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***Research Article***

# Innovative Pedal Design Using a Double Rocker Mechanism: An Analysis of Link Length Suitability Across Rider Heights

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***Abstract –*** This study explores the transmission performance of a novel tricycle pedal mechanism based on an adjustable Double Rocker Mechanism (DRM), designed to enhance mechanical efficiency across a range of rider anthropometries. Conventional crank-based tricycle systems often fail to accommodate user height variation effectively, leading to suboptimal torque transfer and increased discomfort. To address this challenge, the proposed DRM allows independent adjustment of both input and output link lengths, tailored to individual rider dimensions. The relationship between link geometry, transmission angles, and anthropometric parameters was evaluated using the Bee Algorithm, a bio-inspired optimization method well-suited for multidimensional design problems. Constraints were introduced to ensure biomechanical efficiency and mechanical feasibility. Results indicate that appropriate link length adjustments significantly improve transmission angles and overall pedaling performance across various rider heights. The proposed mechanism thus enables a single tricycle platform to serve a broader user population without compromising mechanical advantage, comfort, or energy efficiency.

*Keywords – Innovative Pedal Design, Double Rocker Mechanism, Suitability.*

## I. INTRODUCTION

The development of bicycles, tricycles, and other human-powered vehicles dates back to the early 19th century, a time marked by the aftermath of the Napoleonic Wars and the eruption of Mount Tambora, both of which led to severe food and animal shortages[1]. In response, German inventor Karl Drais created one of the first man-powered four-wheeled vehicles to assist in transporting goods and people[2]. Shortly after, he introduced a more compact two-wheeled version which was later called as Laufmaschine or "running machine". it was propelled by pushing the feet along the ground, similar to how modern scooters function[3]. Later designs incorporated pedals and cranks mounted directly to the front wheel hub, improving propulsion and speed but decreasing safety and comfort[4]. In tricycles and similar systems, pedals serve as the initial point of force transfer from rider to drivetrain. However, conventional designs are not optimized to support the rider's full body weight over time[5]. This leads to uneven stress on the chain and sprocket, resulting in deformation, higher maintenance needs, and reduced component lifespan.

Furthermore, traditional crank pedals often cause discomfort, particularly knee strain, during extended use[6]. These systems are also primarily designed for seated riding, which restricts balance and limits dynamic body engagement. These mechanical and ergonomic limitations suggest the need for more adaptive pedal systems. A design that effectively uses both leg power and body weight, while accommodating different rider postures, could improve comfort, performance, and long-term durability[7].

Fig. 1 A conventional tricycle with chained pedal.

In addition to mechanical limitations, conventional pedals shown in Fig. 1 do not effectively utilize the rider's body weight to assist in propulsion[8]. As a result, the potential for generating auxiliary power such as producing electricity during pedaling is severely restricted. This shortcoming is especially critical in the context of electric tricycles, where extending the trip distance without frequent battery recharges could greatly enhance usability. Without the ability to efficiently harvest energy from pedaling, current tricycle designs limit opportunities for sustainable self-charging systems.

To address these issues, this study proposes an innovative Double Rocker Mechanism (DRM) for bicycle pedals, inspired by the motion of a non-impact cardio machine commonly found in fitness centers, as illustrated in Fig. 2[9]. This reference device, known as the ARC Trainer, utilizes crank-rocker linkages to generate an arcing pedal trajectory. The arc-like motion closely mimics the action of stair climbing, which is particularly effective for engaging and strengthening the lower back muscles that are often neglected and whose weakness is a common cause of fatigue during a casual physical activity[10]. While the ARC Trainer was designed primarily for stationary exercise, its mechanical principles have been adapted in this study to develop a mobile, high-torque pedal system capable of converting both leg muscle force and body weight into forward motion.


Fig. 2 ARC trainer.

The pedal mechanism used in the ARC Trainer can be traced back to the 19th century with the invention of the MacMillan's Lever-Driven Bicycle shown in Fig. 3[11]. While innovative for its time, this early design ultimately proved impractical for widespread use. The main limitation stemmed from the method of power transmission: cranks attached directly to both sides of the rear wheel hub. This configuration prevented the rear wheel from rotating freely when descending a hill. As a result, during downhill travel, when gravity naturally propels the bicycle, the pedals would continue to rotate without rider input, often accelerating uncontrollably. This led to sudden, unintended forces being applied to the rider's feet, making it difficult to maintain control and slow the bicycle effectively. Such handling difficulties compromised rider safety and comfort, contributing to the eventual abandonment of the MacMillan design. Moreover, driving this type of pedal is not ergonomic for knees.

Fig. 3 MacMillan's bicycle.

