Design and Development of a 10-DoF Humanoid Lower Body System Using Proximal Actuation and Transmission Mechanisms

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***Abstract*— This paper presents a 10-DoF bipedal robot with proximal actuation for lightweight and low-inertia leg dynamics. Unlike conventional designs with joint-mounted actuators, our approach places actuators near the torso to reduce mass and inertia. The robot uses low gear ratio Quasi-Direct Drive (QDD) actuators, transmitting power via a timing belt at the knee and a four-bar linkage at the ankle. The robot's mass is distributed such that both weight and rotational inertia decrease toward the end of the leg, improving responsiveness and control stability. Experimental evaluation showed a knee RMSE of 0.0048 rad, confirming the accuracy of the belt-driven transmission. In addition, simulation results demonstrated that joint torques during 0.4 m/s walking remained within actuator limits. Future work includes hardware walking experiments and integration of an upper body to complete the humanoid platform.**

I. INTRODUCTION

Humanoid robots are gaining attention as general-purpose automation platforms due to their human-like morphology, which allows direct deployment in human-designed environments. They are studied for applications such as logistics, manufacturing, and domestic tasks, where physical interaction and adaptability are essential [1]. However, achieving human-like dynamic performance requires fast and stable motion, which poses challenges in mechanical design and control. Most humanoid lower limbs mount actuators directly at the joints, concentrating mass and inertia in the legs. This degrades control responsiveness, limits backdrivability, and increases susceptibility to impacts [2]. High gear ratio transmissions are often used to compensate for limited actuator torque, but they amplify reflected inertia and reduce mechanical transparency [3], [4].

To address these limitations, we propose a bipedal robot with proximal actuation, placing high-torque, low gear ratio Quasi-Direct Drive (QDD) actuators near the torso. This physically separates the heavy actuators from the distal links, reducing leg inertia. Power is transmitted via a timing belt at the knee and a four-bar linkage at the ankle. As shown in Fig. 1, this configuration enhances impact resilience and energy efficiency while supporting lightweight, high-performance locomotion with simple sensing and control.

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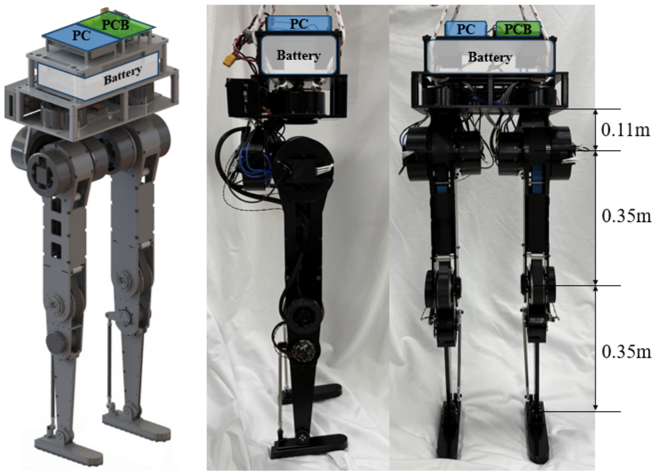

Fig. 1. Overview of the proposed bipedal robot: CAD model and fabricated hardware.

II. HARDWARE DESIGN

A. Mechanical Design of the Leg

The proposed robot is designed for locomotion in adult-sized environments, with a target height of approximately 1.6 m. Each leg has a length of about 0.9 m. As illustrated in Fig. 2(a), each leg has 5 degrees of freedom (DoF), including three rotational DoFs at the hip (yaw, roll, and pitch), and one pitch DoF at the knee and ankle. Considering that actuator mass dominates the leg's total mass, the ankle roll function is omitted and compensated by the hip roll, enabling a lighter 5-DoF configuration.

To reduce inertia and mass, actuators are placed proximally near the torso. As shown in Fig. 2(b), the actuators for the hip and knee are located at the upper thigh, while the ankle actuator is positioned just below the knee. This proximal arrangement reduces mass at the distal segments and inertia, thereby enhancing control responsiveness and energy efficiency.

To implement this configuration, transmission mechanisms were designed, as shown in Fig. 2(c). A 1.5:1 timing belt is applied at the knee to meet high torque requirements. To accommodate periodic tension variations during motion, two pairs of fixed and adjustable tensioners are placed near the input and output pulleys, ensuring consistent torque transmission without slack or slippage. For the ankle, which is particularly susceptible to external impacts, a four-bar linkage is used to provide stable 1:1 torque transmission.

