Developing a Primitive Humanoid Legged Locomotion to Gain an Understanding of Human Mobility

Tvash Bansal
Department of Mechanical Engineering, Dr. Vishwanath Karad MIT World Peace University Pune

Vivek Patel
Department of Mechanical Engineering, Dr. Vishwanath Karad MIT World Peace University Pune

Mitul Solanki
Department of Mechanical Engineering, Dr. Vishwanath Karad MIT World Peace University Pune

Mohit Bumb
Department of Mechanical Engineering, Dr. Vishwanath Karad MIT World Peace University Pune

他

https://doi.org/10.5109/7342470

出版情報：Evergreen. 12 (1), pp.504-515, 2025-03. Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Japan
バージョン：

Developing a Primitive Humanoid Legged Locomotion to Gain an Understanding of Human Mobility

Tvash Bansal[1], Vivek Patel[1,*], Mitul Solanki[1], Mohit Bumb[1], Kanhaiya Deshmukh[1]
[1]Department of Mechanical Engineering, Dr. Vishwanath Karad MIT World Peace University Pune, Survey No, 124, Paud Rd, Kothrud, Pune, Maharashtra 411038, India

*Author to whom correspondence should be addressed:
E-mail: vivekmanit0031@gmail.com

(Received April 21, 2024; Revised January 10, 2025; Accepted February 19, 2025).

Abstract: This research paper delves into the design and development of a humanoid-legged locomotion model aimed at understanding human locomotion. This interdisciplinary study integrates principles from robotics, biomechanics, and control systems to create a model that emulates the intricate movement of human legs. The investigation encompasses the utilization of a robotic manipulator with a specific focus on Degrees of Freedom (DoF), incorporating calculations to simulate biological dimensions. Utilizing DoF in planar and spatial contexts, the manipulator's design integrates advanced materials, modular components, sensors, wireless connectivity, and machine learning algorithms. The study also makes use of Arduino Mega 2560, in developing the model. The designed system is then observed to analyze its performance and reliability. The contribution of the paper lies in offering insights and a better understanding of this complex area to facilitate improved and newer applications. The study will be value adding for both researchers and practitioners in paving the way for future advancements in humanoid robotics.

Keywords: Humanoids; Locomotion; Legend Robots; Biomechanics; Arduino

1. Introduction

Humanoid robots represent a captivating fusion of cutting-edge technology and the timeless fascination with replicating human form and function. Over the past few decades, advancements in robotics have propelled the development of increasingly sophisticated humanoid robots, mainly in service[1–4)] and bio-inspired[5–7)]. Apart from above well-known field it also used in various commercial applications[8–12)]. Humanoid robotics striving to bridge the gap between artificial systems and the intricacies of human capabilities[13,14)].

Traditional heavy-duty industrial robots, while stationary and difficult to reconfigure, remain the backbone of a significant portion of industrial automation[15)].

The researchers highlighted the implications of Optimus in manufacturing and artificial intelligence, where collaborative robots (cobots) excel in enabling flexible, safe, and reconfigurable human-robot interactions in industrial assembly.

Tesla, known primarily for its electric vehicles, revealed its ambitious humanoid robot project named "Optimus" at the company’s A.I. Day event held in August 2021[16)]. The announcement showcased Tesla's vision of leveraging its advancements in artificial intelligence and robotics.

Optimus is Tesla's humanoid robot designed to enhance manufacturing automation by handling dangerous, repetitive, and tedious tasks. Aimed at revolutionizing assembly tasks in automobile production, Tesla envisions Optimus becoming a larger business than its electric vehicles. The project has garnered significant attention since its launch.

Gidey et al.[17)] delves into the architectural challenges in developing cognitive bots capable of complex behaviors within information systems. While not directly focused on Tesla's Optimus, the insights from this research are pertinent to the development of advanced humanoid robots like Optimus, which require sophisticated cognitive architectures to operate effectively in dynamic environments.

Malik et al.[18)] examine the integration of humanoid robots, such as Tesla's Optimus, into manufacturing settings. They propose a framework for incorporating humanoids to enhance automation and address labour shortages. The study highlights the need for industrial safety standards, collaboration protocols, and ROI assessments in deploying humanoid robots in manufacturing.

Building on this, a subsequent study by Malik et al.[19)] investigates the potential benefits and challenges of humanoid integration, particularly in comparison to conventional robotic arms. It emphasizes the importance of effective methods for assessing their return on investment. Supported by simulation results, the findings demonstrate the potential of humanoids to improve manufacturing efficiency. Additionally, the research underscores the significance of safety standards in human-robot collaboration and offers valuable insights for managers and researchers on the future of industrial automation.

These studies highlight Tesla's Optimus robot's potential to transform manufacturing by tackling labor shortages and skill gaps with advanced automation. They also address the ethical and practical challenges of integrating humanoid robots, emphasizing the need for ongoing research to ensure responsible and effective deployment.

As the integration of robotic systems into various facets of society becomes more prevalent, the emulation of human-like motions remains a paramount challenge. The research in biped robots and humanoid robotics involves interdisciplinary collaboration, combining principles from robotics, artificial intelligence, control systems, and engineering[20–23]. Given its remarkable energy economy, human-like locomotion has drawn a lot of attention in scientific study, with the goal of addressing the issue of excessive energy consumption in bipedal robot walking[22] and quadruped walking robot[24]. The intricacies of human locomotion, with its seamless blend of precision, adaptability, and energy efficiency, pose a complex puzzle for engineers and researchers in the realm of robotics[25]. The historical evolution of humanoid robotics showcases a journey from rudimentary designs to sophisticated systems capable of remarkable tasks. From early attempts at mimicking human movements with basic servomechanisms to the advent of advanced materials and intricate control algorithms, the pursuit of creating robots that move and interact like humans has been a driving force in the robotics community[26,27]. Notable milestones include the development of bipedal and quadrupedal robots, each iteration bringing us closer to the vision of robots seamlessly navigating human environments[28,29]. Despite these strides, replicating human locomotion in robots remains a formidable challenge. The sheer complexity of the human musculoskeletal system, coupled with the continuous adaptation to varying environments, poses a multifaceted problem[30,31]. Achieving the natural, intuitive movements of a human requires not only a profound understanding of biomechanics but also advancements in control algorithms, sensor technology, and materials science

Despite the remarkable progress achieved in humanoid robot development, numerous technical and ethical challenges remain[32]. Achieving human-like dexterity, mobility, and cognitive capabilities in robots requires overcoming complex engineering hurdles, such as designing robust yet lightweight materials, developing sophisticated control algorithms, and integrating sensory feedback systems[33]. Moreover, concerns about job displacement, privacy, and the ethical implications of creating machines that resemble humans raise important questions about the responsible deployment and regulation of humanoid robots in society.

The current work sets out to contribute to the ongoing dialogue in humanoid robotics by focusing on the development of a basic humanoid-legged locomotion model. The motivation for this endeavor lies in the recognition that understanding and emulating human locomotion is a cornerstone for creating robots that can seamlessly integrate into diverse human-centric environments. By dissecting the intricate interplay of mechanics and control in human walking, this research seeks to unravel the complexities of legged locomotion, using the knowledge gained to enhance the capabilities of robotic systems.