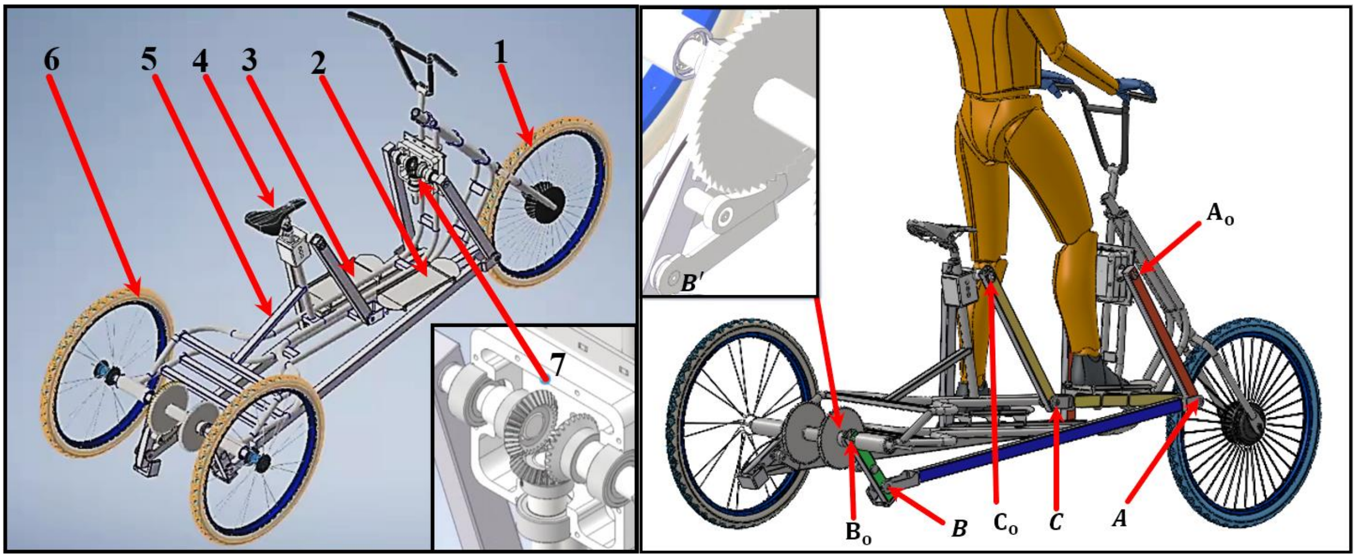
The DRM is composed of rigid components capable of bearing the rider's body weight. As the rider steps forward, the links of the DRM swing in a manner similar to climbing stairs. The system features a pair of DRMs, one mounted on each side of the tricycle, interconnected by a conical gear set. This arrangement ensures that when one DRM is pushed downward by a rider's foot, the opposite DRM is lifted upward, transmitting rotational motion to the rear wheel through a ratchet mechanism. One of the key advantages of this system is that both body weight and leg muscle force contribute to pedaling, thereby generating significantly higher torque compared to conventional designs. The other is high torque that can make electricity production possible by the help of high torque on the rear hub. The last but not least advantage, the pain in the knees can be eliminated as well as the veins in the leg are not exposed high pressure for a long time.

The primary objective of this study is to determine the optimal link lengths for the DRM based on various rider heights. Rider height plays a crucial role in pedal mechanics, as it directly affects the rise of the input link, influencing both the efficiency of power transmission and the torque applied to the rear wheel. By tailoring the link dimensions to the rider's anthropometry, the proposed system aims to offer a more efficient, comfortable, and sustainable cycling experience. Moreover, this new design can help to increase the travelling distance of electric tricycles with only one time charging by producing and storing electricity during pedaling.

## II. MATERIALS AND METHOD

This study emerges from the need to revisit historical innovations in search of solutions to long-standing ergonomic and mechanical problems identified in the literature[12]. Common issues such as knee pain, vascular pressure during pedalling, and the inability to effectively utilize body weight in propulsion have highlighted the limitations of conventional pedal systems. With modern advancements in mechanical design and manufacturing, some earlier concepts which are once considered impractical, may now be re-evaluated and refined for contemporary use.

One such historical concept is MacMillan's Lever-Driven Bicycle in Fig. 3, one of the earliest applications of a linkage-based drivetrain. MacMillan employed a crank-rocker mechanism, where the pedal was attached to the rocker. This configuration produced an arcing motion that generated continuous rotation of the rear wheel through a coupler and crank connected directly to the rear hub. Although innovative, the design lacked a crucial component; a ratchet mechanism which permits freewheeling. As a result, during downhill travel, the pedals would continue to rotate uncontrollably, applying sudden force back onto the rider's feet, compromising safety and comfort. Additionally, the seating position in MacMillan's design contributed to biomechanical inefficiencies. The fixed seat placed continuous pressure on the rider's knees, especially during forceful pedalling, exacerbating discomfort over long distances. While these limitations rendered the design infeasible in its time, revisiting it with modern technology offers new potential. By integrating components like ratchet mechanisms and adjustable linkages, such historical concepts can be adapted into more ergonomic, efficient systems suited to today's cycling demands.




a) b)

Fig. 4 The proposed tricycle model; a) components of tricycle, b) DRM with marked joints.

