JOURNAL OF MECHANICS OF CONTINUA AND MATHEMATICAL SCIENCES
www.journalimcms.org

ISSN (Online) : 2454 -7190 Vol.-21, No.-07, July (2026) pp 176-195 ISSN (Print) 0973-8975

ENERGY-EFFICIENT BIPEDAL ASSISTIVE LOCOMOTION USING A MODIFIED HUMANOID-JANSEN WALKING MECHANISM

Amer Matrood Imran[1], Hayder M. Abbood[2], Ghanim M. Hachim[1], Salah Mahdi Ali[2], Mohammad Reza Haghjoo[3], Borhan Beigzadeh[4]

[1] Department of Mechanical Engineering, College of Engineering, University of Kerbala, Iraq, 56001

[2] Department of Biomedical Engineering, College of Engineering, University of Kerbala, Iraq, 56001

[3]Faculty of Mechanical and Energy Engineering, Shahid Beheshti University, Tehran, Iran, 009821

[4] School of Mechanical Engineering, Iran University of Science and Technology, Tehran, Iran, 009821

Email: [1]amer.m@uokerbala.edu.iq, [2]eng.haydarm@uokerbala.edu.iq, [3]ghanim.m@uokerbala.edu.iq, [4]salah.m@uokerbala.edu.iq, [5]m_haghjoo@sbu.ac.ir, [6]b_beigzadeh@iust.ac.ir

Corresponding Author: **Amer Matrood Imran**

https://doi.org/10.26782/jmcms.2026.07.00011

(Received: April 11, 2026; Revised: July 05, 2026; Accepted: July 16, 2026)

Abstract

The modified Humanoid-Jansen Walking Mechanism provides bio-inspired gait patterns for assistive mobility devices. This study presents a novel bipedal prosthetic-leg system designed to replace wheelchair locomotion by enabling users to traverse multiple terrains with reduced energy demand. Each leg consists of an eight-bar linkage actuated by a motor–gearbox assembly mounted beneath a medical saddle-chair support. Dynamic simulations show that the mechanism generates a natural foot trajectory with a 5.2-unit step length and 2.7-unit step height, closely matching human gait kinematics. Comparative kinematic analysis demonstrates that the hip, knee, and ankle angle patterns follow the temporal and amplitude trends of natural walking. Energy-consumption analysis reveals that the baseline fully motor-driven system requires relatively high electrical input, while the integration of a passive spring system reduces motor load by approximately 20–30%, and using lightweight materials lowers total energy consumption by an additional 15–25%. Implementing an intelligent control algorithm further decreases effective motor duty cycle by ~30% per gait cycle. Simulation results also show that the proposed mechanism maintains stable walking over sandy, uneven, and sloped terrains and improves dynamic weight distribution for *the seated rider. These findings indicate that the system offers a feasible, energy-efficient mobility solution for individuals with severe physical disabilities.*

Keywords: Humanoid-Jansen walking mechanism, bipedal prosthetic leg, assistive mobility device, gait rehabilitation, energy-efficient actuation, kinematic analysis.

I. Introduction

Mobility plays a significant role for healthy, ordinary people in performing their duties and activities by moving within locations and areas [V], [VIII], [XX], [XXIV]. Daily life activities are greatly enhanced by continuous walking with minimal energy consumption [XV]. Therefore, improving walking technique is economically beneficial for both society and individuals [XIV]. On the other hand, many people are unable to move due to leg injuries, paralysis, accidents, birth defects, or amputations K0 [III] (referred to as people with physical disabilities; a physical disability is a deformity in the body that makes it difficult for the affected person to move) suffer from mobility problems from one place to another all over the world [VII], [IX], [I]. As a result, their disabilities make them unequal to perform their daily jobs, tasks, and essential life activities [IV], [II]. The use of assistive devices, which are tools or means that enable people with disabilities to overcome the challenges they face in their daily lives, can be of great benefit to these individuals [XXI]. Wheelchairs are among the most widespread and commonly used assistive devices worldwide, representing the primary solution that enables people with disabilities to move around freely and independently. Many designs and types of wheelchairs are obtainable in various wheel sizes; the aim is to help patients with their needs and daily life activities [XXVI]. The enhancements to develop the wheelchairs included new changes on the previous designs, like adding novel wheels or electrical motors [XXVII]. The definition of a wheelchair is simply a chair with many wheels or tires which can be transferred readily to many places [XVIII]. The source of motion for manual traditional wheelchairs is from the user or helper. This action needs a huge physical force and causes inconvenience, especially with bones and muscles [XXX]. Therefore, a lot of patients are prioritized for the electric wheelchairs over the old wheelchairs [XXIII]. An electric wheelchair is characterized by comfort, ease of utilization, and does not require any physical effort [XVIII]. Both the traditional and electrical wheelchairs represent a major and effective solution for the transition of patients [XIII]. Healthy problems like visual weakness, cognitive impairment, and seizures of tremors and spasms for some disabilities people cause difficult, hard, and unsafe challenges when they use conventional wheelchairs [XVI]. Cause of their essential dependence on helpers for the motion thence it required a more developed wheelchair. Subsequently, this assisted in the production smart wheelchair which provides them the a safe motion and self-controlled transportation [XXIX].

In numerous cases, the difficulty of the terrain, like ground levels, stairs, etc. [XXV], hinders the motion of the tire or wheel of the wheelchair during use [XX]. Thus, the transportation of disabled individuals cannot be completed properly [XXVIII]. Smart and hardworking researchers have tried to solve the locomotion problems by depending the revelation from nature. The morphology of multi-legged systems became the main focus of the design studies, with coordination and flexibility [XIX]. One of the most notable and innovative models in this arena is the design of the Dutch artist and engineer Theo Jansen, which he called this design "Strandbeest" machines. It depended on the Jansen linkage for the locomotion mechanism [XXII]. The Jansen linkage mechanism is composed of a system that contains different lengths of rods organized in a technique that simulates the legs and limbs of an insect. The source of the actuator is a rotational input for this system, giving it exclusive locomotion and mechanical motion with creative beauty [XI].

