Crutches-Like Bipedal Walker with a Reduced Number of Actuators

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***Abstract*—This paper presents the design and implementation of a compact biped robot inspired by rehabilitative exoskeletons equipped with robotic crutches. The proposed system adapts the compass-like biped concept for practical real-world applications while requiring only three actuators. The robot is capable of performing both straight-line walking and steering manoeuvrers. The mechanical design emphasizes cost-efficiency and simplicity, leveraging the unactuated crutches to provide stability during locomotion, reduce load on the actuated leg. Experimental results validate the robot's ability to navigate indoor environments with flat and regular surfaces, showcasing the practicality and robustness of the proposed approach.**

I. INTRODUCTION

Small bipedal robots can navigate narrow spaces with simpler mechanical designs than their quadruped and hexapod counterparts. This inherent simplicity makes them strong candidates for exploration missions in tight environments that wheeled systems cannot traverse. However, bipedal robots face the dual challenge of maintaining stability and ensuring effective and efficient motion control. These challenges are further exacerbated by the miniaturization of components, as reduced size limits the available space for the actuators required for fundamental locomotion tasks such as turning.

The *compass-like biped robot* proposed in [1], [2] serves as a template model for studying the fundamental characteristics of human locomotion. One of its most valuable features is its ability to achieve a highly human-like walking pattern without external actuation, relying solely on gravity for propulsion. This makes it a promising reference model for the development of miniaturized biped robots with a reduced number of actuated degrees of freedom (DoFs). In the field of gait generation and locomotion control, the compass-like biped has also been utilised as the reference model for energy-based periodic locomotion control strategies [3]–[5]. However, it remains primarily a conceptual model, as practical implementation is constrained by issues such as scuffing between the swing leg and the ground. Addressing this limitation necessitates more complex kinematic structures that include additional joints [2]. Furthermore, the compass-like biped is intrinsically restricted to periodic walking on straight paths, which limits its applicability for real-world robotic systems.

This paper introduces a *crutches-like biped robot* capable of walking straight and steering, adapting the compass-like concept for practical use on real-world planar surfaces. Drawing inspiration from [6]–[8], where robotic crutches were employed in upper-limb exoskeletons to reduce the effort required for upright stabilization and alleviate upper extremity loads, the proposed design repurposes crutches as external legs. These crutches provide stability during both static and swing phases, mimic the stance leg of a compass-like robot, and reduce the load carried by the inner leg, where all the actuators are housed. Furthermore, the crutches are not actuated, delivering all these benefits without the need for additional actuators. This design offers benefits from two distinct perspectives. From the standpoint of legged robotics, the crutches assist in stabilizing the robot's center of mass (CoM) and alleviate the load on the inner leg, which mirrors the kinematics of a single human leg, thus reducing energy consumption. From the perspective of upper-limb exoskeletons, this innovative approach could inspire new systems that provide enhanced support for individuals with motor impairments, improving mobility and minimising physical strain.

The contributions of this paper can be summarized as follows: (i) the design and development of a novel compact biped robot featuring a crutches-like mechanism, drawing inspiration from the domain of rehabilitative exoskeletons, and (ii) the implementation of a simplified actuation system utilizing only three actuators, demonstrating a low-degree-of-freedom design with high functional adaptability.

The rest of the paper is organized as follows. Section II provides a literature review on compact biped robots. Section III presents the main contributions of the paper, including the innovative mechanical structure and the proposed locomotion strategy. Section IV evaluates the effectiveness of the robot through three case studies of locomotion on flat terrain. Finally, Section V discusses the findings and outlines directions for future research.

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II. STATE OF THE ART

Research on small-scale biped robots has garnered increasing interest in recent years. A robot walker featuring a novel single-DoF six-bar leg mechanism enabling rectilinear, non-rotating foot movement was presented in [9]. This design, in particular the presence of lateral legs, ensure static stability and requires only two actuators, one for each side, to achieve effective walking on flat surfaces. This robot was then deployed in [10] as a starting point for a small walker able to transverse up and down slopes and gaps. The walker was created by connecting two modules of the walker presented in [9] in series. Every pair of legs (inner-external), is actuated by one stepper motor through a single-DoF ten-bar linkage thus resulting in a four-DoF walker. Despite the total weight reduction and the control design simplification led by the limited number of actuators, relying on complex articulated legs requires predetermined footpaths, shrinking the system's versatility.