The research objectives of present research are: i.) to explore the intricacies of humanoid legged locomotion using robotic manipulator focusing degrees of freedom; ii.) to develop an appropriate model considering anatomical accuracy by integrating biological dimensions of the human body into the design process, iii.) to employ Arduino Mega 2560 with a view to facilitate applications and as user-friendly control interface for the developed model.

The ability to create robots that move in ways familiar to us opens avenues for deployment in healthcare, assistive technologies, and environments that require human-robot collaboration. Thus, this research endeavors to offer insights into the challenges and opportunities inherent in replicating human locomotion, with implications reaching far beyond the confines of the laboratory.

2. Pre-requisites for developing a model

2.1 Robotic Manipulators

The selection and utilization of a robotic manipulator form a pivotal aspect of this research, as it serves as the foundational platform upon which the humanoid-legged locomotion model is constructed. The choice of a specific robotic manipulator is not arbitrary; rather, it is a deliberate decision based on careful consideration of the kinematic structure, degrees of freedom, and overall compatibility with the research objectives.

2.2 Kinematic Structure

The chosen robotic manipulator, the humanoid legged manipulator, boasts a kinematic structure designed to emulate the complexities of human leg movements. Its articulation and joint configurations are tailored to provide a versatile range of motions, mirroring the joints and linkages found in human legs. The kinematic structure is a critical component in achieving the desired degrees of freedom necessary for replicating natural human locomotion.

Practical applications of the humanoid-legged locomotion model include healthcare, assistive technologies, and environments requiring human-robot collaboration. For example, the model could be used in rehabilitation robotics to assist patients with mobility issues or in service robots that need to navigate human environments autonomously. The model's ability to replicate human movements opens up possibilities for diverse applications in industries that require sophisticated interaction between humans and robots.

The joints in the manipulator are designed to mimic the anatomical joints of the human leg, encompassing hip, knee, and ankle-like articulations. This intentional design choice aims to capture the essence of human leg movements, allowing for a more authentic representation of walking patterns. Understanding and mimicking these kinematic nuances are crucial for the model to reproduce the intricate interplay of muscles and joints involved in human walking.

2.3 Degree of Freedom

The degrees of freedom (DOF) of the robotic manipulator play a fundamental role in determining its ability to replicate human-like movements. The DOF defines the number of independent parameters required to specify the configuration of the manipulator fully. In the context of legged locomotion, understanding and optimizing the DOF are essential for achieving a dynamic and adaptable gait.

Equation (1) shows the formula for calculating degrees of freedom (DOF), is a guiding principle in assessing the manipulator's flexibility.

$$DOF = 3n - (m + s) \tag{1}$$

where, (n) represents the number of links, (m) denotes the number of joints, and (s) signifies the number of constraint equations and the formula provides a quantitative measure that helps determine the manipulator's range of motion and its ability to reproduce the intricate movements observed in human walking. A comprehensive analysis of the degrees of freedom is crucial for identifying potential limitations and refining the manipulator's design to align more closely with the intricacies of human locomotion. It is within this calculated flexibility that the manipulator gains the capacity to adapt to varying terrains and exhibit a level of versatility akin to human walking.

2.4 Rationale for Manipulator Selection

The choice of the humanoid legged robotic manipulator is rooted in a thoughtful evaluation of various factors. These factors include the manipulator's cost-effectiveness, availability, and compatibility with the research goals.

The manipulator's ability to seamlessly integrate with the control systems, sensors, and actuators essential for legged locomotion further solidifies its suitability. This integration is paramount in ensuring a coherent and synergistic approach to modeling human-like movements. The humanoid legged manipulator, with its carefully designed kinematics and degrees of freedom, serves as the canvas upon which the intricate brushstrokes of humanoid-legged locomotion are painted.

In essence, the robotic manipulator stands as the cornerstone of this research, embodying the mechanical foundation upon which the exploration of human locomotion through robotics is built. Its kinematic intricacies and degrees of freedom are not merely technical details but represent the key determinants of the model's ability to transcend the realm of machinery and approach the fluidity and naturalness inherent in human movement.

2.5 Arduino

Arduino boards typically consist of a microcontroller, input/output pins, voltage regulators, crystal oscillators, and USB connectivity. The microcontroller is the brain of the Arduino, responsible for executing the programmed instructions. Input/output pins allow communication with external devices, and voltage regulators ensure a stable power supply. Crystal oscillators regulate the clock speed, enabling precise timing of operations, while USB connectivity facilitates programming and data transfer.

The Arduino Mega 2560 acts as the central control unit for the humanoid-legged locomotion model. It coordinates the sensor inputs and actuators responsible for movement, using real-time data to control and adapt the robot's walking patterns. This board, chosen for its versatility and processing power, ensures the model is capable of handling complex motion algorithms while maintaining adaptability to environmental changes.

Variations of Arduino boards cater to different requirements, with models like Arduino Uno, Arduino Mega, and Arduino Nano offering varying sizes, pin configurations, and capabilities. The Arduino Mega 2560, a robust variant of the Arduino family, is chosen for its expanded capabilities suited to current humanoid-legged locomotion model. It is powered by the ATmega2560 microcontroller, providing ample memory and processing power for more complex projects. Arduino Mega 2560 operates on a voltage of 5V and can be powered via USB or an external power supply (7-12V).

2.6 Coding in Arduino

Arduino programming is facilitated through the Arduino IDE, a user-friendly platform supporting the C++ programming language. The IDE provides a simplified environment for code development, compilation, and uploading to the Arduino board. Further, the serial monitor, a crucial tool for debugging and monitoring, is facilitated by the serial library in Arduino. It allows bidirectional communication between the Arduino board and the computer, aiding in real-time data exchange and debugging. For visualizing data trends and system performance, the Arduino IDE can be extended with third-party libraries for graph plotting. These libraries facilitate the creation of real-time graphs, enhancing the debugging and analysis capabilities of our system.

3. Model development

The model is designed and developed using biomechanical principles, incorporating the calculated degrees of freedom and biological dimensions. The integration of sensors, actuators, and feedback control systems ensures the accurate emulation of human locomotion.

Sensors, such as accelerometers, gyroscopes, and force sensors, are critical for gathering real-time data on the model's movements and its environment. These sensors enable the model to adapt to changes in terrain and posture by providing feedback to the control system. This allows for dynamic adjustments to gait, balance, and overall locomotion, enhancing the model's ability to navigate complex environments.

3.1 Mechanical Design

The mechanical design of the model as shown in Fig. 1 is rooted in biomechanics and human anatomy, aiming to replicate the structure and movement of human legs. The choice of a suitable robotic manipulator, the 3R humanoid Legged Model, with its carefully designed kinematic structure and degrees of freedom, forms the mechanical foundation for model.

Insights from biomechanical studies, especially those focused on the musculoskeletal system and joint movements during locomotion, inform the design. Emphasis is placed on mimicking natural joint angles, stride lengths, and proportions to achieve lifelike movements.

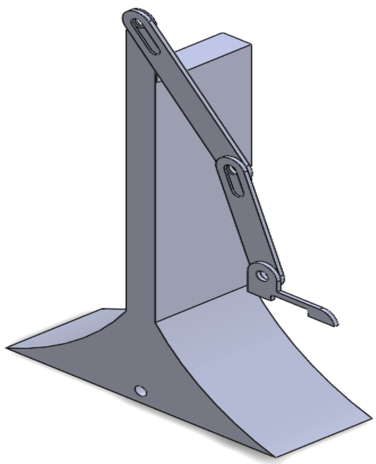


Fig. 1: Mechanical model depicts human anatomy.