This mechanical leg design is characterized by moving across various types of terrain lightly. Also, the traditional propulsion systems don't enter into these designs [XXXI]. The movement by this system is stable and flexible without any obstacles that the tires and wheels on uneven terrain. Thus, it is an effective and innovative choice in the field of mobile robotics [X]. A high service is supplied by these inventions to humanity, especially the patients [XII]. A perfect application that applies the Jansen mechanism is the Mech-Walker. A Mech-Walker is a rehabilitating system for lower limb motion that mimics the motion of natural walking, an effective method to assist disabled people [X]. A rare and unique robot has been industrialized based on an eight-bar linkage mechanism of Theo Jansen. A remote control is utilized for moving and guiding it to the target, and engineering software is used to analyze its mechanism [XXXI]. A legged robot has been fabricated in this study, distinguished by advanced locomotion, which is based on the Jansen mechanism. The unique mechanism consists of four linkages with a special arrangement connected by a motor to move the whole leg. This design of the leg is characterized by low cost, accuracy, simplicity, and ease of use. It can generate a smooth motion path via an odd rotational motion [XXXII]. The main idea of this research was about the development of a crab-shaped robot that analyzed its locomotion precisely. It showed a great capability for movement without any effect on its external body. Therefore, it is considered appropriate for various engineering applications that need stability in motion [XVII]. An inspired idea from the Jansen mechanism of a four-legged robot has been prototyped (13 links). Its actuator runs via a central crank arm connected to a rotary motor. After input of the source of the movement, all links and bars move mechanically without self-governing motors. It can be used for scrutiny in fieldwork tasks by appending to devices like radar [VI].

In our study, an accurate proposal design has been introduced, and it combines Theo Johnson's legs and the wheelchair. Any part of the prototypical design was modeled individually using SOLIDWORKS® (Dassault Systèmes). Then, all parts were assembled to simulate the range of motion for each element within the structure. MATLAB® (MathWorks) was then used to perform a more accurate dynamic simulation, analyzing joint angles during movement and calculating the differences in energy consumption resulting from changes in mechanical positions during the gait cycle. The design proposal presented in this research will contribute to enabling people with mobility disabilities to move efficiently and smoothly from one site to another by using the leg mechanism inspired by Theo Jansen's design that effectively mimics the natural movement of human limbs.

II. Energy Systems Investigation

The importance of energy systems for operating and moving mechanical parts must be understood and accurately defined. Each energy system consists of energy inputs, outputs, storage, and transfers within the system. The mean mechanical energy of the system remains constant because any electrical or chemical energy input to the system is released as heat, and no mechanical work is done on the body or the surrounding environment. Therefore, the energy efficiency depends on the energy inputs and outputs within a unified system. Thus, we conclude that energy effectiveness in terms of transportation costs refers to the energy used per unit weight based on each unit of distance traveled.

In the conventional system of energy, metabolic energy is used for many purposes, the most important of which is to accomplish mechanical work and generate force, etc., knowing that the energy in the muscles is released in the form of heat. Thus, energy is exchanged with both the body and the muscles with the mechanical parts of the system. On the other hand, a dissipation of mechanical energy occurs due to damping, friction, or resistance. It is noted that this process is highly efficient from the mechanical point of view.

Passive energy systems have no additional energy source available. They rely on reducing the overall energy loss of the system and enhancing overall efficiency to reduce metabolic energy consumption. The fundamental change in energy flow is the inclusion of components such as springs, whose function is to store and transfer passive mechanical energy within the system. As a result, movement is more energy-efficient.

The most important system of energy sources is active energy, such as electricity. In this system, the inputs of energy are safely augmented; thus, the overall system and energy economy will be affected. The applications of this system are in all devices that depend on battery energy and aim to minimize the consumption of metabolic energy for the body. There are two possible methods that can theoretically enhance the overall energy economy. The first involves the powered device operating similarly to an unpowered device, using only minimal electricity to regulate the timing of mechanical components such as clutches. The second involves the motor operating more efficiently, potentially replacing the positive mechanical action of muscles.

In the case of a physical disability like the amputee (K-level 0), who is completely helpless, as he has no ability or energy to transfer, walk, or move around, even with or without assistance. The perfect solution for him is to use a wheelchair that helps him move from one place to another for his daily work and activities. The manual wheelchair's energy is human muscle energy. This energy is generated by the user's arm or upper body muscles, which causes tiredness and exhaustion for the users, and its efficiency is poor. However, the energy source for the Powered (Electric) Wheelchair is the electric battery, for example, the electric battery (e.g., lithium-ion). The actuator works through a motor driver that generates the required movement and then transmits it to the wheels. In our research, the appropriate energy is the active energy to move all mechanical parts and ensure a coordinated, efficient, and appropriate gait without causing any muscular effort on the patient.

III. Foundational concept design

The Jansen-inspired human leg mechanism represents a unique engineering model that combines mechanical simplicity with kinetic precision, offering innovative solutions to traditional mobility problems, whether in wheelchairs or assistive devices for people with disabilities.

In this model, the total number of mechanical links in the complete system is 16 main links for both legs, in addition to some secondary or supporting links (such as small rods or shafts that transmit motion or hold gears), as shown in Fig. **1**.

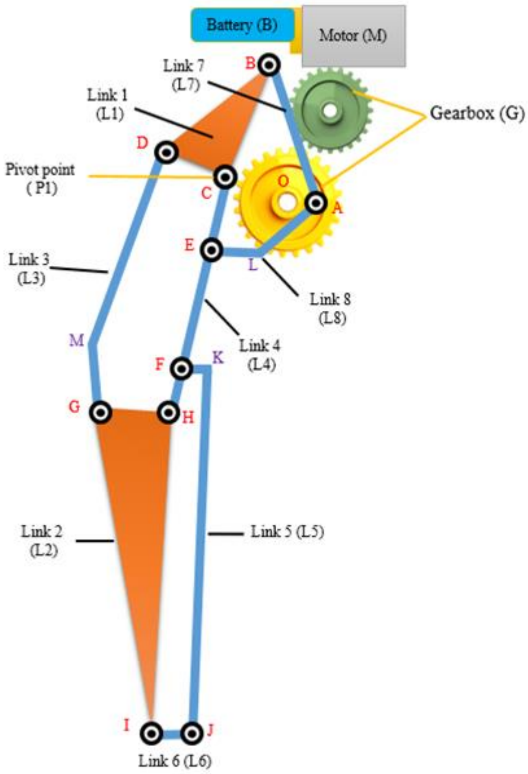


Fig. 1. The schematic of the Humanoid-Jansen links mechanism for the bipedal prosthetic Leg

The link one (L1) is triangular in shape and is connected to the link three (L3), four (L4), and seven (L7). L1 represents the main upper link, which is connected to the chair for the purpose of installation and support. Link two (L2) is also triangular and is connected to the foot, link six (L6), from below and from above to link three and link four. While Link 5 (L5) is parallel to Link 2 and is connected from above to Link 4 and from below to Link 6. Link 5 is responsible for controlling the angle of the walking foot.