Research on compact bipeds often leverages passive walking principles to reduce actuator and controller loads, addressing space and power constraints. This concept, originating from McGeer's work in [2], demonstrated stable gait on slopes without actuation or control. However, passive-dynamic walkers need gravity and inclined surfaces. To address this, Collins introduced bipedal robots with two actuators for level ground walking in [11], blending passive walking with some actuation. A significant achievement in this field is the Cornell Ranger, which completed a 40.5-mile ultra-marathon on a single charge, thanks to its lightweight body, low-inertia leg design, steering mechanism, and model-based control approach. Building on passive walking principles, a small quasi-passive walker with 15 cm legs, two actuators, and spherical feet was proposed in [12], capable of walking and turning using open-loop sinusoidal profiles. This design was further refined in [13], where the Mugatu robot uses a single hip actuator to walk straight and steer by varying its turning radius. As for the STAR robot [9], this minimal actuation reduces drastically the mobility and dexterity of the robot.

An essential consideration for the design of the robot's structure is the number of legs it should have. Literature includes various bipedal robot configurations with differing numbers of legs; for instance, prototypes in [1], [2], [11], as well as the Cornell's Ranger presented in [14], feature four legs: two inner legs and two outer legs that act as lateral supports. This choice influences the system's overall degrees of freedom. For instance, a leg can be fitted with either passive or active joints, depending on the number of actuators available. Furthermore, the robots presented in [1], [2], [11] are restricted to walking straight along their sagittal plane, exhibiting limited mobility. In contrast, the Cornell Ranger is capable of making turns.

A significant challenge for bipedal robots during locomotion is the issue of ground contact during the swing phase. The robot must avoid scuffing the ground while moving its legs to ensure a smooth gait. This is achieved through the exploitation of knee joints and dedicated feet design in [1], [2], [11] or using tendon-driven feet in [14].

III. CRUTCHES-LIKE BIPEDAL ROBOT

A. *Kinematic Structure*

The biped robot proposed in this paper is designed to easily transverse indoor environments. From this perspective, the following design guidelines have driven the mechanical design: *i)* the robot must be easy to control; *ii)* the robot must be able to walk stably straight and curve, even in the presence of small disturbances accountable to local terrain deformations or dynamic friction variations; *iii)* the robot must be energetically efficient. To meet design requirements, the structure incorporates: *i)* two firmly connected external legs, which serve as lateral supports, which function as crutches, helping the robot improve stability and reduce load on the internal leg during swing motions; *ii)* an internal leg powered by three motors, placed in the hip, knee, and ankle joints, respectively, that, similarly to the exoskeletons proposed in [8], [10], mimics the role of a nonimpaired leg in disabled patients, fully managing the swing motion.

The final design consists of an internal, actuated leg, and a crutches-like, lateral support. The three motors in the internal leg provide as many degrees of freedom (DoFs), that is, hip flexion/extension, knee flexion/extension, and ankle abduction/adduction.

B. *Mechanical Design*

A key design principle was to minimise overall costs by utilising existing materials and avoiding the purchase of additional components. Smaller components, such as those used to connect the various links, were modelled and 3D-printed.

1) Feet Design: The crutches must ensure that the structure remains statically balanced during the swing phase of the internal leg. The foot's surface should be longer in the sagittal plane, aligning with the robot's walking direction. However, the foot does not need to be wide, as the two lateral supports always work together to provide stability. The contact surface with the ground measures approximately 13 cm in length and 5 cm in width.

A similar approach applies to the internal foot. However, unlike the crutches, the internal foot must be wider since it is the only point of contact during the swing phase of the lateral supports. Therefore, the internal support must prevent both rolling and pitching movements.

2) Legs Design: The crutches were designed using two simple square aluminium tubes with external dimensions of 10×10 mm, internal dimensions of 8×8 mm, and a length of 270 mm. Each crutch is connected to the external foot on one end and, via a PLA 3D-printed hook, to a 10 mm-diameter aluminium shaft that rigidly binds them together, as can be seen from Fig 1.

To ensure the smooth walking of the robot and prevent it from dragging and scuffing on the ground during the swing phase, the structure of the internal leg features: *i)* a link connected to the first motor, simulating the function of the

(a) Three-quarter view. (b) Front view.

Fig. 1. CAD prototypes of the external support legs with feet.

(a) HEBI X5-4. (b) DYNAMIXEL MX-28AT.

Fig. 2. Actuators deployed in the inner leg.

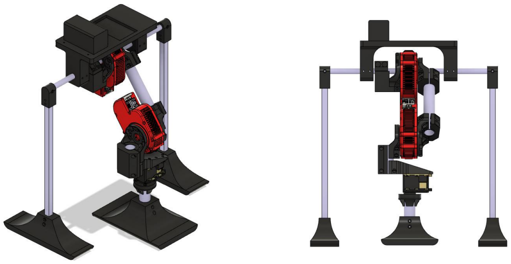
femur (thigh), with the first motor actuating the hip joint; *ii)* a link connected to the second motor, which is rigidly attached to the first link, simulating the function of the tibia (shin), with the second motor actuating the knee joint; *iii)* a link connected to the third motor, which is rigidly attached to the second link, simulating the function of the ankle, with the third motor actuating the ankle joint. The internal leg serves as both the housing for the motors and the primary body of the structure. Consequently, its total height exceeds that of the lateral supports. The leg was designed to be as symmetrical as possible to ensure the structure remains statically balanced, as this part carries most of the robot's weight.

