Bipedal gait bio-mimicry using a foldable mechanism

Foldable Robotics Group Assignment 1

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Project Outline

Bipedalism is the ability of animals to walk or run by bearing weight on two legs, a trait often seen in birds and some mammals, including humans. Birds, such as ostriches, are a prime example of bipedal locomotion, using their strong limbs for walking and running at high speeds. This type of locomotion is characterized by distinct gait patterns, including walking, hopping, or running, which vary depending on terrain and speed. The skeletal structure of birds is adapted for efficient bipedal movement, with lightweight bones and muscular legs designed for propulsion. Despite variations in body size across bird species, their skeletal framework remains consistent, emphasizing flight and ground locomotion adaptation.

Types of gait in birds vary depending on their size, habitat and need for speed or stability. For example, ostriches, known for their remarkable running ability, use walking and sprinting gaits, with transitions to more complex patterns at higher speeds, such as bounding strides where both legs may leave the ground. These gait variations allow birds to efficiently adapt to their environment, balancing speed, endurance, and stability on different terrains. Researchers have also explored bipedal gait biomechanics to design bipedal robots. Bipedal robots that mimic bird locomotion leverage dynamic gait patterns and energy-efficient trajectories to achieve stability and agility on uneven terrain. This project focuses on studying and replicating such gait mechanics using a foldable mechanism. Utilizing the material's inherent stiffness and flexibility, the goal is to analyze the effects of gait transitions on speed and terrain adaptability, offering valuable insights for both robotics and biomechanical applications.

This project's scope is to replicate two legs of a bird, such as an ostrich, and study two primary gaits, walking and hopping, using a foldable five-bar mechanism. This mechanism's kinematics are to be studied and simulated using MuJoCo (MuJoCo is a physics engine for detailed, efficient rigid body simulations); using servo motors and a microcontroller, the position and orientation of legs can be controlled to implement different gaits. The gait pattern can be created using the simulated mechanism and extracting the joint angles from the simulation to implement in the control of the robot; the simulated gait and experimental gait can be further compared and validated.

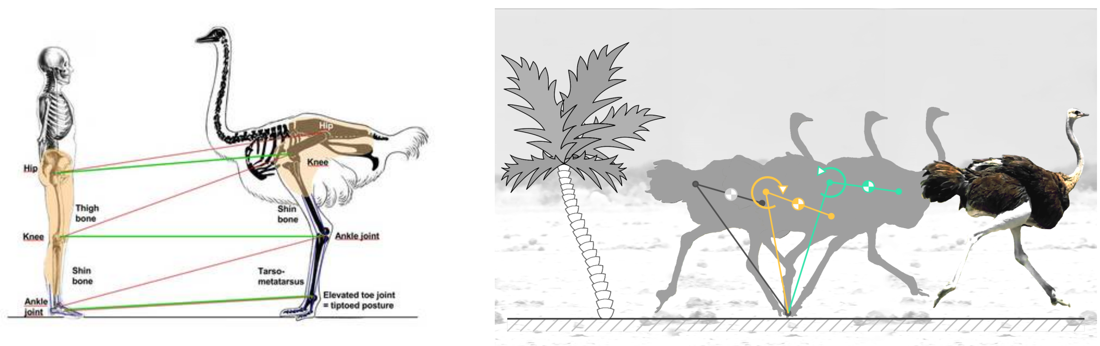
Using a five-bar linkage system leveraging the foldable mechanism, the biomimicry of an ostrich's legs mimics the intricate, multi-joint motions of real limbs, offering important insights into bipedal biomechanics. This design makes smoother and more flexible motion possible in robotic applications, which captures the kinematics and dynamics of different gaits. Biped biomechanism has been a hot research topic for decades thanks to its adaptability and low energy required to walk and get higher mobility. This project aims to study, develop, and mimic bipedal gait using foldable robotic techniques to further the utility and understanding of the nuances of foldable mechanisms' structural rigidity and the flexibility of joints and links.