The proposed tricycle model is illustrated in Figure 4. For clarity, the components are labeled numerically in Figure 4a. Component 1 represents the front wheel, which is equipped with a hub motor for electric-assisted propulsion. Components 2 and 3 denote the right and left pedals, respectively. Component 4 is the seat with telescopic tube, designed for rider comfort during electric mode operation. The chassis of the tricycle is shown as component 5, while 6 represents the rear wheels, which are coupled with a ratchet mechanism detailed in Figure 4b. Component 7 is a conical gear set that synchronizes the motion of both pedals in opposite directions. This conical gear system ensures that when the rider steps on the right pedal with their full body weight, the force not only propels the rear wheel forward but also causes the left pedal to move upward in a counterclockwise direction. The use of body weight for propulsion does not require the rider to lift either foot off the pedal during operation. This pedaling action closely resembles the motion of walking up a descending escalator. The rider's vertical position remains nearly constant while mechanical energy is generated. This innovative mechanism allows for high torque generation with maximal muscular effort, offering both biomechanical efficiency and ergonomic comfort.

A stationary, non-impact exercise machine designed to provide a full-body cardiovascular workout while minimizing joint stress[13], The Cybex Arc Trainer, which is the main inspiration of this proposed design, can be adjusted in various levels to burn out the fat in the body. It must be used at low difficulty levels in the beginning of exercise and increased the level gradually. In that way, one can produce up to 900 Watts per minute.

### *A. The Double Rocker Mechanism*

Grashof's Theorem is a foundational principle in the kinematic analysis of four-bar linkages. It states that in a planar four-bar mechanism with one fixed link, if the sum of the shortest and longest link lengths is less than or equal to the sum of the remaining two link lengths, at least one link is capable of completing a full rotation relative to the others[14]. This condition, known as the Grashof condition, is mathematically expressed as:

$S+L \leq P+Q$

where S and L denote the lengths of the shortest and longest links, respectively, and P and Q are the lengths of the intermediate links.

Mechanisms that satisfy this inequality are classified as Grashof linkages, and can be further categorized as:

Crank-Rocker: One link rotates continuously while the opposite link oscillates.
Double Crank (Drag Link): Both adjacent links can rotate fully.
Double Rocker: No link can rotate fully; only oscillatory motion is observed.

When the Grashof condition is not satisfied ($S+L>P+Q$), the mechanism is termed non-Grashof, and all links exhibit oscillatory motion[14]. For the purpose of this study, the crank-rocker and double crank configurations are excluded due to their full rotation characteristics, which are unsuitable for the pedal drivetrain of a tricycle or bicycle. The primary inspiration for the proposed linkage-driven pedal mechanism stems from the arched trajectory exhibited by machines such as the ARC Trainer, as shown in Figure 2. This arc-like motion has been shown to minimize joint stress and is biomechanically advantageous. However, direct replication of the pedal output link from the ARC Trainer or MacMillan's lever-driven bicycle in Figure 3 is impractical due to potential singularities in mechanisms that allow full rotation. To address this, a ratchet mechanism is incorporated, enabling freewheeling of the rear wheel and allowing the output link to operate within a controlled range of transmission angles, avoiding singularity and improving efficiency[14]. Consequently, an optimization is needed to find the best parameters for riders with various height to keep the performance of the mechanism.

### *B. Optimization*

The kinematic diagrams of the DRM are presented in Figures 5 and 6, illustrating the configuration of joints and links in two extreme positions: the lowest and highest positions of the pedal plate, respectively. The key joints which are denoted as $A_0$, A, B, $B_0$, C, and $C_0$, correspond directly to those previously detailed in Figure 4b. In this configuration, the links connecting $A_0$ to A and B to $B_0$ represent the input and output links of the mechanism respectively. These links are designed to be adjustable to accommodate riders of varying heights, ensuring efficient and ergonomic pedalling.

To determine optimal link lengths, an optimization problem was formulated and solved using the Bee Algorithm[15]. The primary objective of the optimization was to maintain the transmission angle which is a key determinant of mechanical efficiency, within a practical range throughout the pedal motion. According to existing kinematic literature, effective transmission typically occurs when the transmission angle ($\mu$) remains between 40° and 90°[14]. Figures 5 and 6 depict this angle variation across the mechanism's motion path. The input and output link lengths were varied within a feasible design space, constrained by standard tricycle geometry such as overall wheel diameter and pedal clearance from the ground. Furthermore, to comply with ergonomic stair-step standards and ensure comfortable user motion, the vertical travel distance of the pedal plate from its lowest to highest position was restricted to lie between 17 cm and 34 cm. For this analysis, the diameter of the tricycle wheels was fixed at 70 cm, corresponding to a standard 27.5” rim.