The actuators consist of two HEBI X5-4 motors for the hip and knee joints, along with a DYNAMIXEL MX-28AT motor for the ankle joint, see Fig. 2. The HEBI X5-4 motors can provide a torque of 4 Nm, with the potential for higher torque outputs at reduced rotational speeds, depending on the supply voltage. Therefore, it is essential to consider the robot's maximum weight, as the motors must generate enough torque at the leg joints during the swing phase to counteract gravity and ensure the robot's stability.

The final CAD model, comprised of crutches and internal leg, motors, and feet is depicted in Fig. 3. The robot measures, in the shown position, $40x37 * 27$ cm, while with its internal leg fully extended vertically it reaches $42.5x37.5x18$ cm.

C. Locomotion Strategy

In this work, the desired kinematic path is provided as open-loop actuation position inputs at the joint level, similar to its use in controlling rehabilitative exoskeletons with robotic crutches [8]. The trajectory of the two flexion/extension actuators was designed and manually reproduced on the robot, with positions recorded at a sampling frequency of 100 Hz.



(a) Three-quarter view. (b) Front view.

Fig. 3. CAD prototypes of the complete structure.

The trajectory has two phases based on ground contact. When the foot is in contact and the crutches are not, the body moves forward. When the crutches are in contact and the foot is not, the foot moves forward. The gait is periodic. During both phases, the leg passes through a singularity where the upper and lower leg links align. This singularity does not present an issue in this context, as operations are conducted directly in joint space. It allows two movement strategies: traversing it before moving the foot forward or encountering it after the foot is brought forward and bent. The latter was chosen to avoid a significant shift in the center of mass. In the first scenario, there's a high risk of falling backward, making recovery difficult. In the second scenario, a forward loss of balance is more manageable, as repositioning the foot typically restores stability.

The recorded trajectory, which can be seen in Figure 4 takes 20 seconds to complete, which is considered excessively slow. To address this, the trajectory is scaled to achieve faster execution. Various scaling factors were tested, identifying a maximum factor of 5 (resulting in a duration of $4\,\mathrm{s}$). Scaling beyond this value leads to significant instability and actuator limitations. A scaling factor of 2 was selected as an optimal compromise, balancing reliability, velocity, and stability. The ankle joint, whose position was not recorded, enables the yaw of the robot to be adjusted when actuated at a specific point in the trajectory. This occurs when the foot is in contact with the ground, and the crutches are sufficiently distant from it. This adjustment can address two specific issues: executing curved trajectories in the 2D plane and compensating for yaw disturbances.

IV. EXPERIMENTAL RESULTS

To evaluate the performance of the proposed robotic platform, three case studies were conducted[1]: straight walking with yaw drift compensation (CS1), straight walking with compensation for exogenous disturbances (CS2), and curve walking (CS3).

A. CS1 - Case study 1

In this case study, the robot is commanded to move straight forward, with the ankle joint being actuated so that it constantly keeps the central position. This is then tested in two

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[1] https://youtu.be/WY6R3MiEIxY

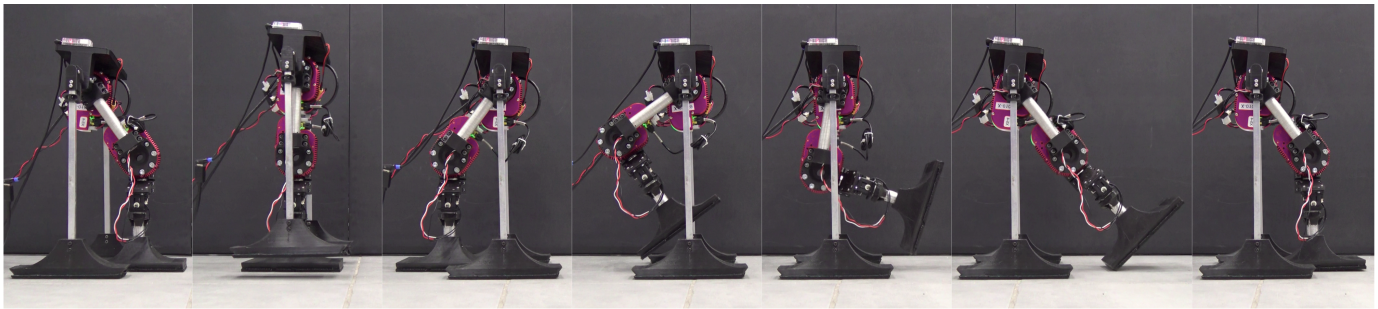

Fig. 4. Recorded locomotion path for the proposed robotic structure; movement is from the left to the right.