Links three and four (L3 & L4) are in the middle of the mechanical leg, and they represent the front support link and the back support link, respectively. Also, link four connects to link eight (L8) from above and five from below, in addition to L1 and L2.

When examining the configuration of the mechanical links and joints in the proposed model, it is noted that the set of links consisting of (L1, L2, L3, and L4) forms a similarity to the four-bar mechanism, a mechanical mechanism known for its ability to generate complex rotational motion through simple components. The design of this mechanism is similar to modern prosthetic knees. It provides the flexion and extension motion with uniform force distribution through the joints, which is beneficial to improve the accuracy and precision of locomotion.

Links L7 and L8 symbolize the back mechanical parts of the prosthetic leg, and they join the motor (M) and the gearbox (G). They are responsible for rotational motion transmission from the motor to the leg as they rotate around the main pivot point P1. As a result, the rotary motion transfers to the controlled rhythmic gait and achieves the preferred independent motion for the total system.

The link L6 is the foot in our mechanical model and is enveloped by a flexible and lightweight underlayment. The aim of adding this layer is to improve shock absorption during walking and reduce the vibrations and effects when the foot contacts the ground.

Points (M, K, and L) represent the flexion angles on the links (L3, L5, and L8). The final value for each point was calculated after many trials. Their primary function is to generate the movement balance and motion control of the links during the gait cycle. The major idea of our design includes a set of links that connect with others through joints to mimic the motion of a natural leg, within a lightweight body that keeps a standard quality of rigidity and durability. The essential function of a leg is to supply vigorous support that can bear the proposed design. Additionally, it ensures the balance and stability of the leg during standing and walking.

To perform kinematic and dynamic analysis of the mechanism, let θ_i denote the angle of link i with respect to the fixed reference frame. The generalized coordinate vector can then be defined as:

$$q = [\theta_1 \ \theta_2 \ \theta_3 \ \theta_4 \ \theta_5 \ \theta_6 \ \ \theta_7 \ \theta_8]^T \tag{1}$$

where the superscript T denotes the transpose operator.

Furthermore, from the loop-closure constraints of the mechanism, we have several constraint equations of the form:

$$\theta i = f_i(q) \tag{2}$$

such that only one independent link angle exists—for example, θ_2—corresponding to the single degree of freedom of the mechanism.

For each link, the position of its center of mass can be expressed as:

$$x_i = x_{Ai} + (L_i/2)cos\theta_i \tag{3}$$

$$y_i = y_{Ai} + (L_i/2)sin\theta_i \tag{4}$$

where (x_i and y_i) are the Cartesian coordinates of the center of mass of link i, and (y_{Ai} and y_{Ai}) are the Cartesian coordinates of the first joint (point Ai) of link i.

The mass moment of inertia of each link about its center of mass is given by:

$$I_i = 1/12\, m_i L_i^2 \quad (5)$$

where I_i is the mass moment of inertia of the link i about its center of mass (kg·m^2), and m_i is the mass of the link i (kg).

The total kinetic energy and total potential energy of the system are written as:

$$T = \Sigma \left(\frac{1}{2} m_i v_i^{\,2} + \frac{1}{2} I_i\, \theta_i^{\,2}\right) \quad (7)$$

$$V = \Sigma m_i\, g\, y_i \quad (8)$$

The Lagrangian is then defined as:

$$L = T - V \quad (9)$$

Thus, the dynamic equation corresponding to each generalized coordinate is obtained from:

$$d/dt(\partial L/\partial \dot{q}_i) - \partial L/\partial q_i = \tau_i \quad (10)$$

Finally, after simplification, the complete dynamic equations can be expressed in matrix form as:

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = \tau \quad (11)$$

where: $M(q)$ is the mass matrix, $C(q,\dot{q})$ is the Coriolis term- centrifugal force matrix, $G(q)$ is the gravitational effect vector, and τ is the input torque vector.

IV. Comprehensive assembly design

This mechanical proposal provides a group of functional ameliorations to disabled individuals with the ability to achieve mobility without being based on classical wheelchairs, advantageously enhancing mobility across uneven and various terrain. The detailed description for each part and assembly is below, with a focus on the principles of mechanical mechanism engineering that maintain efficiency and performance.

IV.i. Saddle chair

The saddle chair is a modern medical chair that supports the lower back and buttocks by holding up the patient's back. The chair's structure must be made of a highly durable and lightweight material. The chair is covered on the patient's seating side with several layers of high-density sponge and cotton for the patient's comfort, with leather upholstery for aesthetics and protection, as shown in Fig. **2**.

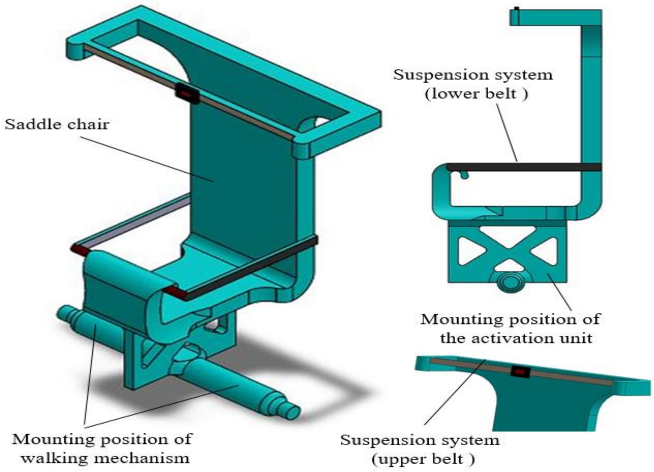


Fig. 2. Saddle chair and its accessories

In our design, the saddle chair is considered one of the substantial portions to perform the fundamental function. The reason is that all the other assembled parts are directly connected to it. At the top, the special belts are attached to the suspension system. The first one is at the lower chest region, and two others at the pelvic area. The purpose of tying and fixing the patient is to prevent him from falling during the movement and gait. At the bottom of the chair is connected to the actuator that operates the mechanism, which consists of a motor, a battery, and a set of mechanical gears connected to the leg links. On the sides of the chair, the artificial legs of the Humanoid-Jansen Walking Mechanism are connected to it.