The link lengths in Figure 5 and Figure 6 can be named; input link as $a_2$, coupler link as $a_3$, output link as $a_4$ and the fixed link between $A_0$ and $B_0$ as $a_1$ to express them in equations. The lowest level of the pedal was resembled as line of i. The rise of the input link from the initial state should not higher that 34 cm. Therefore, equations consisted of angles and link lengths for constraints can be;

$$g_1: 28cm < |A_0 i| - a_2 \cos\delta < 38cm \quad (1)$$

$a_4$ must has lower length than the radius of the rear wheel;

$$g_2: 0 < a_4 < 35cm \quad (2)$$

The fixed link length $a_1$ must higher than 100 cm and lower than 200 cm according to standart measures of bicycles;

$$g_3: 100cm \leq a_1 \leq 200cm \quad (3)$$

The angle for the fixed link with respect to the horizontal axis must be constrained according to the horizontal distance between $A_0$ and $B_0$ which must be between 35 cm and 80 cm;

$$g_4: 35cm \leq a_1 cos\gamma \leq 66cm \quad (4)$$

An inequality between mechanism link lengths must be constrained as non-Grashof to ensure the coupler of the mechanism is not shortest link and the overall lengths of shortest and longest links is higher than the overall lengths of the other two.

$$g_5: \ a_2 < a_4 < a_1 < a_3 \quad (5)$$

The transmission angle can be model by using cosine theorem within the triangle composed by the joints $ABB_0$. If the distance between joint A and $B_0$ is symbolized as “$l$ “, the formulation can be derived as;

$$g_6: \ \frac{\pi}{8} \leq \mu = cos^{-1}\left(\frac{{a_4}^2+{a_3}^2-l^2}{2a_4a_3}\right) \leq \frac{\pi}{4} \quad (6)$$

Therefore, the overall optimization problem and objective function can be described as;

$$x^* = (a_1, a_2, a_3, a_4, \gamma)$$

$$g_k(x^*) \ \ k = 1,2,3,4,5,6$$

$f(x^*) = \max [\mu(x^*)]$

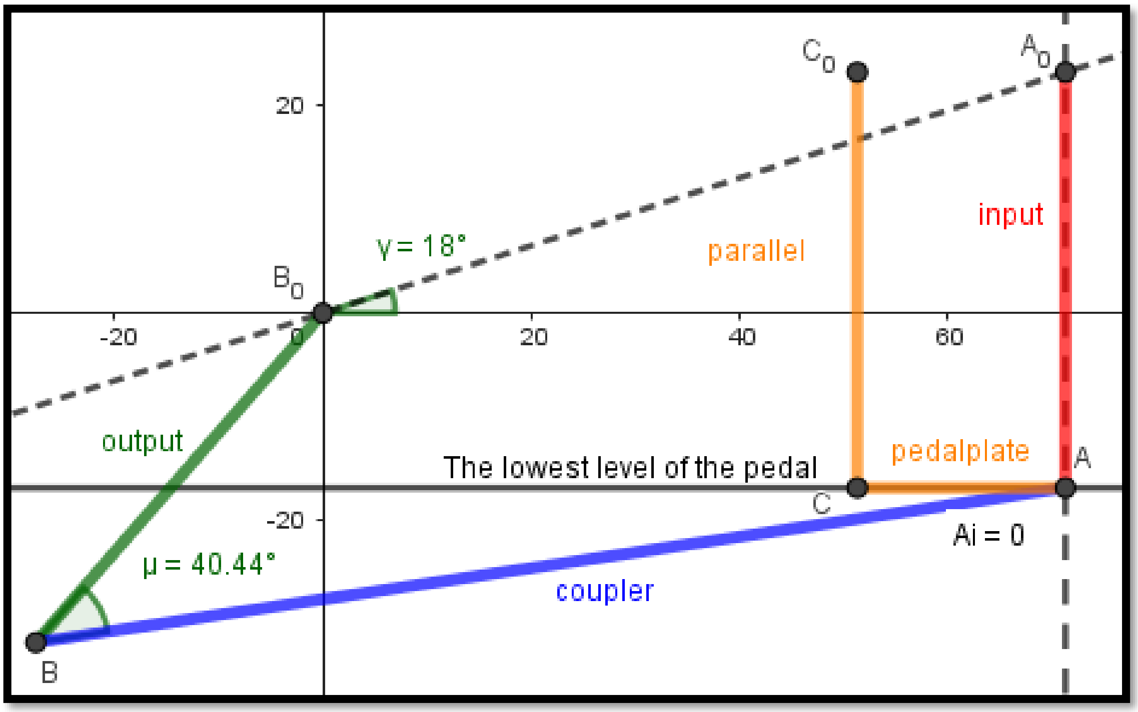



Fig. 5. The lowest level of pedal plate within the schematical DRM.