This project demands various skill sets, including but not limited to prototyping, simulation using MuJoCo, control theory, and designing the mechatronic system. Our team members have experience in the required skills for this project and hope to further our understanding of integrating complex systems using course material on foldable mechanisms, kinematics, and dynamics of five-bar mechanisms. Our ability to plan, execute, and validate this project throughout the semester takes into account our individual interests within the project and collective coordination to promptly meet the deliverables and deadlines.

A few of the deliverables of this course, foldable robotics, include kinematic and dynamic analysis of joints and links leveraging various foldable mechanisms that include spherical, hinge, prismatic joints, etc., and physics-based simulation using MuJoCo by defining all the joints and links. All of these concepts are being utilized and studied within this project's scope while studying a bipedal biomechanism for terrestrial locomotion. The foldable five-bar link mechanism is to be implemented as a leg of an ostrich, the size of which is chosen arbitrarily considering the torque capacity of servo motors and the weight of material used in making foldable joints and links.

1. Background

Compared to crawler or wheeled robots, bipedal robots have advantages when navigating rough terrains because of their discrete gait trajectories, giving them adaptability and mobility [1]. The anatomy of birds which rely on feet rather than wings for locomotion, like ostriches, over evolution, is adapted for agility and adaptability to different terrains, giving them different types of gaits. Ostriches have evolved with skeletal structures for running and stability. Their limbs play a critical role in balance and navigation, with muscles and joints working harmoniously to stabilize the body, particularly during directional changes or running at high speeds. Muscles such as digital flexors and extensors contribute significantly to propulsion, providing strength and flexibility during movement cycles [2]. Figure 1(a) shows a dog's swing and stance phase during walking.



(a)

(b)

Figure 1: Illustrations of bio-inspired bipedal mechanisms: (a) Comparative anatomy of human and ostrich bipedal walking structures; (b) Walking gait pattern of an ostrich.

Ostriches exhibit a variety of gaits that adapt to different speeds and terrains. These gaits consist of walking, running, and hopping. Each gait involves a unique sequence of limb movements, impacting speed, posture, and stability. Figure 1(b) shows the walking gait of an ostrich. For example, in the running gait with moments of suspension—muscles stretch and contract eccentrically to store elastic energy, which enhances speed and reduces fatigue during sprinting [3]. Understanding these natural gaits shows how ostriches can move efficiently and quickly irrespective of terrain topography.

Inspired by these biomechanics principles, researchers have been developing bipedal robots capable of imitating the natural gaits. These robots use sophisticated control algorithms to replicate the alternating and synchronous gait patterns found in animals. Such designs enhance mobility, making them suitable for rescue missions or autonomous exploration applications. Researchers developed walking algorithms for different requirements of inclination and topography of the terrain and tested them in physics-based simulators and on the physical robot, which showed promising performance [4] [5].

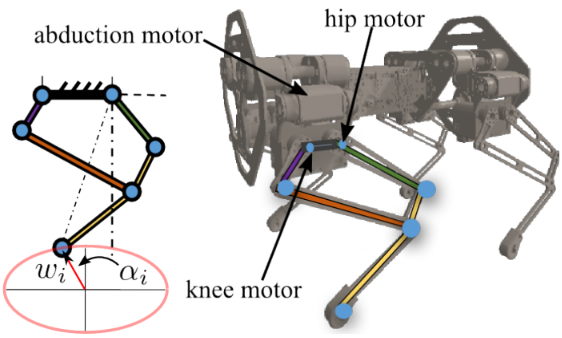


Figure 2: A five-bar mechanism is used as the legs of the quadruped robot. This mechanism is actuated by the motors located at the main torso of the robot [6]

This project is based on the design explored in [6], where rigid links were used to form a five-bar mechanism, as shown in Figure 2. Using reinforcement learning, libraries of walking trajectories were generated to deploy onto the physical robot; these libraries included different gaits, including trot, side-step, etc. While this robot is made using rigid links, our project focuses on leveraging the concept of using a foldable mechanism to form limbs of the biped using the five-bar mechanism; this offers greater adaptability and compliance, allowing it to absorb shocks and adjust dynamically to uneven terrain, unlike rigid-link designs that can transmit high-impact forces directly to joints. This flexibility enhances energy efficiency and stability, especially in complex environments, by mimicking the natural elasticity found in animal limbs.