IV.ii. Rider-suspension system

The medical straps or belts of the suspension system are directly connected to the saddle chair to support the patient. If the amputee does not sit on the saddle accurately, this will lead to a major, obvious defect in the balance system of the mechanism design during the walking gait cycle. To protect the patient from falling, crawling, or bending, a two-stage suspension system consisting of attachment and fixation was added. The first stage of stabilization is a medical belt attached to the chair, which supports the patient's lower chest area and prevents him from bending forward. Fig. **2** shows the suspension and linkage systems.

The second stage of fixation is below the pelvic area, employing a pair of belts or medical tapes. As a result, the pelvic area is fixed, and the patient is seated on the chair in a precise and comfortable manner.

IV.iii. Activation unit (driving mechanism)

The actuation unit (actuator) is the key component responsible for generating optimal leg movement in the proposed design. It contains a set of components like an electric motor, a battery, and a set of gears. The primary functions of gears are to transfer the motion from the motor to the legs.

The necessary mechanical motion is generated by the motor and is transferred regularly by the system of gears to ensure a smooth and precise motion. The major work for the actuation unit is to convert this mechanical energy into rotational motion that provides the leg with the required mechanical motion.

The completed system design represents a substantial solution for patients who have problems with muscle strength. It allows them to control their movement independently and reduces the user's physical effort. Therefore, we obtain and conclude that the proposed actuation unit is a significant step toward improving the assistive-generated power and motion devices. Also, the principles of biomechanics and medical engineering are applied in this model for ensuring safety and effectiveness in walking innovations. As shown in Fig. **3**.

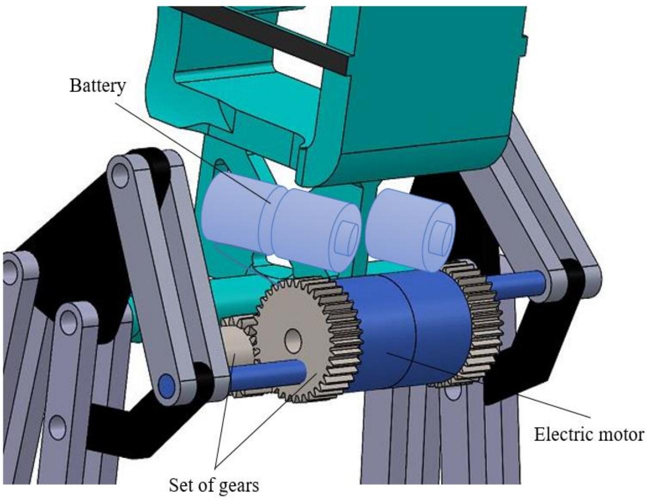


Fig. 3. Activation unit (driving mechanism)

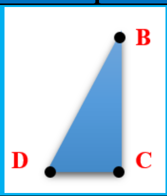
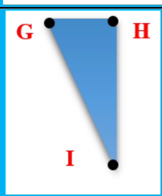
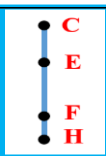
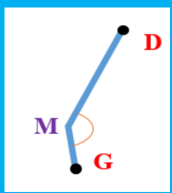
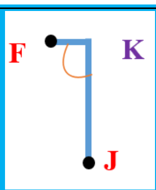
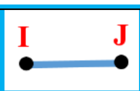
IV.iv. Humanoid-Jansen links mechanism

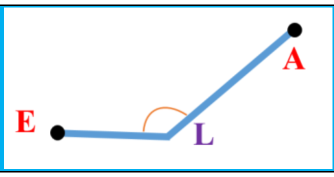
The proposed design of the mechanical leg depends on the scientific principle of walking that was introduced by Dutch artist and engineer Theo Jansen. The integrated system converts the normal rotational motion to the wonderful and regular gait motion, mimicking the human leg's motion mechanism precisely. This mechanism consists of an incorporated structure of many links and other mechanical parts. The synchronised movement of the mechanical parts produces a footpath that is elliptical or semi-elliptical in shape, near to the gait cycle of the natural human. According to the adjusted mechanism taken from Jansen's design, the mechanical leg of our design contains eight links connected by a system of gears that join with two rotary motors providing a consistent motion. As it was mentioned earlier, the actuation unit (an electric motor, gear set, and battery) is responsible for moving the whole system without relying on sophisticated or complicated control systems.

The key features of the design are able to distribute the weights across the different links and joints of the leg. As a result, it minimizes the energy consumption for the whole system and maximizes the performance and mechanical efficiency. In addition, the innovative mechanical construction supplies great adaptability to irregular terrain. The outcome of that makes it appropriate for mobility applications that demand regularity, consistency, and stability.

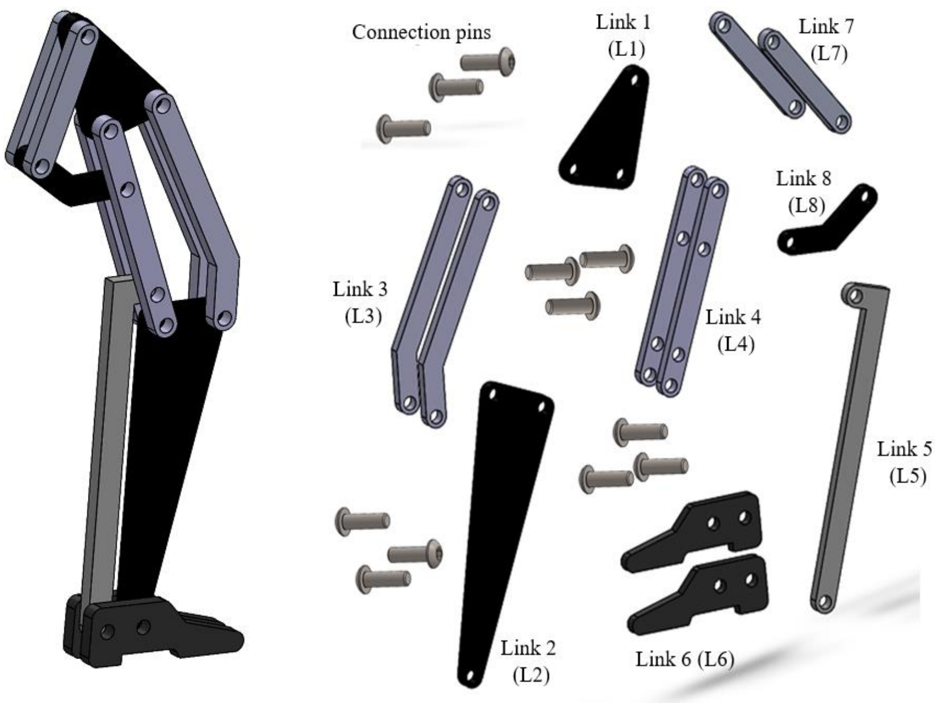
The most accurate dimensions, lengths, and angles for the leg design were obtained after many successive attempts, as shown in the table below.