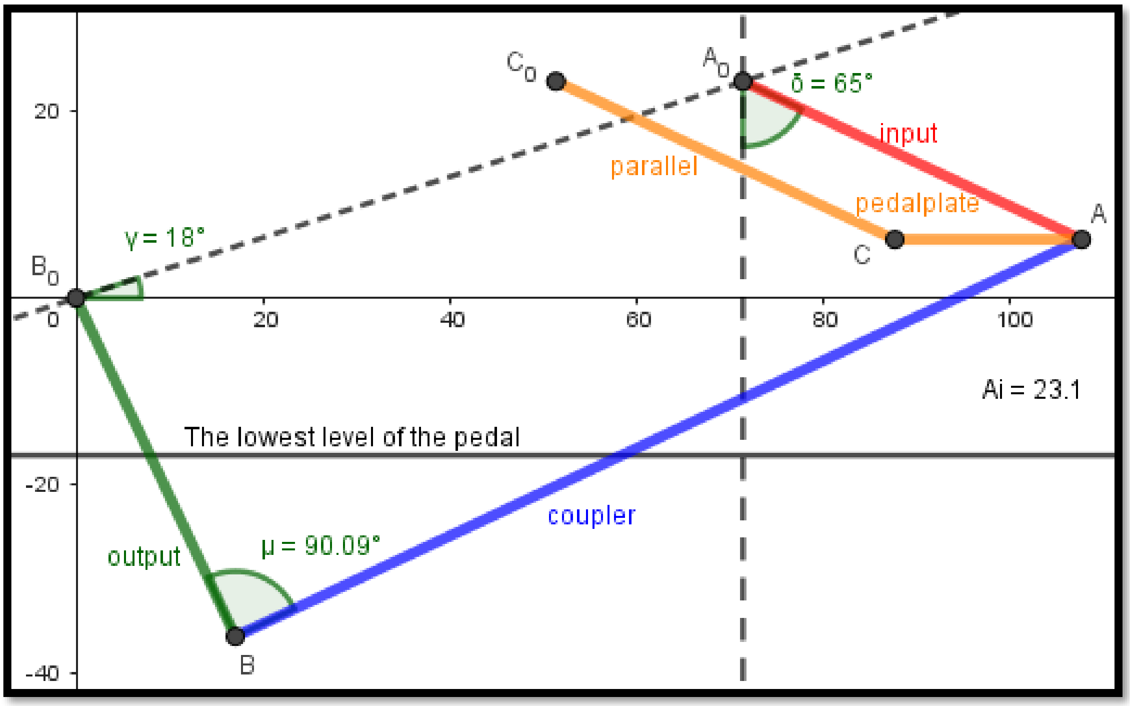



Fig. 6 The highest level of pedal plate within the schematical DRM.

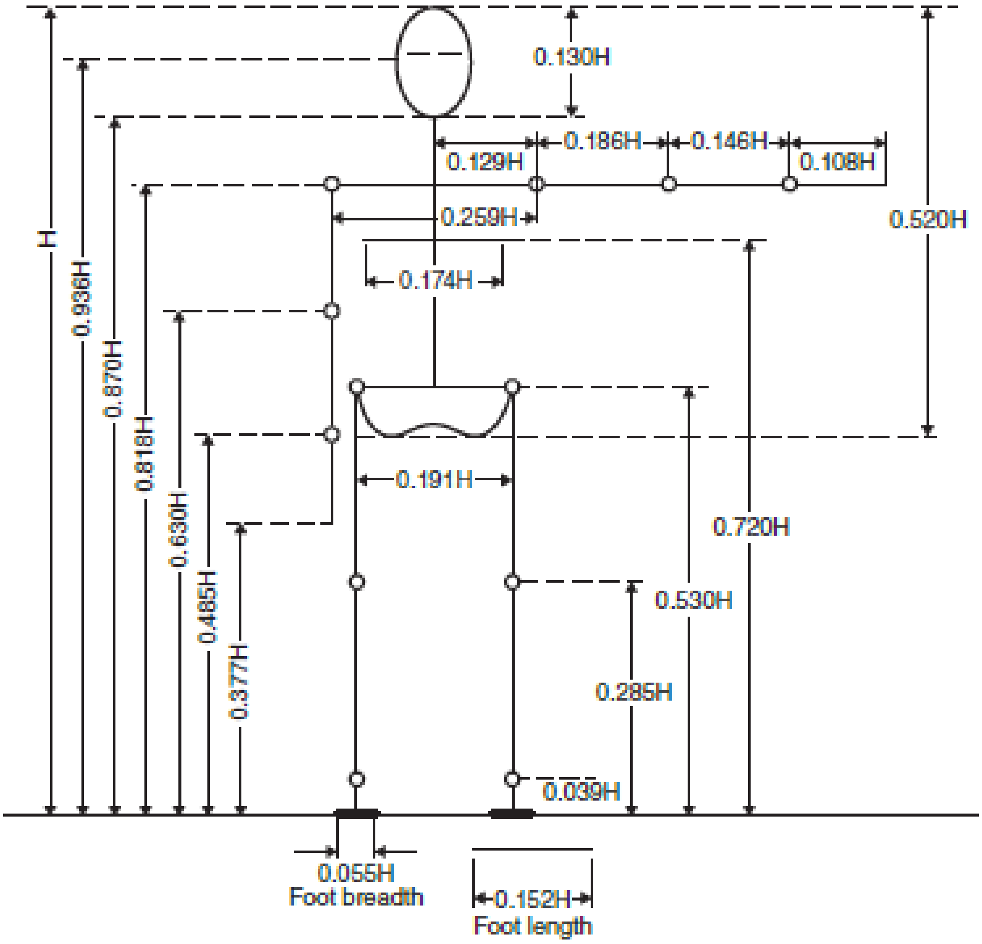



Fig. 7 Graphical illustration of the ratio of body parts with respect to the height[16].