3.2 Conceptual model capturing basics

3.2.1 Model Description

The robotic arm consists of four links connected by revolute joints. Each joint can rotate around its axis, controlled by three input variables representing the joint angles ($\theta_1, \theta_2, \theta_3$). The conceptual model of joints is shown in Fig. 2.

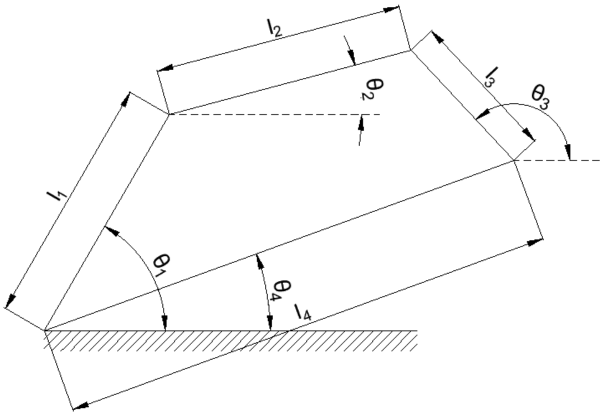


Fig. 2: Conceptual model.

The goal is to determine the position and orientation of the end-effector in cartesian coordinates (x, y, z), with symbols and notations having their standard meaning. Before any modelling attempt, it is necessary to clarify regarding the assumptions used as suggested in published literature[34–36]. Accordingly, the assumptions for developing the model are:

3.2.1.1 Rigid Body Assumption

The robotic arm is assumed to consist of rigid links and joints without any flexibility or compliance. This allows practitioner to neglect deformations and to focus on the kinematics of the system.

3.2.1.2 Revolute Joints

The joints connecting the links of the robotic arm are assumed to be revolute joints, allowing rotation about a single axis. This assumption simplifies the kinematic analysis and enables the use of standard transformation matrices.

3.2.1.3 Fixed Links

One out of the four links of the robotic arm is assumed to be fixed in position and remaining links can demonstrate orientation relative to each other. This simplifies the model by reducing the degrees of freedom and focusing on the motion of the end-effector.

3.2.1.4 Full Rotational Motion of the Fourth Link

The fourth link of the robotic arm is assumed to have the capability of full rotational motion around its own axis. This assumption allows for a wider range of end-effector orientations and enhances the flexibility of the robotic arm.

3.2.1.5 Kinematic Constraints

The mathematical model does not consider external factors such as joint limits, singularities, or collision avoidance. These constraints may need to be addressed in practical applications but are omitted for simplicity in the mathematical model.

3.2.1.6 No External Forces and Torques

The mathematical model assumes that there are no external forces and torques acting on the robotic arm during its operation. This assumption simplifies the dynamics analysis and focuses solely on kinematics.

3.2.1.7 Perfect Actuation and Sensing

The actuators and sensors of the robotic arm are assumed to be ideal, providing precise control and accurate measurement of joint angles and end-effector position. This assumption facilitates the development of the mathematical model but may not hold true in real-world scenarios.

3.2.1.8 Homogeneous and Isotropic Materials

The materials used to construct the robotic arm are assumed to be homogeneous and isotropic, with uniform mechanical properties throughout.

These assumptions serve to simplify the mathematical model of the robotic arm while still capturing its essential kinematic characteristics. They provide a basis for further analysis and development of control algorithms for practical applications.

3.2.2 Forward Kinematics

The forward kinematics problem involves computing the position and orientation of the end-effector given the joint angles. This can be represented using a transformation matrix:

$$T_0^4 = T_0^1 \cdot T_1^2 \cdot T_2^3 \cdot T_3^4$$

Each transformation matrix T_i^{i+1} represents the transformation from link i to link $i+1$. For the position and rotation analysis of the fourth link (T_3^4), we consider both translation and rotation components.

Transformation matrix for the Fourth Link:

$$T_3^4 = \begin{bmatrix} R_x & R_y & R_z & p_x \\ R_x & R_y & R_z & p_y \\ R_x & R_y & R_z & p_z + l_4 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Where R_x, R_y, R_z represent the rotation components, and p_x, p_y, p_z represent the position components of the fourth link. l_4 is the length of the fourth link.

Inputs and Outputs:

Inputs: $(\theta_1, \theta_2, \theta_3)$ (joint angles)

Outputs: (x, y, z) (end-effector position)

3.2.3 D-H parameter

The Denavit-Hartenberg (D-H) parameters provide a systematic way to represent the kinematic properties of a robotic manipulator. Here's the D-H parameter table for the open-ended robotic arm with four links:

Table 1. D-H parameter table for the four links.

Link i	$\boldsymbol{\theta_i}$	$\boldsymbol{d_i}$	$\boldsymbol{a_i}$	$\boldsymbol{\alpha_i}$
1	θ_1	0	0	$\pi/2$
2	θ_2	0	l_2	0
3	θ_3	0	l_3	0
4	0	0	l_4	0

Where:

θ_i represents the joint angle about the z_{i-1} axis.

d_i represents the joint angle about the z_{i-1} axis.

a_i represents the link length along the x_i axis.

α_i represents the twist angle about the x_i axis

3.2.4 Transformation Matrices

The individual transformation matrices T_i^{i+1} can be computed using the D-H parameters:

$$T_i^{i+1} = \begin{bmatrix} \cos(\theta_i) & -\sin(\theta_i)\cos(\alpha_i) & \sin(\theta_i)\sin(\alpha_i) & a_i\cos(\theta_i) \\ \sin(\theta_i) & \cos(\theta_i)\cos(\alpha_i) & -\cos(\theta_i)\sin(\alpha_i) & a_i\sin(\theta_i) \\ 0 & \sin(\alpha_i) & \cos(\alpha_i) & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

For $i = 1,2,3$ and for forth link:

$$T_3^4 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & l_4 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

This mathematical model allows us to compute the position and orientation of the end-effector given the joint angles of the robotic arm.

The DH parameters serve as a representation of the robot's configuration and the kinematic equations may vary for different manipulator structures. Additionally, employing the DH convention in kinematics equations may introduce singularities, rendering the equations challenging to solve or even unsolvable in certain scenarios. Furthermore, the DH convention fails to properly define the common normal when the axes of two joints are parallel, leading to a singularity in the DH method. This singularity arises because even a slight alteration in the spatial coordinates of parallel joint axes can result in a significant misrepresentation of their relative position in DH coordinates.

3.2.5 Inverse Kinematics

Inverse kinematics involves determining the joint angles required to achieve a desired end-effector position and orientation. This can be represented using a function:

$$\theta = f^{-1}(x_d, y_d, z_d)$$

Where, $\theta = [\theta_1, \theta_2, \theta_3]$ represents the joint angles, and (x_d, y_d, z_d) represent the desired end-effector position.

The inverse kinematics problem may not have a direct matrix representation due to its nonlinear nature. It typically involves numerical methods or optimization techniques to solve for the joint angles given the desired end-effector position and orientation.