Table 1: The values of dimensions, lengths, and angles for the leg prosthetic design

Link	Shape	Points / Angles	Dimension
L1		B – C C – D	21.00 12.00
L2		G – H H – I	13.00 61.00
L3		C – H C – F C – E	44.00 37.00 13.20
L4		D – M G – M ∠	37.68 11.42 153.82°
L5		F – K J – K ∠	5.59 67.60 90°
L6		I – J	8.00
L7		A – B	26.60

L8		A – L E – L <	12.07 10.10 139.46°

The flexion determines the flexibility and responsiveness of the lower extremity during activity, and the degree of flexion for each associated rib also has an impact on function and balance.



a **b**

Fig. 4. The 3D schematic of the suggested design for the Humanoid-Jansen links mechanism for the bipedal prosthetic Leg. (a) Whole leg view, (b) The parts.

Fig. **4** (a) shows the 3D schematic of the suggested design for the whole prosthetic leg. Fig. **4** (b) displays an exploded view of the components of the Human-Jansen Linkage Mechanism. It is important to note specific characteristics of the linkage mechanism parts.

Fig. **5** shows the principal parts of the proposed design for the bipedal prosthetic leg in a 3D schematic: saddle chair, rider-suspension system, activation unit (driving mechanism), and humanoid-Jansen mechanism.

The movement begins with the transfer of essential energy from the battery to the electric motor, which rotates a set of gears within the activation unit (driving mechanism). As a result of the rotational motion of the gears, particularly the gear connected to links (7) and (8), these two rear links move, which in turn drives the rest of the mechanism. This movement takes place around the center of rotation of the connected gear. Link (8) contributes primarily to the process of flexing and extending the leg during the gait cycle, in cooperation with link (7). As a result of this coordinated movement, the rest of the mechanism's parts move sequentially. They cause one leg to move forward regularly and symmetrically with the other leg, thus forming the first step in the gait pattern.

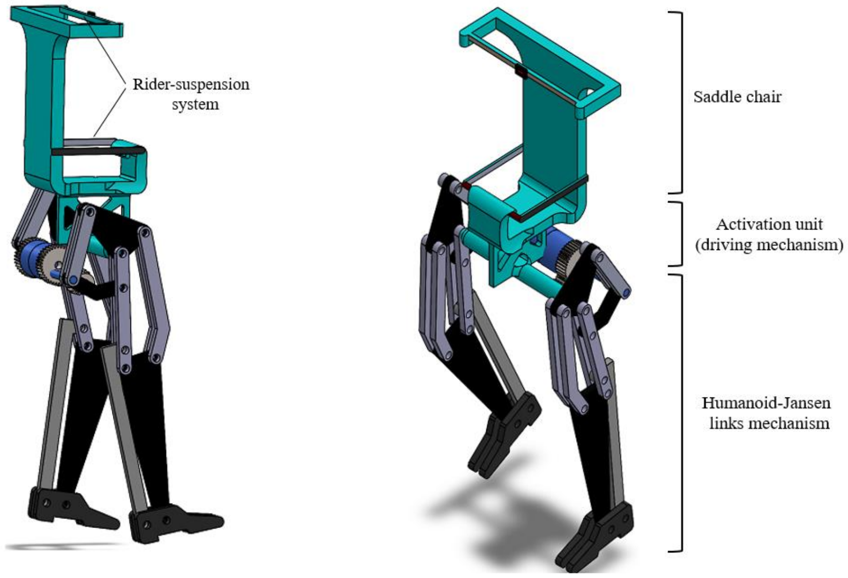


Fig. 5. The whole 3D schematic of the proposed design for the bipedal prosthetic leg

V. Results & Discussions

The proposed mechanical leg, based on the Jansen mechanism, is designed to provide multiple functional improvements, enabling a large number of people with disabilities to perform their daily tasks without relying on a wheelchair. This mechanism aims to enable the user to navigate various terrains by mimicking natural leg movement and reducing the energy required for movement. It is also ideal for improving individuals' ability to carry out their urgent and necessary activities with ease and efficiency.

V.i. The motion of Jansen's leg mechanism

Fig.6 represents the proposed leg motion in the Jansen mechanism design depending on rotation angles, adjusted by the rotation of point A (which is located on the gear and the connection point between links 7 and 8) around the origin point O (the center of the gear). The motion is generated by the movement of the motor connected to the mechanism and the gear system. The motion shows the leg moving during one gait cycle, that equivalent to one full step from a rotation angle of 0° to 360° for point A, attributed to point O.

360° 330° 300° 270° 240° 210° 180° 150° 120° 90° 60° 30° 0°

Fig.6. Jansen's leg mechanism configuration with different angles of the rotation axis from 0° to 360°

Fig. **7** shows the stride length and height based on the foot's path (the foot point trajectory) during a single cycle, in addition to the foot's take-off and landing positions. The figure also shows the position of maximum height for ankle reaches during movement, with the horizontal line (step length) being 5.2 units, while the vertical line (step height) is 2.7 units.