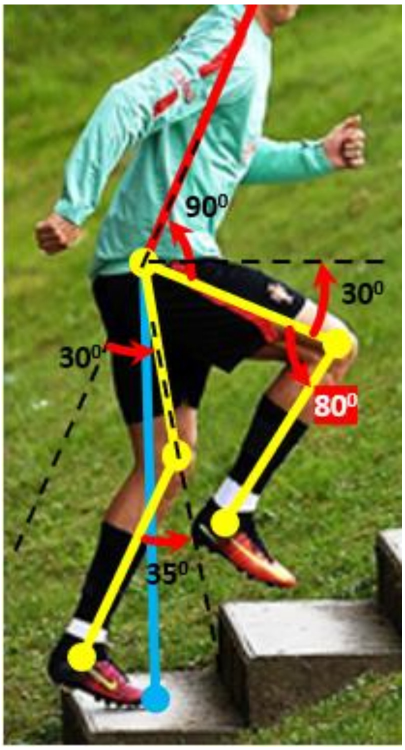



Fig.8 The illustration for angles of hip and knee.

Table 1. Six different heights and their maximum heights of foot.

| Height (cm) | Height of Hip(cm) | Height of Knee(cm) | Length of Femur(cm) | Maximum Height of Foot(cm) |
|---|---|---|---|---|
| 200 | 106 | 57 | 49 | ~38 |
| 190 | 100.7 | 54.15 | 46.55 | ~36 |
| 180 | 95.4 | 51.3 | 44.1 | ~34 |
| 170 | 90.1 | 48.45 | 41.65 | ~32 |
| 160 | 84.8 | 45.6 | 39.2 | ~30 |
| 150 | 79.5 | 42.75 | 36.75 | ~28 |

## III. RESULTS

In the design of the adjustable mechanism, six distinct user heights were considered to ensure adaptability and ergonomic efficiency. The selected heights are 150 cm, 160 cm, 170 cm, 180 cm, 190 cm, and 200 cm, representing a broad spectrum of potential users. To achieve optimal biomechanical performance, particularly in lower-limb movement, specific flexion angle ranges were defined based on established recommendations in the literature. Efficient hip flexion was targeted within the range of 30° to 90°, while efficient knee flexion was considered to fall between 20° and 100°. These angle ranges are widely regarded as suitable for maintaining comfort, safety, and functional movement during activities such as sitting, standing, and walking. Using these parameters, a simple mathematical operation by using the geometry in Fig. 8 was performed to relate user height to the mechanical design constraints. Table 1 was generated by applying a straightforward ratio-based calculation derived from Fig. 7, which illustrates the proportional relationships among the key dimensions of the mechanism. Additionally, the angular data shown in Fig. 8 were incorporated to ensure that the resulting configurations complied with the desired flexion ranges.

Table 1 serves as a foundational dataset from which optimal link length combinations can be identified for each of the six heights by using maximum height of foot. To determine these optimal configurations, the Bee Algorithm was employed. This algorithm iteratively searches for the best solution by simulating the foraging behaviour of honey bees, making it particularly well-suited for solving complex, multidimensional optimization problems such as this.

The results of the optimization process are summarized in Table 2. This table presents the optimal set of link lengths corresponding to each user height, ensuring that both hip and knee flexion angles fall within the efficient range. Moreover, the transmission angles of the resulting mechanisms, which influence the force transmission and mechanical advantage, were evaluated to ensure that they remain within theoretically acceptable limits. Maintaining appropriate transmission angles is essential for the smooth and efficient operation of the mechanism, preventing mechanical jamming and ensuring user comfort.

Table 2. Optimal combination of link lengths for six different heights

| Height (cm) | Input link ($AA_0$, cm) | Coupler link (AB, cm) | Output link ($BB_0$, cm) | Fixed link ($A_0B_0$ cm) | Transmission angle range (degree) |
|---|---|---|---|---|---|
| 200 | 18,9 | 132,1 | 34 | 109,6 | from 40,1 to 77,19 |
| 190 | 18 | 127,1 | 34 | 105,2 | from 40,43 to 75,38 |
| 180 | 17,2 | 122 | 34 | 100,3 | from 40,17 to 73,87 |
| 170 | 16,3 | 117 | 34 | 94,7 | from 40,51 to 72 |
| 160 | 15,5 | 111,9 | 34 | 91,1 | from 40,02 to 70,44 |
| 150 | 13,7 | 101,7 | 34 | 86,2 | from 40,12 to 68,68 |