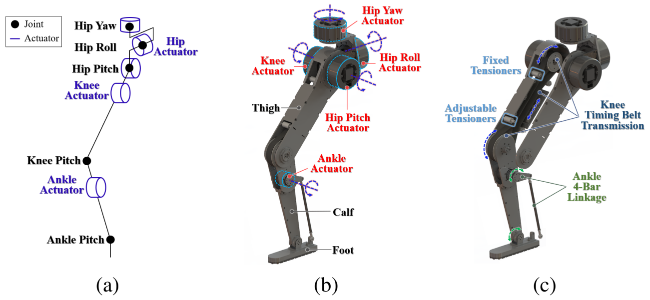

Fig. 2. Leg configuration and transmission mechanisms: (a) Kinematic structure and joint arrangement, (b) Proximal actuator placement, (c) Knee timing belt and ankle four-bar linkage transmission design.

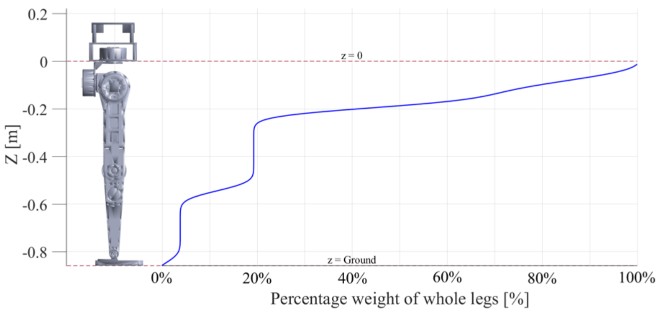

Fig. 3. Mass distribution of the lower body from ground, illustrating the concentration of total leg mass near the torso to reduce inertia.

B. Hardware System Architecture

The robot employs Quasi-Direct Drive (QDD) actuators with high torque and a low gear ratio. By minimizing inertia and backlash typically introduced by gear reducers, QDD actuators offer superior transmission characteristics, high control bandwidth, and enhanced impact resilience. This approach enables precise torque control and improved backdrivability, which are essential for dynamic legged locomotion. In this study, a custom-designed QDD actuator was developed using a single-stage planetary gear system, achieving a 10:1 reduction ratio and a maximum torque of 120 Nm. A lightweight variant was also developed for the ankle joint, considering its lower torque demand.

For precise real-time joint torque control, an EtherCAT-based communication system is implemented, operating at a 1 kHz control loop. All motor drivers are configured as EtherCAT slaves, with a dedicated real-time control PC functioning as the master. An IMU is mounted as close as possible to the torso's center of mass to minimize rotational acceleration effects and enhance state estimation accuracy. Power and signal distribution are handled by a custom-designed PCB, which provides stable supply to all actuators and sensors. Based on this architecture, a complete low-level controller was developed to manage real-time communication and motor control.

III. DESIGN AND EXPERIMENTAL RESULTS

The robot was designed to weigh 31.6 kg including the torso, with a total height of 1.1 m. A single manufactured leg weighs 9.5 kg, which is lighter than those of most existing humanoid lower limbs. As illustrated in Fig. 3, the cumulative mass distribution shows a strong proximal concentration, with inertia rapidly decreasing toward the distal end.

TABLE I

JOINT SPECIFICATIONS

Joint	Range of Motion (°)	Max. Torque (Nm)	Req. Torque (Nm)
Hip Yaw	[–80, 80]	120	12.90
Hip Roll	[–35, 30]	120	51.70
Hip Pitch	[–120, 10]	120	61.73
Knee Pitch	[–120, 120]	180	99.01
Ankle Pitch	[–45, 45]	34	19.29

Table I summarizes the joint range of motion (RoM). All joints were designed to cover the typical human RoM, enabling natural and agile leg movements. Using the designed robot model, whole-body control was applied in Gazebo simulation. When walking at a target velocity of 0.4 m/s, the required torques per joint remained within the specified maximum torques, as shown in Table I, confirming the adequacy of the actuator design for dynamic walking.

After manufacturing the physical robot, we evaluated positional deviation in the transmission to assess control accuracy. The knee actuator was driven with a sinusoidal target position input of 0.2 rad amplitude and 0.5 s period for 5 min, while a rotary encoder mounted externally at the knee joint was used to record the joint position. The difference between the actuator position and the joint encoder reading was then analyzed. A belt drive with dual tensioners was employed to ensure consistent torque transfer and eliminate slack. As a result, the RMSE was measured to be 0.0048 rad, verifying that the mechanical design effectively minimizes backlash and supports precise joint motion.

IV. CONCLUSIONS

This paper presented the design and implementation of a 10-DoF bipedal robot with proximally placed QDD actuators, a timing belt at the knee, and a four-bar linkage at the ankle, reducing leg inertia and enhancing impact robustness.

Simulations verified that joint torques stayed within actuator limits during walking. The complete system was built and tested, and the experiments showed minimal transmission error. Future work includes integration with an upper body and validating real-world walking.

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