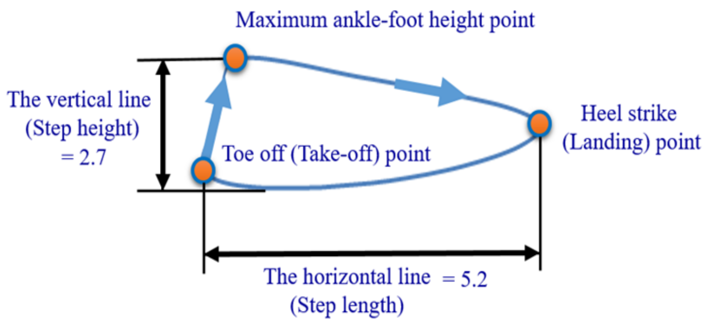


Fig. 7. The foot point trajectory for the proposed design of the Jansen leg mechanism

Fig. ***8*** clarifies a detailed illustration of the components and angles of leg movement in the proposed Jansen prosthetic mechanism design during the complete gait cycle. Leg movement begins in the stance phase, where the foot touches the ground, starting with heel strike. Then, flat foot is the next stage; at that moment, the leg does not bear all of the body's weight. The movement then transitions to mid-stance, where the leg is in a stable position and works to support the body in a balanced manner.

As the movement continues, the leg reaches the heel-off phase, where the heel gradually lifts off the ground in preparation for the next phase. It is followed by the toe-off phase, marking the end of the stance phase. The swing phase then begins, where the foot lifts completely off the ground and moves forward in preparation for contact with the ground again, completing one full gait cycle or one full step.

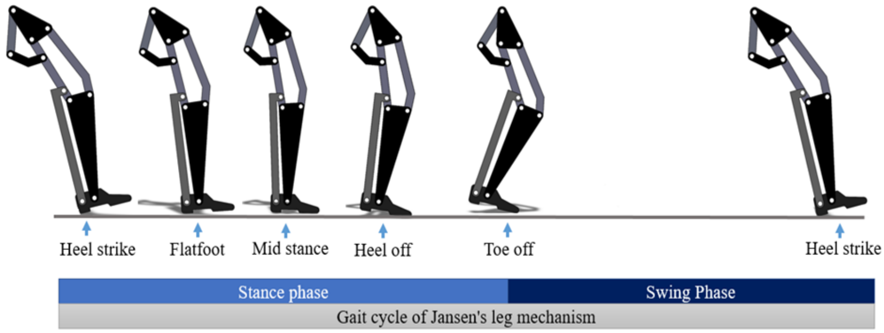
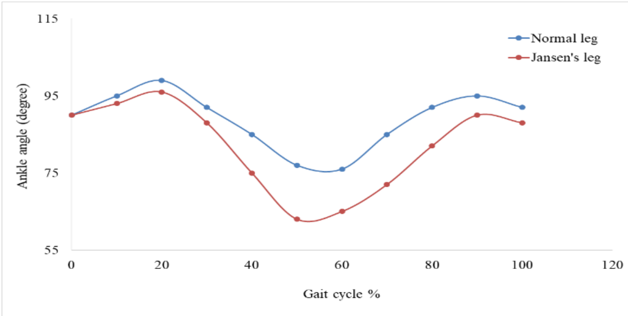


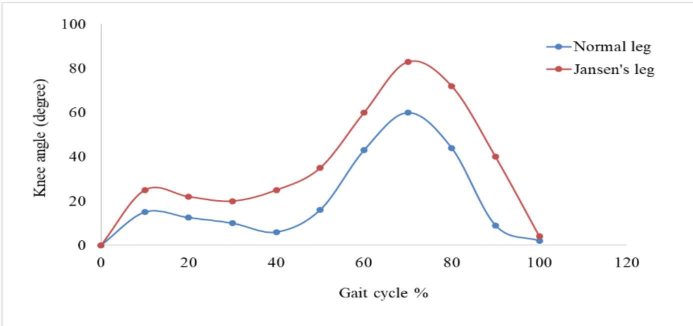
Fig. 8. The standard motion of the Jansen leg mechanism during a single walking gait cycle.

Fig. **9**-a, -b, and -c illustrate typical angular changes of the hip, knee, and ankle joints during a complete walking gait cycle, compared to the corresponding kinematic patterns of a natural leg. The results show that the kinematic curves generated by the proposed design follow a dynamic behavior very close to the natural physiological pattern of the lower limbs [XIV].

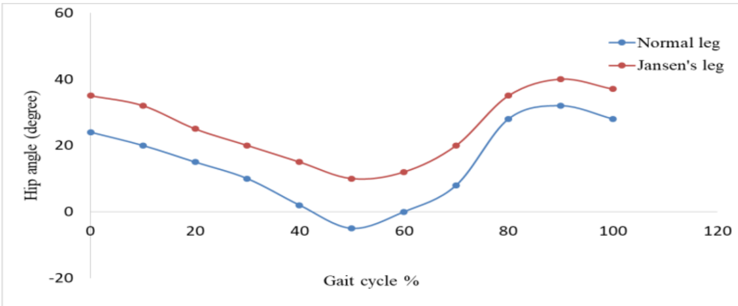
At the beginning of the walking gait cycle, the hip joint initiates a slight flexion movement followed by an extension phase as the leg transitions into stance, providing stability and support for movement. The knee exhibits a clear transition between flexion and extension during the different phases of the gait cycle, indicating the mechanism's ability to mimic the natural functioning of a real joint. As for the ankle, a logical sequence of plantar and dorsiflexion angles is observed during stance and swing phases, reflecting good compatibility with the biomechanical behavior of natural human gait.



a



b



c

Fig. 9. (a) Ankle angles during the gait cycle, (b) Knee angles during the gait cycle, (c) Hip angles during the gait cycle.

V.ii. Improving the energy performance of Jansen's leg mechanism

Through precise theoretical and approximate calculations, which were performed using SolidWorks and MATLAB. It was found that the energy consumption during one walking cycle (one step) in the basic system is relatively high, due to the complete reliance on the electric motor to generate the required movement, which is entirely battery-powered, without any additional mechanical assistance.

Software analysis of the system showed that incorporating a spring-based mechanical support system resulted in a significant reduction in overall energy consumption. This is attributed to the spring's ability to store a portion of the mechanical energy during the compression phase and subsequently release it during the recoil phase, reducing the load on the motor and reducing the electrical torque requirements.