Goal Performance Metrics

The primary objective of this research is to conduct a systematic analysis and characterization of gait patterns in quadruped robots, focusing on walking and galloping behaviors. The study aims to understand how specific morphological features, such as knee length and foot geometry, influence the robot's overall speed, stability, and energy efficiency performance. A comprehensive set of performance metrics has been defined to achieve this, encompassing kinematic, dynamic, and contact-based parameters. These metrics will be assessed through simulations using MuJoCo, with validation via precise tracking of link positions of the hardware prototype. The following sections elaborate on the specific goals and associated performance metrics.

1. Locomotion Performance

1.1. Maximum Forward Walking Speed

Maximum forward walking speed represents the highest achievable velocity during stable locomotion. In a 5-bar linkage mechanism, this is fundamentally limited by actuator capabilities, link lengths, and inertial properties [7]. The maximum achievable forward velocity is primarily determined by:

$$v_{max} = f(P, l, \theta_{max}, m(x)) \tag{1}$$

where:

- P = actuator power output
- l = characteristic leg length
- θ_{max} = joint range limits
- $m(x)$ = mass distribution function

1.2 Cost of Transport (CoT)

CoT measures the energy efficiency of locomotion, which is particularly important for battery-powered robots. For 5-bar linkages, this metric is heavily influenced by the mechanical design and actuation strategy [8]. Energy efficiency metric defined as:

$$\text{CoT} = \frac{E}{mgd} \tag{2}$$

where:

- E = total energy consumed
- m = robot mass
- g = gravitational acceleration
- d = distance traveled

2. Control System Performance

2.1 Joint Position Accuracy

Position accuracy determines the precision of foot placement and overall motion control. In 5-bar linkages, this is complicated by the coupled nature of the parallel mechanism [9]. Position error is defined as:

$$\epsilon_{pos} = f(\text{sensor resolution}, \text{backlash}, \text{rigidity}) \tag{3}$$

3. Payload Performance

3.1 Maximum Payload Capacity

Payload capacity defines the maximum additional mass the robot can carry while maintaining stability and performance [10]. This is particularly important for service robots or industrial applications. Load carrying capability:

$$m_{payload} = f(\tau_{max}, \text{structural strength}) \tag{4}$$

Subject to stability constraint:

$$\text{CoM}_{total} \in \text{support polygon} \tag{5}$$

3.2 Stability Impact

Stability metrics ensure the robot maintains balance during locomotion and load carrying. The ZMP criterion is particularly important for dynamic stability [11]. Payload-dependent stability metric:

$$S_{payload} = f(A_{foot}, m(x), \text{CoM}_{height}) \tag{6}$$

where A_{foot} represents foot contact area.

These performance metrics and their impact on the design of the bipedal robot are described in Table 1

Performance Metric	**Design Constraints**
1. Locomotion Performance	
Maximum Forward Walking Speed	• Actuator torque-speed characteristics • Link length ratios (L_1/L_2, L_3/L_4) • Maximum joint angular velocities • Mechanical transmission limits
Cost of Transport (CoT)	• Motor efficiency curves • Transmission efficiency • Link mass distribution • Joint friction characteristics
2. Control System Performance	
Joint Position Accuracy	• Encoder resolution • Mechanical backlash • Link/joint stiffness • Controller bandwidth
3. Payload Performance	
Maximum Payload Capacity	• Maximum actuator torque • Structural strength of links • Joint bearing load ratings • Static/dynamic stability margins
Stability Impact	• Foot contact area • Center of mass location • Ground reaction force limits • ZMP constraints

Table 1: Performance Metrics and Design Constraints for 5-Bar Linkage Bipedal Robot