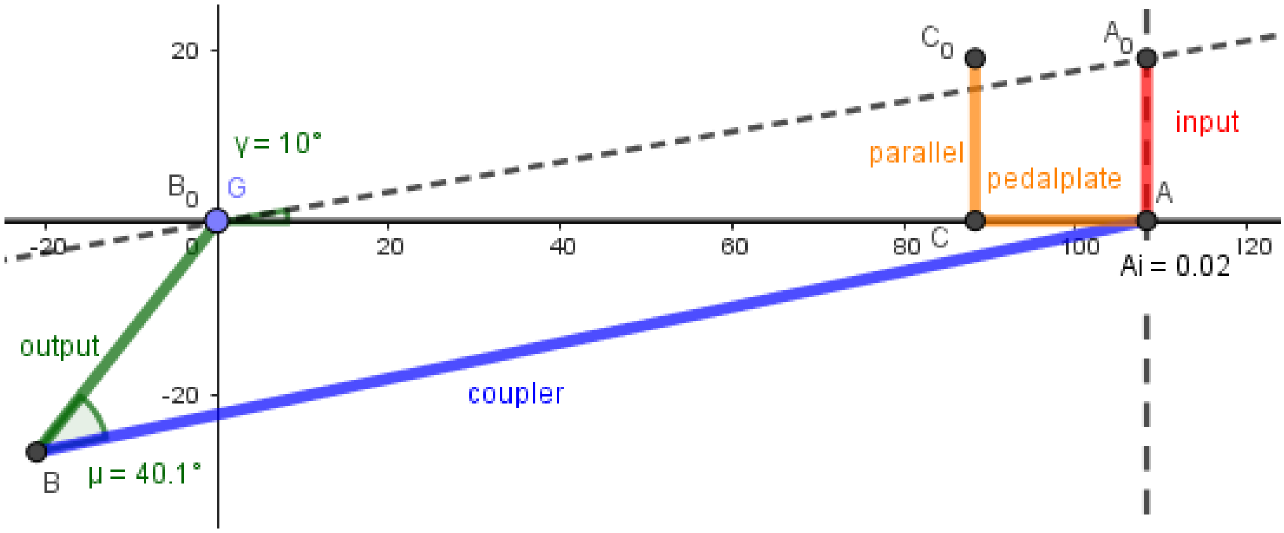



Fig. 9. The lowest position of the pedal mechanism for a user with 200 cm height

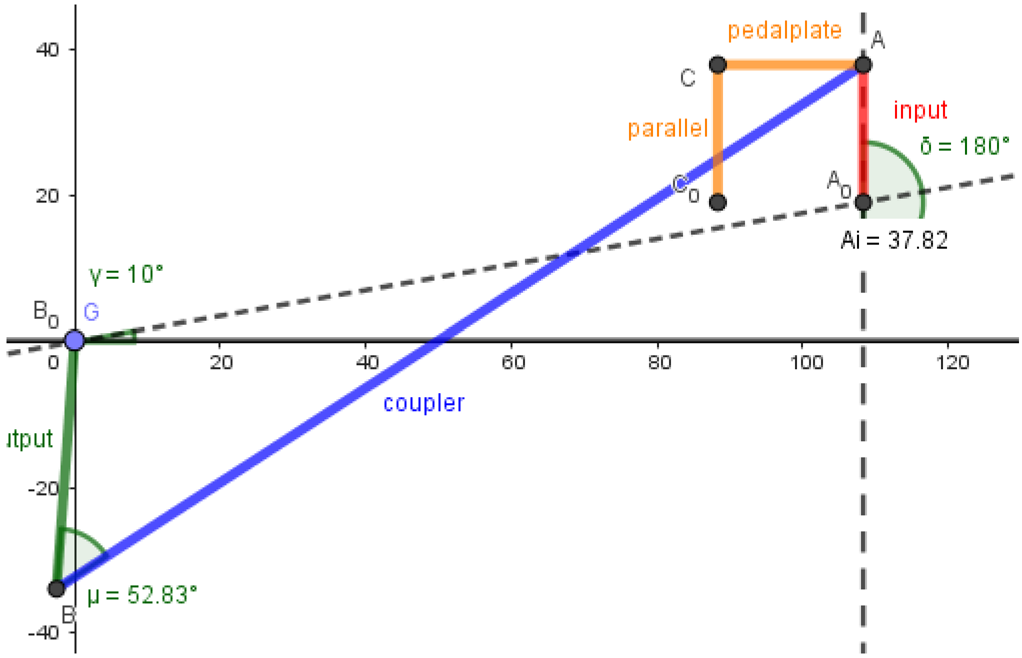



Fig. 10 The highest position of the pedal mechanism for a user with 200 cm height