The weight reduction for all parts of the whole system leads to minimizing the consumption of energy in modeling results. For example, the usage of lightweight and good-strength materials like reinforced aluminum or carbon fiber contributes largely to reducing the mass. Thus, the necessary torque is minimized to move the mechanical leg during the walking gait cycle. Comparing models created in SolidWorks, it was found that reducing weight by 20% to 30% can reduce energy consumption by approximately 15% to 25% compared to the original values.

Additionally, the introduction of intelligent control algorithms, such as the Fuzzy Logic algorithm, has significantly improved operational energy management. This algorithm dynamically turns the motor on and off based on the actual motor state of the leg, preventing unnecessary, continuous operation and significantly reducing energy consumption without compromising motor performance. Simulation results in Simulink have shown that implementing this algorithm reduces the motor's effective operating rate by approximately 30% in some phases of movement.

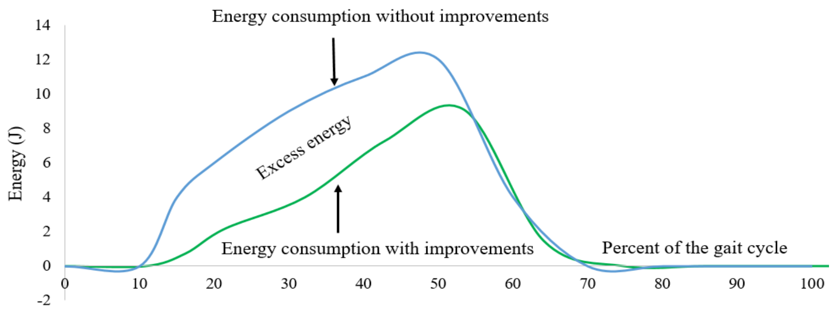


Fig.10. Excess energy of the system after adding improvements to the single walking gait cycle

Fig.10, comparing the different models, shows that energy consumption is significantly higher in the unoptimized system, while it decreases significantly when a spring system is used, lightweight materials are used, and intelligent control algorithms are incorporated. All these results prove that intelligent control and improved design are the main keys to getting superior energy efficiency in our proposed mechanical legs.

VI. Conclusions

In this study, a modern and novel proposed design, relying on a Humanoid-Jansen Walking Mechanism, has been designed in a professional way to help mobility-impaired patients in transference across various terrains efficiently and with low consumption of energy.

The primary design consists of a set of essential components, such as a saddle chair to seat the patient that is connected strongly via a rider-suspension system to ensure safety, stability, and consistency during the motion. Two mechanical legs supported the saddle chair. Each mechanical leg consists of eight links arranged in a geometrical way to mimic the locomotion of a human leg, plus the foot. Also, the leg can move backward and forward through the generated motion from motors, which are recharged by a battery.

An overall analysis of the entire system of the leg was performed and compared to the walking patterns of humans. The results indicated that the trajectories of motion are close to the normal biological motion of the lower limbs. Thus, this approach shows future opportunities to improve the life method for people who suffer mobility impairments, and it deserves research and development in the future.

Simulations demonstrated the proposal design's strength and its capacity to cross arenaceous and uneven terrain, and even slopes; it performed more effectively than conventional wheels for wheelchairs. Computational outcomes also showed that the consumption of energy is reduced gradually by using a mechanical spring system, lightweight materials, or integrating intelligent control algorithms. The design of the saddle-chair also provides a perfect dynamic weight distribution and mitigates the pressure on the spine and seating regions.

For future research, it is recommended to manufacture the proposed mechanical leg entirely using 3D printing to determine the numerical patterns of movement during walking and energy consumption. Practical experimental testing can also contribute to achieving the main objective of developing this mechanism.

Conflict of Interest:

There was no relevant conflict of interest regarding this paper.

References

I. Andrews, Karen L., et al. *International Journal of Physical Medicine & Rehabilitation Determining K-Levels Following Transtibial Amputation*. Vol. 5, no. 2, 2017, pp. 4–7. 10.4172/2329-9096.1000398.

II. Batten, Heather R., et al. “Gait Speed as an Indicator of Prosthetic Walking Potential Following Lower Limb Amputation.” *Prosthetics and Orthotics International*, vol. 43, no. 2, 2019, pp. 196–203. 10.1177/0309364618792723.

III. Botros, Michael, et al. “Development of a Powered Four-Bar Prosthetic Hip Joint Prototype.” *Prosthesis*, 2025, pp. 1–26.

IV. Brauckmann, Vesta, et al. “Report on Prosthetic Fitting, Mobility, and Overall Satisfaction after Major Limb Amputation at a German Maximum Care Provider.” *Applied Sciences (Switzerland)*, vol. 14, no. 16, 2024. 10.3390/app14167274.

V. Collins, Steven H., et al. "Reducing the Energy Cost of Human Walking Using an Unpowered Exoskeleton." *Nature*, vol. 522, no. 7555, Nature Publishing Group, 2015, pp. 212–15.

VI. Deshmukh, Nilaj, et al. "Design and Development of Bot Using Theo Jansen Mechanism." *Indian Journal of Engineering and Materials Sciences*, vol. 31, no. 6, 2024, pp. 899–908. 10.56042/ijems.v31i6.10211.

VII. Dillon, Michael P., et al. *Predict the Medicare Functional Classification Level (K-Level) Using the Amputee Mobility Predictor in People with Unilateral Transfemoral and Transtibial Amputation : A Pilot Study*. 2018. 10.1177/0309364617706748.

VIII. Farris, Dominic James, and Gregory S. Sawicki. "The Mechanics and Energetics of Human Walking and Running: A Joint Level Perspective." *Journal of the Royal Society Interface*, vol. 9, no. 66, 2012, pp. 110–18. 10.1098/rsif.2011.0182.

IX. Gailey, Robert, et al. "Review of Secondary Physical Conditions Associated with Lower-Limb Amputation and Long-Term Prosthesis Use." *Journal of Rehabilitation Research and Development*, vol. 45, no. 1, 2008, pp. 15–30. 10.1682/JRRD.2006.11.0147.

X. Haghjoo, Mohammad Reza, et al. "Mech-Walker:A Novel Single-DOF Linkage Device with Movable Frame for Gait Rehabilitation." *IEEE/ASME Transactions on Mechatronics*, vol. 26, no. 1, 2021, pp. 13–23. 10.1109/TMECH.2020.2993799.