Specifications Table

Parameter	Value	Unit	Reference
Locomotion Performance			
Maximum Walking Speed	1.5	m/s	[7]
Cost of Transport	0.2	dimensionless	[8]
Link Length Ratio (L_1/L_2)	1.2	dimensionless	[12]
Control System			
Joint Position Accuracy	0.01	rad	[9]
Payload Performance			
Maximum Payload	0.1	kg	[10]
Maximum Actuator Torque	0.1765	N m	Design spec
Link Mass (per leg)	0.05	kg	Design spec
Foot Contact Area	0.002	m^2	Design spec
Ground Clearance	0.05	m	Design spec

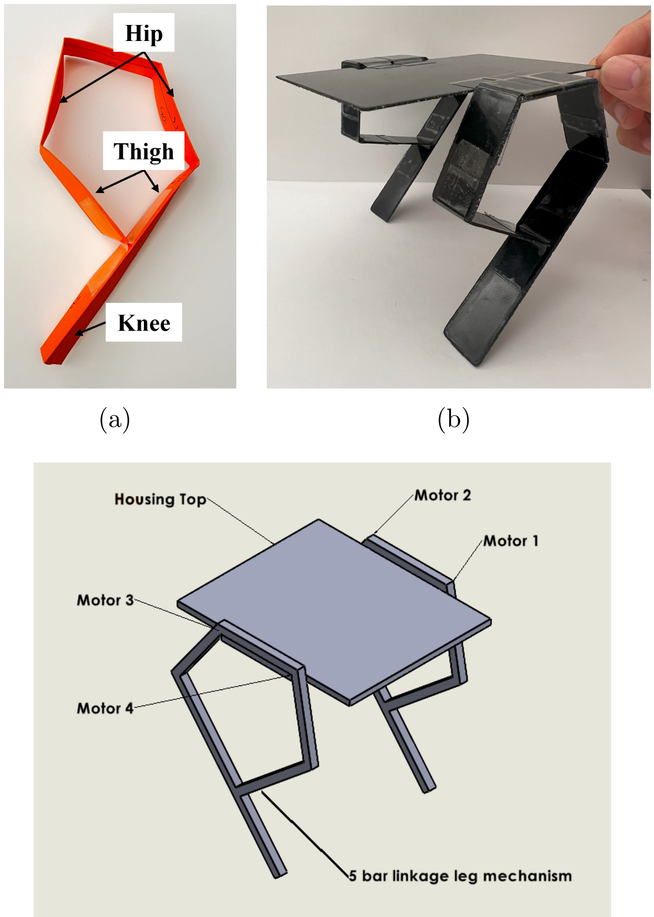
Table 2: Specifications Table for 5-Bar Linkage Bipedal Robot

Develop an analogous mechanism

The diagram illustrates a bipedal gait bio-mimicry system's left and right leg mechanisms. Being a 5 bar linkage mechanism, each leg consists of interconnected joints and links (labeled $l_1, l_2, \ldots, l_5$) with various points of rotation ($P_0, P_1, P_2, P_{00}, P_{11}, P_{22}$, etc.) and orientation vectors. These components are organized to simulate natural gait dynamics, with angles ($\Theta_1, \Theta_2, \ldots$) representing joint movements. The foldable aspect allows the leg to compactly retract, contributing to efficient energy usage and realistic movement.

The mechanism operates under specific angle constraints that are critical for achieving realistic and efficient motion. Each joint angle, denoted as $\Theta_1, \Theta_2, \Theta_3, \Theta_4$, is constrained within a predefined range to mimic the natural motion of bird legs. These constraints ensure that the legs move within permissible limits to prevent excessive bending, thereby maintaining the stability and balance of the mechanism during gait cycles.

These angle constraints are optimized to synchronize the movement of both the left and right legs, allowing for an alternating pattern that promotes a balanced, efficient, and bird-like gait. Moreover, the constraints also help in energy conservation by preventing excessive movements, enhancing the mechanism's overall efficiency.