While the forward kinematics equation can be represented in matrix form, the inverse kinematics problem usually requires iterative methods or numerical optimization algorithms to find the joint angles that satisfy the desired end-effector position and orientation. Therefore, it's challenging to represent the inverse kinematics problem solely in matrix form.

3.3 Biomedical Dimension

The incorporation of biomedical dimensions ensures anatomical accuracy and enhances the model's ability to replicate human movements. The biological dimensions, obtained from reputable biomedical studies, are incorporated into the design. Leg length, joint angles, and other relevant parameters are meticulously considered to align the model with average human dimensions. Further, the model accommodates variations in posture, incorporating data from biomedical research on joint angles and muscle engagement during different activities such as standing, walking, and crouching. Moreover, understanding the dynamic nature of human movement, the model is designed to adapt its dimensions in real-time during locomotion, capturing the nuances of a changing gait, even in a suspended configuration.

Biomechanical principles, such as joint angles, leg lengths, and muscle engagement, inform the design of the humanoid-legged locomotion model by providing anatomical accuracy. This ensures that the robot's movements reflect human physiology. By aligning with average human dimensions and incorporating dynamic adaptability during locomotion, the model is designed to replicate natural human walking with a high degree of precision.

3.4 Electrical Desing

The electrical design as shown in Fig. 3 focuses on the integration of electronic components, sensors, actuators, and the control system. It includes, Arduino Mega 2560, sensor and actuator implementation which serves as the central control unit, orchestrating the movements based on sensory input. The inclusion of sensors, like accelerometers, gyroscopes, and force sensors, enhances the model's responsiveness to the environment. These sensors feed real-time data to the control system, enabling adaptive and context-aware locomotion even in a suspended setup. The core of the coding design revolves around controlling the servo motor SG90 that strategically placed to mimic human joint movements. The electrical design ensures the precise coordination of these actuators for fluid and lifelike motions.

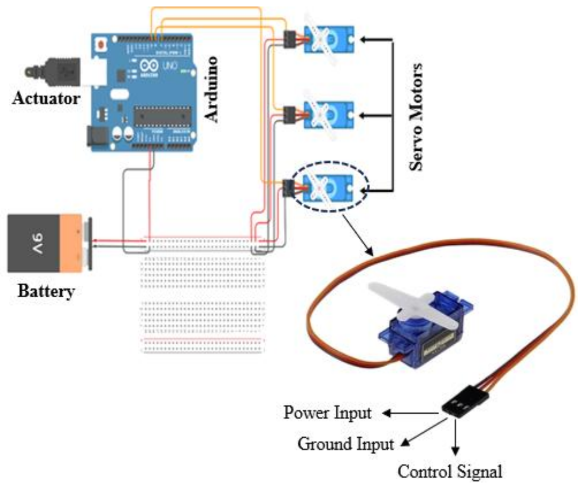


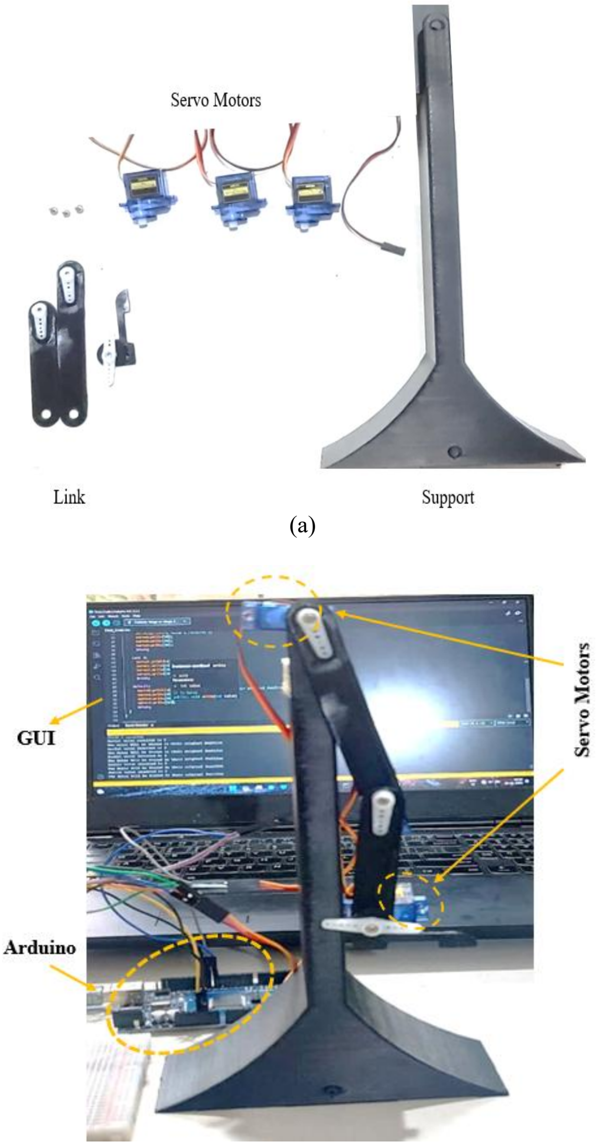
Fig. 3: Electrical design arrangement.

3.5 Coding Desing

The coding design is implemented in the Arduino IDE and involves the development of algorithms and control logic to drive the model's movements. The primary key considerations include control algorithms that help to translate sensor data into coordinate movements. In this context proportional-integral-derivative (PID) controllers employed for precise control of joint angles, considering the dynamic challenges posed by a suspended configuration. Secondary key element is adaptive gait patterns that allowed the model to adjust its walking style based on the terrain, speed and user input. This adaptability enhances the model's versatility in different environments, including situations where the links are suspended. Real-time feedback loops are used to ensure that the model can adapt dynamically to changes in its surroundings and take into account the particular dynamics triggered by the suspended links.

PID controllers are employed to provide precise control over joint angles, ensuring that the movements of the model closely resemble human gait patterns. These controllers allow for real-time adjustments based on sensor feedback, making it possible to achieve smooth and controlled movements, even in dynamically changing environments. This ensures the model's adaptability and accuracy in replicating human locomotion.

Furthermore, even when the model is in a non-mobile suspended state, insights can be gained by using an intuitive graphical user interface (GUI) that communicates with the model and lets users enter commands, track sensor data, and see the model's performance in real time[37]. This coding aspect bridges the gap between the mechanical and electronic components, ensuring a harmonious fusion that brings the project to life with accuracy and reliability. The complete model detail is shown in Fig. 4.



(a)

(b)

Fig. 4: Model details: (a) Parts of the model and (b) Complete assembly of the model

4. Discussion

A motion analysis tool Raboanalyzer[38)] is employed to capture and analyze the intricate movements of the humanoid-legged locomotion model. In tandem with Raboanalyzer, the Arduino Serial Graph is employed to visualize real-time data from the model's sensors and control system. The Denavit-Hartenberg (DH) parameters of legged locomotive robot are shown in Table 2. Sudden spikes or irregularities in the Arduino serial graph can indicate anomalies or unexpected behavior.

Table 2. D-H Parameters of legged locomotive robot.

