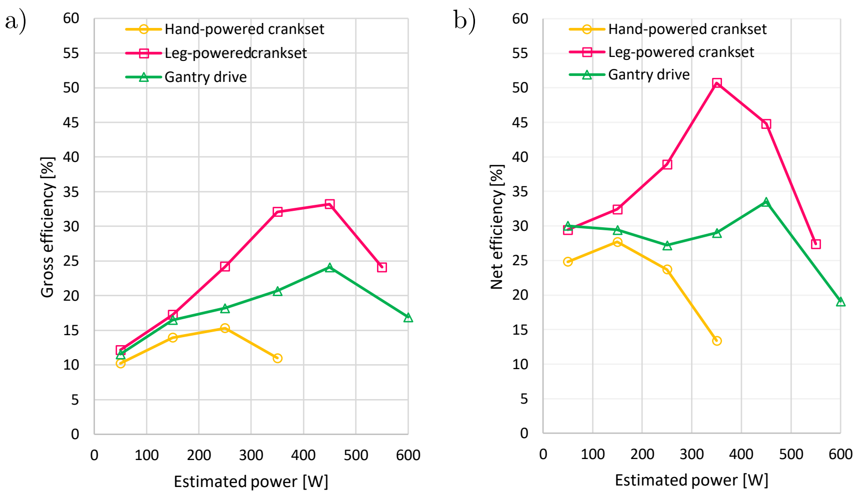

Fig. 13. Gross efficiency (a) and net efficiency (b) graphs for user P.

The net efficiency graphs (see Figs. 12b and 13b) for the gantry drive are very interesting. For both users, efficiency decreases with increasing power, then increases, and decreases again. The remaining characteristics are essentially concave in nature.

The efficiency for user A, in the case of the gantry, is higher at high power compared to the crankset (see Fig. 12). A big surprise is the efficiency for user P, a professional cyclist, where the efficiency is exceptionally higher in favor of the crankset (see Fig. 13).

Both participants indicated in the interview that higher power can be maintained with the gantry drive while experiencing less fatigue than with the crankset powered by legs and arms. Taking into account, in particular, the obtained efficiency graphs and the individual feelings of the participants, it can be concluded that the selected technique of assessing efficiency based on the amount of air absorbed may not be a very good method for describing issues related to exercise and for examining human limitations. Based on the research conducted, it is difficult to identify a specific critical human limitation. While respiratory limitations were noticeable during power tests, as were limitations related to muscle pain, the feeling of fatigue is quite difficult to define.

5. Discussion

Based on the graphs and interviews with the participants, it can be concluded that the gantry drive is generally a more advantageous technique for receiving mechanical energy from humans. According to the results from the power graphs, the gantry drive can maintain higher power levels for a longer time compared to the crankset mechanism.

Table 8 summarizes the key features of various techniques for receiving mechanical energy from humans. The table describes, using pros (+) and cons (−), whether a given feature has an advantage or disadvantage. The issue is quite complex and it is difficult to determine the quantitative contribution of a given feature, but it is possible to say what it is.

The system's operating frequency is crucial in the considered issue of drive optimization, which is why Tables 2 and 3 additionally present cadence and torque. As can be seen, as the power decreases, the operating frequency of the human-mechanism system also decreases, indicating a clear relationship. The research did not capture temperature stress, as the time required for the person to begin overheating was relatively short.

Regarding point 1 from Table 8, in the case of the crankset, lifting the hand or leg in the gravitational field allows using the potential energy of the hand or leg; in other words, recovering energy. However, since the efficiency of the muscular system is about 25% [29, 30], limiting movements in the gravitational field is beneficial. This point 1 in Table 8 refers to the work done by the limbs in a gravitational field. The leg and arm can be conceptually divided into individual members, in the case of the leg into foot, calf and thigh. Each of these members has its own center of gravity. During exercise, each of the members moves up and down in the gravitational field, thereby performing work. Reducing the work in the gravitational field helps conserve energy in the overall calculation. In the gantry drive, compared to the crankset driven by the legs, the work of the legs in the gravitational field is significantly reduced, which is beneficial. While it may seem that all the work (energy) done in the gravitational field returns to the system, since the cranks are connected in the crankset, there is a loss resulting from the limited efficiency of the muscle. Another example would be lifting the hand up to a certain height, where the hand gains potential energy corresponding to the work done, but during the lift there is a loss of energy due to the muscles not working with 100% efficiency.

In relation to point 5 from Table 8, the effect of storing elastic energy in the muscles becomes obvious when a person crouches and attempts to stand up. A significant part of the lifting force comes in the initial phase and it is due to the energy stored in the leg muscles. Another example may be a situation when a person is standing and tries to touch their buttocks with their heel. This is difficult because it requires considerable energy to stretch the muscles, which act like springs. While it is possible to do this, the movement of the leg must be vigorous.

Referring to point 6 in Table 8, the seat must be precisely adjusted to maximize the crankset's performance. In the case of the gantry, the user automatically optimizes the stroke and the range in which they work on the gantry.

Personal vehicles can revolutionize transportation, and the gantry is a perfect fit for these vehicles. It significantly reduces the height of the personal vehicle while maintaining high ergonomics of the drive used. The participants generally did not report any problems with using the gantry drive; however, some mentioned that when the gantry drive is used for a long time, pressure is felt on the pelvic bone, a discomfort that could be relatively easily eliminated by installing a softer seat. Moreover, it was noticed that slightly tilting the seat so that the person sat in a kind of hole could have a better impact on performance. The speed at which the gantry returns to its initial position, and, consequently, greater drive efficiency, can be increased by using seat belts to hold the driver's body to the seat.