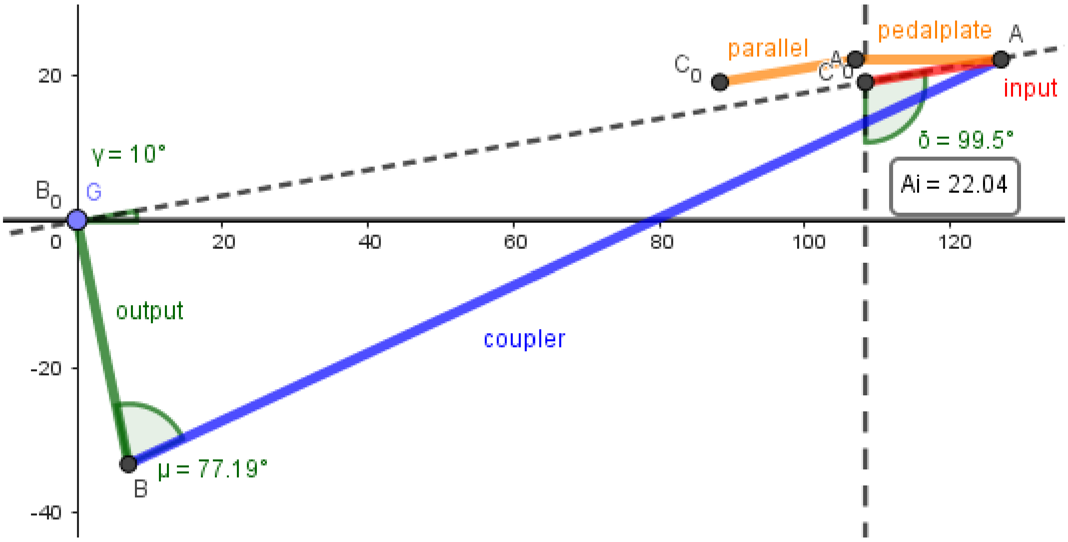


Fig. 11 The position of the pedal mechanism with the highest transmission for a user with 200 cm height

## IV. DISCUSSION

The study presented a novel pedal system using a Double Rocker Mechanism optimized to accommodate a wide range of rider heights while maximizing mechanical efficiency and rider comfort. The use of the Bee Algorithm to tune the link lengths proved effective in maintaining favorable transmission angles, a key factor for smooth force transfer in linkage systems. Compared to conventional crank-based tricycle systems, the DRM offers multiple advantages: higher torque generation, effective utilization of rider body weight, and reduced joint stress, especially at the knees. These benefits address long-standing biomechanical and ergonomic issues that are prevalent in traditional designs. Importantly, by incorporating adjustable link lengths, this system allows for a single tricycle frame to be tailored to individual users, reducing manufacturing complexity and cost.

The transmission angle constraints imposed during optimization ensured that the mechanism avoided singularities and mechanical dead zones, which are often challenges in linkage-driven systems. The consistent transmission angle ranges validate the robustness of the design and its suitability for practical application. This research builds upon foundational mechanical principles, such as Grashof's Theorem, while also modernizing historic concepts like MacMillan's lever bicycle. Unlike the historical designs, which were limited by lack of freewheeling and adaptability, this system integrates a ratchet mechanism and modern design constraints to make an old idea viable for today's cycling demands. Most importantly, the mechanism link lengths are capable of designing a competitive electric bike which can produce its own energy by the help of pedal.

One potential limitation is that the study assumes ideal conditions without accounting for real-world variables such as dynamic rider motion, fatigue, or terrain variability. Future studies could incorporate dynamic simulations or experimental prototypes to validate the modeled results. Furthermore, integrating an energy-harvesting system to store generated torque as electrical energy could further improve the utility of the design, especially for electric tricycles aiming for extended range.

## V. CONCLUSION

This study introduced an innovative tricycle pedal mechanism based on an adjustable Double Rocker Mechanism (DRM), designed to overcome the ergonomic and mechanical limitations of conventional crank-driven systems. By enabling independent adjustment of input and output link lengths according to rider anthropometry, the mechanism ensures consistent torque transmission and biomechanical efficiency across a wide range of user heights.

The optimization process, performed using the Bee Algorithm, successfully identified link dimensions that maintain favorable transmission angles while satisfying constraints related to hip and knee flexion. The effectiveness of the proposed configuration is visually supported by Figures 9 and 10, which depict the lowest and highest positions of the pedal mechanism for a 200 cm-tall user, respectively. Additionally, Figure 11 demonstrates the configuration corresponding to the peak transmission angle, validating the system's capacity for efficient force transfer throughout the pedal stroke.

The inclusion of a ratchet mechanism, conical gears, and non-Grashof linkage design further enhances the robustness and practical applicability of the system. These features not only prevent mechanical singularities but also promote smooth, joint-friendly motion, making the DRM a viable candidate for integration into next-generation electric or hybrid tricycles. With its ability to produce high torque suitable for auxiliary energy generation, the proposed system paves the way for self-sustaining vehicle concepts. Future studies should incorporate dynamic rider models and experimental validation to further evaluate performance under real-world conditions.

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