Joint No.	Joint Type	Joint Offset (b) m	Joint Angle (θ) deg	Link Length (a) m	Twist Angle (α) deg	Initial Value (JV) deg	Final Value (JV) deg
1	Revolute	Variable	0	0.99	0	0	90
2	Revolute	Variable	0	0.75	0	0	-90
3	Revolute	Variable	0	0.45	0	90	-90

This real-time observation enables quick identification and troubleshooting of issues during stimulation. Fig. 5 shows the motion of the model in the standing position.

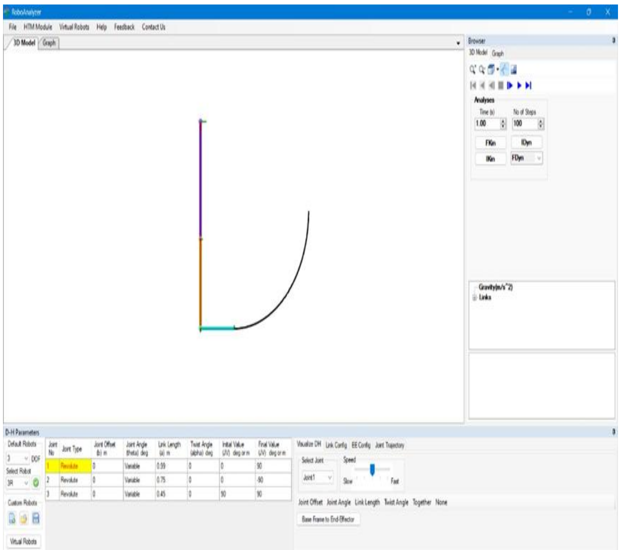


Fig. 5: Track of motion in standing position.

In standing position, the matric is defined for end effector as depicted in Table 3. Further, in this condition the matrices for Link 1 to Link 3 featured in Table 4 to Table 6 respectively.

Table 3. End effector matrix.

1	0	0	0.99
0	1	0	0
0	0	1	0
0	0	0	1

Table 4. Link configuration matrix for link 1.

0	-1	0	0.75
1	0	0	1.44
0	0	1	0
0	0	0	1

Table 5. Link configuration matrix for link 2.

1	0	0	1.74
0	1	0	0
0	0	1	0
0	0	0	1

Table 6. Link configuration matrix for link 3.

0	-1	0	1.74
1	0	0	0.45

0	0	1	0
0	0	0	1

In the same manner, the above discussed motion matrix is defined for the plotted sitting position motion (Fig. 6).

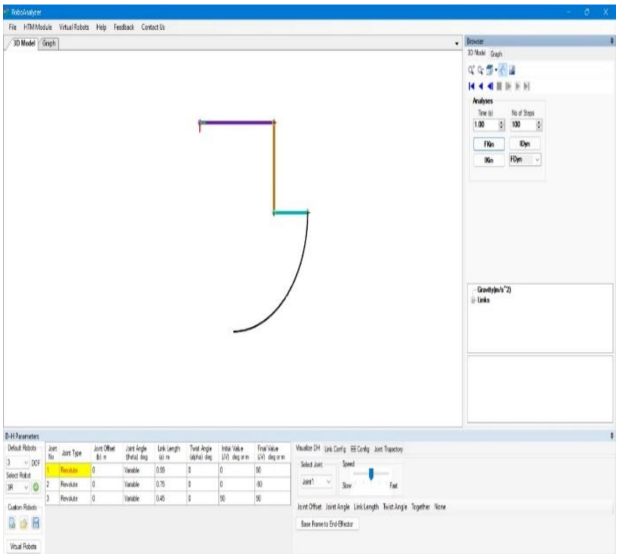


Fig. 6: Track of motion in sitting position.

The assessment of the sitting condition for Link 1 to Link 3 is systematically conducted, adhering to the same sequential order established for the standing position evaluation. This process is delineated and documented in Tables 7 through Table 10, providing a comprehensive tabular representation of the criteria and outcomes associated with each link's seated posture assessment.

Table7. End effector matrix for sitting position.

0	-1	0	0.75
1	0	0	1.44
0	0	1	0
0	0	0	1

Table 8. Link configuration matrix for link 1 (Sitting).

0	-1	0	1.74
1	0	0	0.45
0	0	1	0
0	0	0	1

Table 9. Link configuration matrix for link 2 (Sitting).

0	-1	0	1.74
1	0	0	0.45
0	0	1	0
0	0	0	1

Table 10. Link configuration matrix for link 3 (Sitting).

0	-1	0	0.75
1	0	0	1.44

0	0	1	0
0	0	0	1

The combined insights from motion analysis and real-time sensor feedback, considering the similarities in dimensions and joint angles, provide a comprehensive understanding of how the model navigates through different orientations. In order to better understanding of the motion, individual link motion and corresponding trajectory is shown in Fig. 7 to Fig. 9.

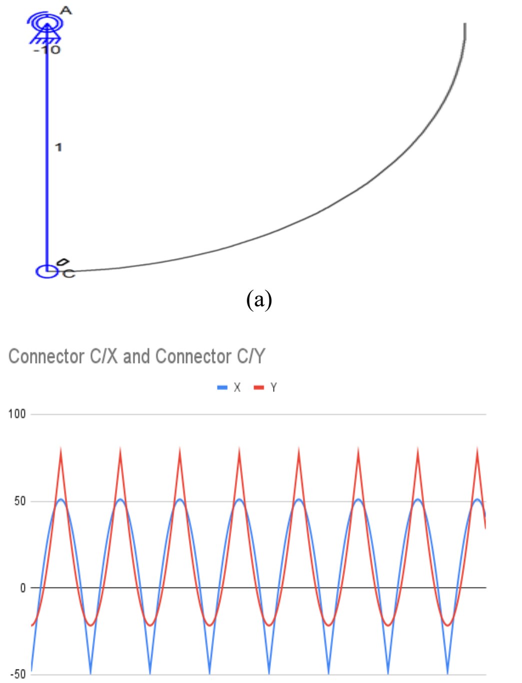
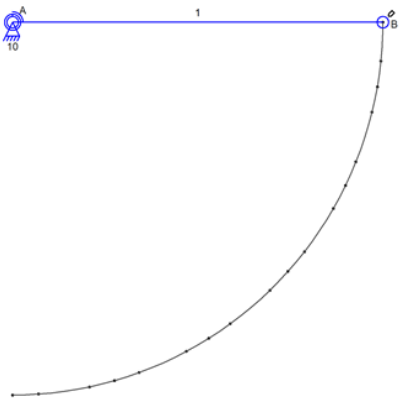
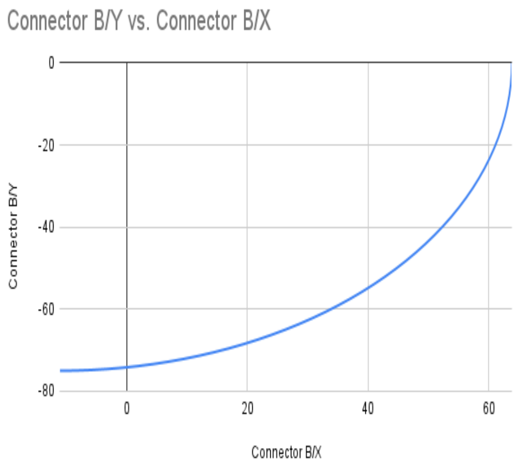