(a) (b)

(c)

Figure 3: Proposed hardware prototype model of the bipedal robot; (a) A paper-based model ; (b) Hardware Model made from Fiberglass Sheet (c) CAD Representation of the Bipedal Robot .

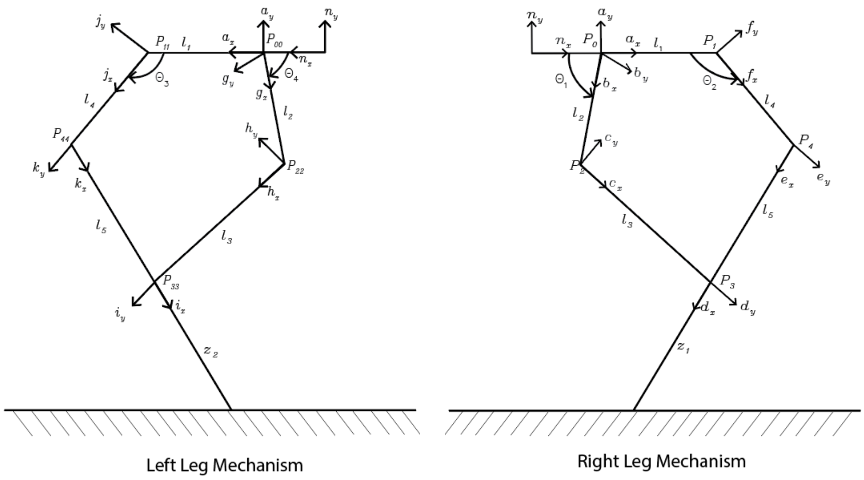


Figure 4: Vector Drawing

System Identification

1. Actuator Parameters

- Motor resistance: measured directly with a multimeter
- Motor inductance: measured with RLC meter
- Rotor inertia: derived from step response
- Gear ratio efficiency: from the input-output power measurement

2. Mass and Inertia Properties

- Link masses: direct measurement of fabricated parts
- Center of mass locations: balancing test for each link
- Combined leg inertia: using swing test of assembled leg

3. Stiffness and Damping Characteristics

- Joint stiffness: force-deflection measurements
- Link structural stiffness: static loading test
- Link material damping: impact response test

4. Experimental Methods

4.1 Motor Characterization

- Setup: Motor test bench with torque sensor and encoder
- Measurements: Current, voltage, position, velocity
- Equipment: Power supply, DAQ, oscilloscope

4.2. Link Properties

- Setup: Precision scale, pendulum test rig
- Measurements: Mass, period of oscillation
- Equipment: High-speed camera

4.3. Simulation Verification

- Setup: Gait testing on hardware
- Measurements: Mass, walking speed, joint trajectory
- Equipment: MuJoCo

4.4. Model Verification

- Setup: Gait testing on hardware
- Measurements: Mass, walking speed, joint trajectory
- Equipment: High-speed camera, markerless-tracking software

Experiment	**Jahnav**	**Kunal**	**Nihar**
Motor Characterization & System Integration	X		
Link Stiffness & Simulation Verification		X	
Hardware Verification & Simulation Comparision			X

Table 3: System Identification Experiments and Team Assignment

Project Part 2 Roadmap

This project requires multi-level planning and execution, which includes a material selection for joints and links, estimates for approximate lengths, prototyping multiple iterations of joint mechanisms, kinematic analysis, simulation using MuJoCo, implementing servo motors, and controlling the robot using microcontroller, collecting data for further analysis. The project roadmap is as follows:

Materials: Legs hold the weight of the robot and all its components while giving mobility, the structural rigidity of the links and joint play a crucial role. Fiberglass is a structurally rigid material which is still flexible to give a natural compliance to the leg, a very thin (0.5 mm) fiber glass sheet is used to make links while a plastic adhesive tape is used to connect the links and form a joint as shown in previous section. Servo motors will be housed on the top of robot using a 3D printed housing that can hold the motor in place, micro controller and power supply are to be placed off board to minimize the load on the legs for the robot.