XI. Haghjoo, Mohammad Reza, and Jungwon Yoon. "Two-Stage Mechanism Path Synthesis Using Optimized Control of a Shadow Robot: Case Study of the Eight-Bar Jansen Mechanism." *Mechanism and Machine Theory*, vol. 168, no. September 2021, Elsevier Ltd, 2022, p. 104569. 10.1016/j.mechmachtheory.2021.104569.

XII. Hernández, Alejandra Carolina, et al. "A Home Made Robotic Platform Based on Theo Jansen Mechanism for Teaching Robotics." *INTED2016 Proceedings*, vol. 1, no. March, 2016, pp. 6689–98. 10.21125/inted.2016.0579.

XIII. Hua, Bin, et al. "Human-like Artificial Intelligent Wheelchair Robot Navigated by Multi-Sensor Models in Indoor Environments and Error Analysis." *Procedia Computer Science*, vol. 105, no. December 2016, The Author(s), 2016, pp. 14–19. 10.1016/j.procs.2017.01.181.

XIV. Imran, Amer, Borhan Beigzadeh, et al. "A New Passive Transfemoral Prosthesis Mechanism Based on 3R36 Knee and ESAR Foot Providing Walking and Squatting." *Theoretical and Applied Mechanics Letters*, vol. 13, no. 5, 2023. 10.1016/j.taml.2023.100476.

XV. Imran, Amer, Mohammad Reza Haghjoo, et al. "Design of a Novel Above-Knee Prosthetic Leg with a Passive Energy-Saving Mechanism." *Engineering Solid Mechanics*, vol. 11, no. 4, 2023, pp. 339–52. 10.5267/j.esm.2023.5.009.

XVI. J Phaneendra Balaji, et al. "Iot-Based Smart Wheelchair for Elderly Healthcare Monitoring." *International Research Journal on Advanced Engineering Hub (IRJAEH)*, vol. 3, no. 05, 2025, pp. 2274–82. 10.47392/irjaeh.2025.0335.

XVII. Kim, Sun Wook, et al. "Analysis and Design of a Legged Walking Robot Based on Jansen Mechanism." *SCIS and ISIS 2010 - Joint 5th International Conference on Soft Computing and Intelligent Systems and 11th International Symposium on Advanced Intelligent Systems*, 2010, pp. 920–24.

XVIII. Kundu, Ananda Sankar, et al. "Design and Performance Evaluation of 4 Wheeled Omni Wheelchair with Reduced Slip and Vibration." *Procedia Computer Science*, vol. 105, no. December 2016, The Author(s), 2016, pp. 289–95. 10.1016/j.procs.2017.01.224.

XIX. Kurkure, Shubham R., et al. "Study of Theo Jansen Walking Machine." *International Journal of Innovations in Engineering and Science*, vol. 4, no. 10, 2019, pp. 2456–3463, www.ijies.net.

XX. L.M., Mooney, et al. "Autonomous Exoskeleton Reduces Metabolic Cost of Human Walking during Load Carriage." *Journal of NeuroEngineering and Rehabilitation*, 2014.

XXI. Li, Bo, et al. "Mechanism Design of a Novel Device to Facilitate Mobility, Sit-to-Stand Transfer Movement, and Walking Assistance." *Machines*, vol. 13, no. 2, 2025. 10.3390/machines13020134.

XXII. Patnaik, Lalit, and Loganathan Umanand. "Kinematics and Dynamics of Jansen Leg Mechanism: A Bond Graph Approach." *Simulation Modelling Practice and Theory*, vol. 60, Elsevier B.V., 2016, pp. 160–69. 10.1016/j.simpat.2015.10.003.

XXIII. Peace Obioma, Chibueze, et al. "Development of Solar Powered Electric Wheelchair for Physically Challenged Persons." *International Journal of Innovative Science and Research Technology*, vol. 6, no. 3, 2021, www.ijisrt.com.

XXIV. Sawicki, Gregory S., and Daniel P. Ferris. "Mechanics and Energetics of Level Walking with Powered Ankle Exoskeletons." *Journal of Experimental Biology*, vol. 211, no. 9, 2008, pp. 1402–13. 10.1242/jeb.009241.

XXV. Sengupta, Somak, and Pramod Bhatia. "Study of Applications of Jansen's Mechanism in Robot." *International Journal of Advance Research and Innovation*, vol. 5, no. 3, 2017, pp. 92–98. 10.51976/ijari.531716.

XXVI. Song, Zhibin, et al. "Mechanism Design and Analysis of a Proposed Wheelchair-Exoskeleton Hybrid Robot for Assisting Human Movement." *Mechanical Sciences*, vol. 10, no. 1, 2019, pp. 11–24. 10.5194/ms-10-11-2019.

XXVII. Sukerkar, Kedar, et al. "Smart Wheelchair: A Literature Review." *International Journal of Informatics and Communication Technology (IJ-ICT)*, vol. 7, no. 2, 2018, p. 63. 10.11591/ijict.v7i2.pp63-66.

XXVIII. Thomas, George, and Vladimir V. Vantsevich. "Wheel-Terrain-Obstacle Interaction in Vehicle Mobility Analysis." *Vehicle System Dynamics*, vol. 48, no. SUPPL. 1, 2010, pp. 139–56. 10.1080/00423111003690496.

XXIX. Utaminingrum, Fitri, et al. "Indoor Staircase Detection for Supporting Security Systems in Autonomous Smart Wheelchairs Based on Deep Analysis of the Co-Occurrence Matrix and Binary Classification." *Intelligent Systems with Applications*, vol. 23, no. June, Elsevier Ltd, 2024, p. 200405. 10.1016/j.iswa.2024.200405.

XXX. Wada, Masayoshi. "Development of a 4WD Omnidirectional Wheelchair." *Proceedings of the SICE Annual Conference*, no. September, 2008, pp. 1767–71. 10.1109/SICE.2008.4654950.

XXXI. Yash Punde. "Design and Linkage Analysis of Theo Jansen Mechanism." *International Journal of Engineering Research And*, vol. V9, no. 09, 2020, pp. 259–63. 10.17577/ijertv9is090170.

XXXII. Zubairuddin, M., et al. "Eight-Legged Robot Using Theo Jansen Mechanism." *International Journal for Advanced Research in Science and Technology*, vol. 12, no. 12, 2022, pp. 332–61.