Fig. 7: For link 1: (a) Path of motion and (b) Graph of motion trajectory

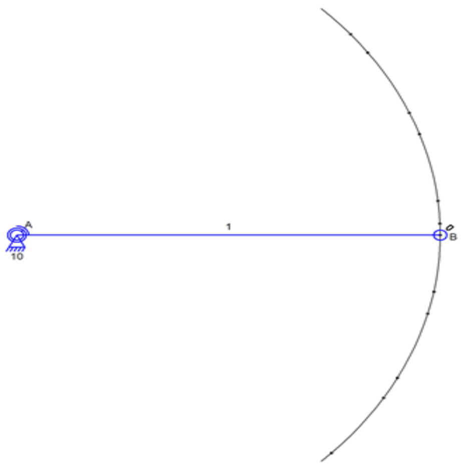


(a)

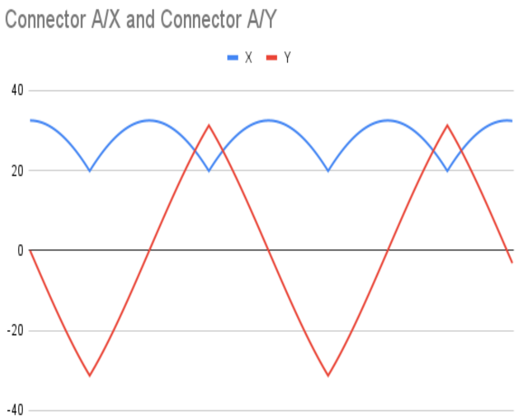


(b)

Fig. 8: For link 2: (a) Path of motion and (b) Graph of motion trajectory.



(a)



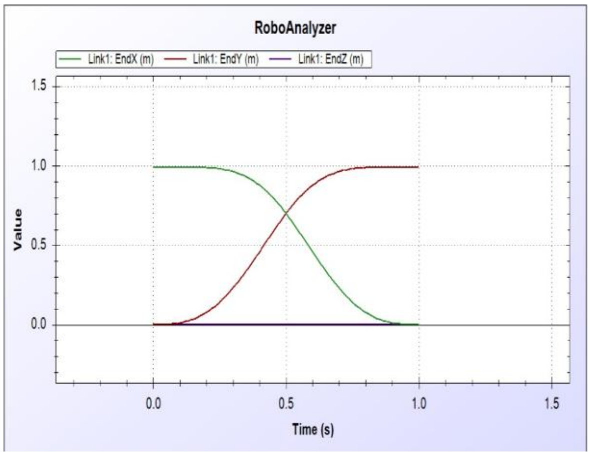
(b)

Fig. 9: For link 3: (a) Path of Motion and (b) Graph of Motion Trajectory

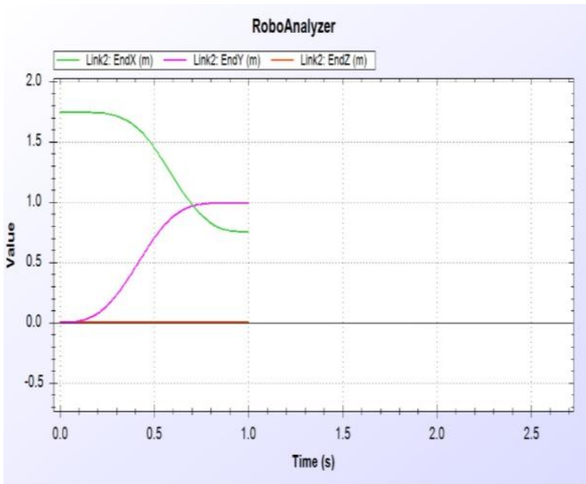
4.1 Iterative Refinement

Observational data, taking into account the similarities in dimensions and joint angles, serves as the foundation for iterative refinement of the humanoid-legged locomotion model. The observations guide adjustments in mechanical design, control algorithms, and overall system behavior, intending to achieve increasingly natural and adaptive locomotion in diverse orientations.

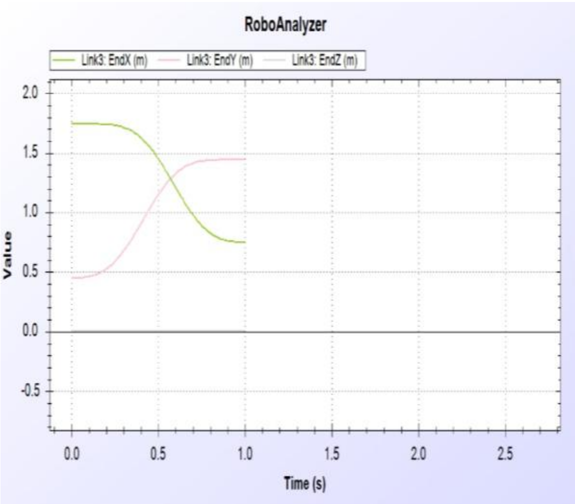
In essence, the observation phase, supported by tools like Raboanalyzer and Arduino Serial Graph, considers the similarities in dimensions and joint angles of the human-legged robotic manipulator to both human legs and typical biped walking mechanisms (shown in Fig. 10). This holistic approach validates the effectiveness of the model's design and control strategies and guides the iterative refinement process, ensuring continual improvement in performance across various orientations.



(a)



(b)



(c)

Fig. 10: Graphical Representation of Trajectory Planning on Roboanalyzer (a) Link 1, (b) Link 2, (c) Link 3

4.2 Biological aspects of Human Body

In the quest to create a humanoid-legged locomotion model that authentically replicates human movements, a meticulous examination of the biological dimensions of the human body becomes paramount.

4.2.1 Medical Research Finding

The foundation of our understanding is rooted in comprehensive medical research conducted by institutions at the forefront of biomechanics and human movement studies. Institutions have delved into the intricacies of human locomotion, dissecting movements across various postures and conditions. The insights gained from these studies serve as a bedrock for our endeavor, guiding the incorporation of anatomically accurate dimensions into the humanoid-legged locomotion model.

Medical research has provided invaluable data on joint angles, muscle activations, and skeletal movements during diverse activities such as walking, running, and standing. In the same manner Qin et al.[23] depicts the new human gait prediction and recognition algorithm with the accuracy near by 99.6% to improve the real time and stability of the lower extremity exoskeleton system. This wealth of information aids in crafting a model that not only mimics the gross movements observed but also captures the subtle nuances of muscle engagement and joint coordination.

4.2.2 Posture-specific Considerations

Medical research has elucidated the variations in muscle activation, joint angles, and overall biomechanics across postures such as standing, walking, and crouching. By incorporating posture-specific dimensions into the model, author aim to create a system that seamlessly transitions between different modes of movement, mimicking the dynamic nature of human locomotion.

Research findings from studies on postural stability, weight distribution, and joint loading in various positions inform the model's design parameters. For instance, the alignment of the spine, the distribution of body weight, and the engagement of supporting muscles are meticulously considered for each posture. This comprehensive approach ensures that the model not only replicates the visual aspects of movement but also captures the underlying physiological principles governing human locomotion.

4.2.3 Average ratio of Human leg parts

The proportions of different parts of the human legs are a key focal point in the design process. Medical institutions have conducted extensive research to establish average ratios between segments such as the femur, tibia, and fibula. These ratios, derived from diverse demographic samples, provide valuable insights into the relative lengths and dimensions that contribute to the harmonious motion of human legs.