One person from the team takes care of prototyping multiple iterations of the robot with different joint parameters until the optimized design is achieved. The body will be kept modular to accommodate multiple iterations of legs with varying parameters and end effector geometries, which is crucial to maintaining enough contact with the ground to leverage friction and move forward or backward.

System data can be analyzed by tracking the motion of the joints, this can be done by taking a video of the joints moving with a given input signal to the servo motors and then further using a Tracker software to plot the mechanism while performing multiple gaits. This can further be validated by simulating the same mechanism in MuJoCo. The performance metrics as specified above (stride length, stride frequency, linear speed and trajectory tracking) can be analyzed using the robot's position tracked from the video. These data points can be visualized using either MATLAB or Python.

Simulation can be done in multiple parts, which include writing the code to define the model and set up the robot, defining the parameters and setting up the experiments, data collection, and model fitting and validating with the experimental data. One of the team mates focuses on writing the code while the others focus on the protocol and parameters of the study, data analysis is planned to be done by everyone post collection to keep everyone in the loop about the final results.

The collected data can be used to make plots that show statistical significance over different gaits and experimental studies; all of these plots and relevant images can be used to make a detailed report along with a folder that contains the simulation and data processing codes and files, all of these can be submitted the end of the semester.

References

[1] A. Abourachid and V. Hugel, "The natural bipeds, birds and humans: An inspiration for bipedal robots," in *Biomimetic and Biohybrid Systems: 5th International Conference, Living Machines 2016, Edinburgh, UK, July 19-22, 2016. Proceedings 5*. Springer, 2016, pp. 3–15.

[2] J. Rubenson, D. B. Heliams, D. G. Lloyd, and P. A. Fournier, "Gait selection in the ostrich: mechanical and metabolic characteristics of walking and running with and without an aerial phase," *Proceedings of the Royal Society of London. Series B: Biological Sciences*, vol. 271, no. 1543, pp. 1091–1099, 2004.

[3] Drama and A. Badri-Spröwitz, "Trunk pitch oscillations for energy trade-offs in bipedal running birds and robots," *Bioinspiration Biomimetics*, vol. 15, no. 3, p. 036013, Mar. 2020. [Online]. Available: https://iopscience.iop.org/article/10.1088/1748-3190/ab7570

[4] M. A. Daley *et al.*, "Running birds, humans and robots: Principles of leg control for robustly stable and agile bipedal locomotion," in *9 International Symposium on Adaptive Motion of Animals and Machines (AMAM 2019)*, 2019.

[5] J. Pratt and B. Krupp, "Design of a bipedal walking robot," in *Unmanned systems technology X*, vol. 6962. SPIE, 2008, pp. 480–492.

[6] S. Tirumala, A. Sagi, K. Paigwar, A. Joglekar, S. Bhatnagar, A. Ghosal, B. Amrutur, and S. Kolathaya, "Gait library synthesis for quadruped robots via augmented random search," *arXiv preprint arXiv:1912.12907*, 2019.

[7] C. Zhou *et al.*, "Dynamic locomotion control for 5-bar linkage bipedal robots," *IEEE Robotics and Automation Letters*, 2020.

[8] S. Rezazadeh *et al.*, "Energy efficient control of 5-bar bipedal robots," in *Proceedings of the International Conference on Intelligent Robots and Systems (IROS)*, 2018.

[9] S. Kuindersma *et al.*, "Optimization-based locomotion planning for bipedal robots," *Autonomous Robots*, 2016.

[10] H. Park *et al.*, "Load capacity analysis of parallel linkage mechanisms," *Mechanism and Machine Theory*, 2021.

[11] M. Vukobratović *et al.*, "Zero-moment point—thirty five years of its life," *International Journal of Humanoid Robotics*, 2004.

[12] J. Liu *et al.*, "Workspace analysis and optimization of a 5-bar linkage for bipedal robots," *Mechanism and Machine Theory*, 2021.