A very interesting alternative to the gantry drive is the piston drive [31], which is very similar to the gantry drive and eliminates the drive discontinuities that are observed in the gantry drive. However, in the case of a piston drive, the exoskeleton effect would be lost.

Thanks to the research conducted, it is possible to develop a research plan for testing with a larger number of participants in order to perform statistical analysis to gain a better understanding of the differences between various mechanical energy collection techniques. This research constitutes a primary knowledge base for planning subsequent tests.

Table 8. Comparison of key features between different techniques for extracting mechanical energy from humans.

Issue	Hand-powered crankset	Leg-powered crankset	Gantry drive
(1) Working in a gravitational field	– The hand is raised two lengths of the crank, and both the forearm and upper arm exert considerable force in the gravitational field	– The foot is lifted by two crank lengths, and the calf and thigh also work extensively in the gravitational field	+ The foot basically does no work in the gravitational field; the work of the calf and thigh is minimal
(2) The path covered by the participant's hand or foot for one complete cycle of the mechanism	– The hand covers a distance equal to the circumference of the circle moved by the pedals, i.e., $2\pi r$	– The foot covers a distance equal to the circumference of the circle moved by the pedals, i.e., $2\pi r$	+ The foot travels a distance essentially equal to two radii of a typical crank, i.e., $2r$, and the stroke can be freely adjusted by the participant and may be increased or decreased depending on the need
(3) Exoskeleton effect	– No exoskeleton effect; the hand muscles stabilize the skeletal system	– No exoskeleton effect; the leg muscles stabilize the skeletal system	+ The second leg, which is active when pushing the overhead crane, stabilizes the skeletal and muscular system, causing the effect of "switching off" some muscles from work
(4) Cross-sections of arteries supplying blood to active muscles [25, 26]	– Cross-sections of the arteries are small compared to those in the legs, which causes high resistance to blood flow and puts greater strain on the heart	– Cross-sections of the arteries are large compared to those in the hands, but it is necessary to supply blood to the entire leg, especially to the calves, which work extensively	+ Cross-sections of the arteries in the groin are very large; the main force is generated by the buttocks and thighs, to which blood is supplied by large veins, causing low resistance to blood flow and reducing strain on the heart muscle

TABLE 8. [Cont.].

(5) Storage of elastic energy in muscles [27, 28]	– No energy storage effect	– No energy storage effect, as the leg must move upwards to prepare for the next work cycle	+ When vigorously pulling the legs down during the gantry return cycle, it is possible to store energy in the muscles because the muscles have the ability to store elastic energy; this energy allows the legs to be pushed back during the gantry push cycle
(6) Possibility to change the muscles that generate force	– It is not possible to change the loaded muscle part, and it is very difficult to change the distance between the crankset and the seat during the exercise	– It is not possible to change the loaded muscle part, and it is very difficult to change the distance between the crankset and the seat during the exercise	+ Great possibilities of changing the load on the muscle group as the participant can adjust the stroke of the gantry and the range in which they work on the gantry, allowing muscles to rest while others are active
(7) Drive continuity	+ There is complete continuity of drive, with momentary zero torque values occurring when there is a change in the active hand	+ There is complete continuity of drive, with momentary zero torque values occurring when a change in the active leg occurs	– No drive on gantry return (zero torque)

6. Conclusions

The gantry drive exhibits completely different characteristics than the commonly known crankset. Based on the test results, the gantry generally provides more favorable performance than the crankset, and, additionally, makes users less tired. With the gantry drive, a person can maintain greater power for longer periods of time. However, the gantry drive imposes significant demands on the vehicle's design. Yet, it integrates well into a three-wheeled vehicle with two front wheels and one rear swivel, with a short transmission system to the front wheels. It is also highly suitable for watercraft. The use of the gantry drive in road vehicles, particularly those that have electric assistance, opens a new path for compact vehicles with the functional features of a car. The gantry drive takes up little vertical space and allows the seat to be placed quite low in the vehicle, which allows the construction of a relatively low vehicle with reduced aerodynamic resistance to movement, mainly due to the small frontal surface of the vehicle. The gantry may open a new direction in the history of the automotive industry, leading to the development of personal vehicles, bicycles, and mopeds that offer the functional characteristics of a traditional passenger car. The gantry exhibits unique properties compared to the crankset. Although the research carried out was of pilot nature. it showed that the gantry drive is definitely worth further research as it could become a valuable invention for humanity. Research shows that the gantry drive allows us to extract the enormous potential of human physical capabilities and could be the perfect technique for receiving mechanical energy from humans.

Fundings

This work was supported by the Innovation Centre of the Warsaw University of Technology (CINN PW, Centrum Innowacji Politechniki Warszawskiej).

Conflict of interest

The authors declare that there are no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Authors' contributions

Łukasz Bereś obtained the funding to conduct this project, built the test stand, conducted tests, developed the theory and carried out the efficiency calculations, wrote the first draft of the manuscript. Marcin Obszański connected the measuring devices and wrote the program to collect data. Łukasz Bereś and Paweł Pyrzanowski, and Marcin Obszański conceived and designed the research. Łukasz Bereś and Paweł Pyrzanowski designed the test stand. All authors reviewed the manuscript and approved the final version.

Data availability

The raw baseline data collected during the tests are available from the corresponding author upon reasonable request.

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Received December 16, 2024; accepted version July 8, 2025.
Online first December 3, 2025.