The study of leg proportions is not limited to static measurements but extends to dynamic considerations during locomotion. Researchers have explored how these ratios vary during different phases of gait, elucidating the intricate adjustments that occur in real time. By integrating these findings, our model aspires to capture the essence of proportional harmony in leg movements, contributing to a lifelike and anatomically faithful representation.

In essence, the incorporation of data from medical research institutions elevates our understanding of human locomotion from a mere imitation of movements to a nuanced replication of the underlying biomechanics. This holistic approach, rooted in scientific inquiry, ensures that the humanoid-legged locomotion model is not only visually accurate but also aligns with the physiological intricacies observed in the diverse movements of the human body. The collaborative synergy between robotics and medical research propels our exploration beyond mere mimicry, striving for a convergence of art and science in the realm of humanoid robotics.

The observation phase plays a crucial role in evaluating the performance of our humanoid-legged locomotion model as it is stimulated to perform different orientations. This section details the use of tools like Raboanalyzer and Arduino Serial Graph for comprehensive data analysis and visualization.

5. Conclusion and contributions

In line with the research objectives the research discusses the design and development of a humanoid-legged locomotion model, meticulously designed with biomechanical realism and adaptability, stands as a pivotal foundation for understanding bipedal locomotion. It integrating the principles from robotics, biomechanics, and control systems, with a specific focus on degrees of freedom, biological dimensions, and the use of Arduino technology.

The model's real-time sensor feedback, facilitated by tools like Raboanalyzer and Arduino Serial Graph, enhances our understanding of how environmental stimuli influence locomotion. Beyond replicating human movements, it serves as a guide for optimizing control algorithms and identifying best practices.

Further, the coding design involves the development of algorithms and control logic to drive the model's movements, with a crucial role played by the observation phase in evaluating the model's performance. Looking ahead, future directions involve enhanced sensor integration, machine learning, and collaboration with neuroscientific studies. This interdisciplinary approach promises continued advancements in biomimicry, refining our understanding of humanoid-legged locomotion and contributing to the evolution of more capable and human-like machines in the field of robotics. Moreover, it highlights the transformative potential of the humanoid-legged locomotion model in education across different levels. So, it is expected that this research will contribute to the body of knowledge and will also pave the way for practical applications of humanoid robotics. Thus, authors believe that this research will be very useful for academicians and to facilitate learnings and for practitioners.

6. Limitations and scope for future work

Like any study, this research also has some limitations. Authors very humbly accept. For example, the research value of the study can be enhanced if simulation studies and scenarios-based analysis as suggested by Manjunatha et al.[39] are also incorporated. Similarly, to check the robustness and responsiveness[36,40] of the model, approaches like sensitivity analysis and critical value check[41], if incorporated then it will further add value to this research.

Researchers can further explore these weaknesses and encompass advanced tools ensuring better responsiveness, sensitivity and simulation-based scenario analyses to add value to this work. These extensions will help in refining the applications and will add more to the body of knowledge of this subject area.

References

1) C.S. Song, and Y.-K. Kim, "The role of the human-robot interaction in consumers' acceptance of humanoid retail service robots," *J. Bus. Res.*, 146 489–503 (2022). doi:10.1016/j.jbusres.2022.03.087.
2) S. Choi, A.S. Mattila, and L.E. Bolton, "To err is human(-oid): how do consumers react to robot service failure and recovery?," *J. Serv. Res.*, 24 (*3*) 354–371 (2021). doi:10.1177/1094670520978798.
3) M. Mende, M.L. Scott, J. van Doorn, D. Grewal, and I. Shanks, "Service robots rising: how humanoid robots influence service experiences and elicit compensatory consumer responses," *J. Mark. Res.*, 56 (*4*) 535–556 (2019). doi:10.1177/0022243718822827.
4) J. Wirtz, P.G. Patterson, W.H. Kunz, T. Gruber, V.N. Lu, S. Paluch, and A. Martins, "Brave new world: service robots in the frontline," *J. Serv. Manag.*, 29 (*5*) 907–931 (2018). doi:10.1108/JOSM-04-2018-0119.
5) J. Lyu, P. Ruppel, N. Hendrich, S. Li, M. Görner, and J. Zhang, "Efficient and collision-free human–robot collaboration based on intention and trajectory prediction," *IEEE Trans. Cogn. Dev. Syst.*, 15 (*4*) 1853–1863 (2023). doi:10.1109/TCDS.2022.3215093.
6) H. Duan, P. Wang, Y. Huang, G. Xu, W. Wei, and X. Shen, "Robotics dexterous grasping: the methods based on point cloud and deep learning," *Front. Neurorobot.*, 15 (2021). doi:10.3389/fnbot.2021.658280.
7) V. Ortenzi, A. Cosgun, T. Pardi, W.P. Chan, E. Croft, and D. Kulic, "Object handovers: a review for robotics," *IEEE Trans. Robot.*, 37 (*6*) 1855–1873 (2021). doi:10.1109/TRO.2021.3075365.
8) J.J. Rainer, R. Galan, B. Al-Hadithi, and A. Jiménez, "A.p.g.: an intelligent automatic generator of presentations for tour-guide robots," *Int. J. Comput. Intell. Syst.*, 4 (*4*) 446 (2011). doi:10.2991/ijcis.2011.4.4.4.
9) R.J.B. Walker, T.A. Stukel, C. de Mestral, A. Nathens, R.H. Breau, W.C. Hanna, L. Hopkins, C.M. Schlachta, T.D. Jackson, B. Shayegan, S.E. Pautler, and P.J. Karanicolas, "Hospital learning curves for robot-assisted surgeries: a population-based analysis," *Surg. Endosc.*, 38 (*3*) 1367–1378 (2024). doi:10.1007/s00464-023-10625-6.
10) S. Ivanov, C. Webster, and F. Seyitoğlu, "Humans and/or robots? tourists' preferences towards the humans–robots mix in the service delivery system," *Serv. Bus.*, 17 (*1*) 195–231 (2023). doi:10.1007/s11628-022-00517-5.
11) H. Srivastava, A. Kaushal, H. Kumar, A. Tripathi, and Anuj Kumar Sharma, "A design and development of baggage sorting robotic system at the airport," *Evergreen*, 9 (*1*) 86–92 (2022). doi:10.5109/4774219.
12) C. Lu, R. Gao, L. Yin, and B. Zhang, "Human–robot collaborative scheduling in energy-efficient welding shop," *IEEE Trans. Ind. Informatics*, 20 (*1*) 963–971 (2024). doi:10.1109/TII.2023.3271749.
13) H. He, J. Gray, A. Cangelosi, Q. Meng, T.M. McGinnity, and J. Mehnen, "The challenges and opportunities of human-centered ai for trustworthy robots and autonomous systems," *IEEE Trans. Cogn. Dev. Syst.*, 14 (*4*) 1398–1412 (2022). doi:10.1109/TCDS.2021.3132282.
14) H.H. Lund, "Modern artificial intelligence for human-robot interaction," *Proc. IEEE*, 92 (*11*) 1821–1838 (2004). doi:10.1109/JPROC.2004.835362.
15) A.A. Malik, and A. Bilberg, "Framework to Implement Collaborative Robots In Manual Assembly: A Lean Automation Approach," *28th DAAM International Symposium on Intelligent Manufacturing and Automation,* 1151–1160 (2017).

doi:10.2507/28th.daaam.proceedings.160.

16) "Tesla, "Artificial intelligence & autopilot"," (2021). https://www.tesla.com/AI. (Accessed 20 January 2025)
17) H.K. Gidey, P. Hillmann, A. Karcher, and A. Knoll, "Towards Cognitive Bots: Architectural Research Challenges," *16th International Conference on Artificial General Intelligence,* 105-114 (2023). doi:10.1007/978-3-031-33469-6_11.
18) A.A. Malik, T. Masood, and A. Brem, "Intelligent humanoids in manufacturing to address worker shortage and skill gaps: case of tesla optimus," 1–20 (2023). doi.org/10.48550/arXiv.2304.04949.
19) A.A. Malik, T. Masood, and A. Brem, "Intelligent Humanoid Robots in Manufacturing," *Companion 2024 ACM/IEEE Int. Conf. Human-Robot Interact., ACM, New York, NY, USA,* 20-27 (2024). doi:10.1145/3610978.3640765.
20) Z. Liu, J. Gao, X. Rao, S. Ding, and D. Liu, "Complex dynamics of the passive biped robot with flat feet: gait bifurcation, intermittency and crisis," *Mech. Mach. Theory*, 191 105500 (2024). doi:10.1016/j.mechmachtheory.2023.105500.
21) M. Safartoobi, M. Dardel, and H. Mohammadi Daniali, "Passive walking biped robot model with flexible viscoelastic legs," *Nonlinear Dyn.*, 109 (*4*) 2615–2636 (2022). doi:10.1007/s11071-022-07600-6.
22) M. Safartoobi, M. Dardel, and H.M. Daniali, "Gait cycles of passive walking biped robot model with flexible legs," *Mech. Mach. Theory,* 159 104292 (2021). doi:10.1016/j.mechmachtheory.2021.104292.
23) A. Surriani, O. Wahyunggoro, and Adha Imam Cahyadi, "A trajectory control for bipedal walking robot using stochastic-based continuous deep reinforcement learning," *Evergreen*, 10 (*3*) 1538–1548 (2023). doi:10.5109/7151701.
24) K.-C. Han, and J.-Y. Kim, "Posture stabilizing control of quadruped robot based on cart-inverted pendulum model," *Intell. Serv. Robot.*, 16 (*5*) 521–536 (2023). doi:10.1007/s11370-023-00480-8.
25) Q. Yang, X. Liu, P. Wang, Y. Song, and T. Sun, "A multi-locomotion clustered tensegrity mobile robot with fewer actuators," *Rob. Auton. Syst.*, 168 104504 (2023). doi:10.1016/j.robot.2023.104504.
26) L. Wang, F. Liu, S. Xu, Z. Wang, S. Cheng, and J. Zhang, "Design, modeling and control of a biped line-walking robot," *Int. J. Adv. Robot. Syst.*, 7 (*4*) 33 (2010). doi:10.5772/10498.
27) Jung-Yup Kim, Ill-Woo Park, Jungho Lee, Min-Su Kim, Baek-kyu Cho, and Jun-Ho Oh, "System Design and Dynamic Walking of Humanoid Robot KHR-2," *Proc. 2005 IEEE Int. Conf. Robot. Autom., IEEE,* 1431–1436 (2005). doi:10.1109/ROBOT.2005.1570316.
28) L. Liu, A.J. Schoen, C. Henrichs, J. Li, B. Mutlu, Y. Zhang, and R.G. Radwin, "Human robot collaboration for enhancing work activities," *Hum. Factors J. Hum. Factors Ergon. Soc.*, 66 (*1*) 158–179 (2024). doi:10.1177/00187208221077722.
29) A. Dahiya, A.M. Aroyo, K. Dautenhahn, and S.L. Smith, "A survey of multi-agent human–robot interaction systems," *Rob. Auton. Syst.,* 161 104335 (2023). doi:10.1016/j.robot.2022.104335.
30) N. Xie, and P.Y. Mok, "Investigation on Human Body Movements and the Resulting Body Measurement Variations," *Advances in Physical Ergonomics and Human Factors*, 387–399 (2017). doi:10.1007/978-3-319-60825-9_42.
31) K. Ono, and X. Yao, "Simulation Study of Self-Excited Walking of a Biped Mechanism with Bent Knee," *Adapt. Motion Anim. Mach., Springer-Verlag, Tokyo,* 131–142 (2006). doi:10.1007/4-431-31381-8_12.
32) J. Nagpal, R. Lal, and R. Rana, "Novel robotic platform for affordable and customizable testing and prototyping," *Evergreen*, 10 (*1*) 454–462 (2023). doi:10.5109/6782148.
33) V. Bargsten, and F. Kirchner, "Actuator-level motion and contact episode learning and classification using adaptive resonance theory," *Intell. Serv. Robot.*, 16 (*5*) 537–548 (2023). doi:10.1007/s11370-023-00481-7.
34) D. Seth, and M.K. Pandey, "A multiple-item inventory model for a non-stationary demand," *Prod. Plan. Control*, 20 (*3*) 242–253 (2009). doi:10.1080/09537280902843607.
35) D. Seth, and M.A.A. Rehman, "Critical success factors-based strategy to facilitate green manufacturing for responsible business: an application experience in indian context," *Bus. Strateg. Environ.*, 31 (*7*) 2786–2806 (2022). doi:10.1002/bse.3047.
36) M.A. Rehman, and D. Seth, "Investigation and modeling of electric vehicle enablers (eve) for successful penetration in context to india: mitigating the effect of urban sprawl on transportation," *Environ. Sci. Pollut. Res.*, 30 (*49*) 107118–107137 (2023). doi:10.1007/s11356-023-26022-4.
37) J. Qi, L. Ma, Z. Cui, and Y. Yu, "Computer vision-based hand gesture recognition for human-robot interaction: a review," *Complex Intell. Syst.*, 10 (*1*) 1581–1606 (2024). doi:10.1007/s40747-023-01173-6.
38) Shailendra Singh Chauhan, and Avadhesh Kumar Khare, "Kinematic analysis of the abb irb 1520 industrial robot using roboanalyzer software," *Evergreen,* 7 (*4*) 510–518 (2020). doi:10.5109/4150470.
39) M. Manjunatha, D. Seth, B. KVGD, S. Roy, and R.B. Tangadagi, "Utilization of industrial-based pvc waste powder in self-compacting concrete: a sustainable building material," *J. Clean. Prod.*, 428 139428 (2023). doi:10.1016/j.jclepro.2023.139428.
40) D. Seth, and A. Panigrahi, "Application and evaluation of packaging postponement strategy to boost supply chain responsiveness: a case study," *Prod. Plan. Control*, 26 (*13*) 1069–1089 (2015). doi:10.1080/09537287.2015.1010626.
41) D. Seth, V.K. Nemani, S. Pokharel, and A.Y. Al Sayed, "Impact of competitive conditions on supplier evaluation: a construction supply chain case study," *Prod. Plan. Control*, 29 (*3*) 217–235 (2018). doi:10.1080/09537287.2017.1407971.