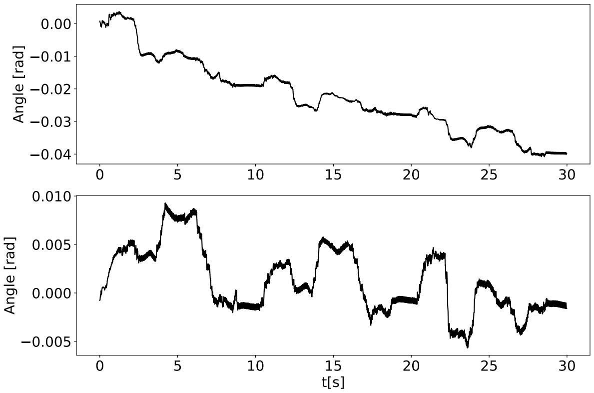

Fig. 5. CS1 - Comparison between the yaw of the robot's base (expressed in radians) with respect to the initial conditions in the case of pure feed-forward control (on the top) and the yaw drift compensation (on the bottom).

cases, both with and without yaw drift compensation, which is measured via onboard accelerometer and gyroscope data filtered via a Madgwick filter [15]. The resulting yaw values are shown in Figure 5. It is clear that, with the absence of the compensation, the robot is subject to a constant drift, while with the compensation the drift is reduced drastically, as the yaw deviation is reduced by an order of magnitude. Moreover, the joint position tracking error shows the periodicity of the movement, with the peaks in error corresponding to the rising of the crutches and of the foot, respectively.

B. *CS2 - Case study 2*

In this case study, the robot is commanded to move straight forward, as in the previous case study, but it is tested only with the yaw drift compensation: during the test, exogenous disturbances are applied to rotate the robot from its straight path, like unexpected pushes or irregularities in the terrain, which cause unexpected rotations of the structure. As can be seen from Figure 7 and from the video, when the robot is significantly rotated from its straight orientation, at the next step the orientation is immediately recovered, even if it is rotated so that it faces backward. However, the actual direction may become imprecise after many rotations or a big and fast rotation.

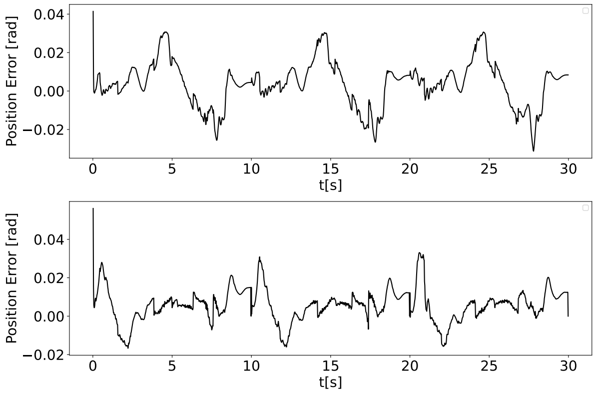

Fig. 6. CS1 - Error between the joint reference values and the actual joint position, recorded during the yaw drift compensation. On the top, the error for the hip motor, fixed onto the floating base, while on the bottom the error for the knee motor.

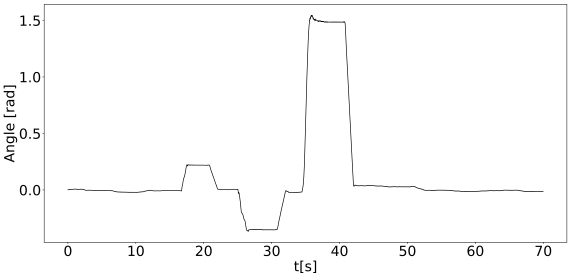

Fig. 7. CS2 - Yaw of the robot's base with respect to the initial conditions when subject to external disturbances. Recovery from $30°$, $-45°$, and $180°$, approximately, can be seen in the first, second, and third spikes, respectively.

C. *CS3 - Case study 3*

In this case study, the robot is commanded to move along a quarter circular curve with a specified radius of $60\,\mathrm{cm}$, rotating by $90°$, and then moving straight for a while. During this, the yaw compensation is active, so if the robot is disturbed, it can easily recover. As can be seen in Figure 8, the robot follows the path, reaching after six steps the end of the curve. After this, it keeps following a straight path, without deviating from its desired direction.

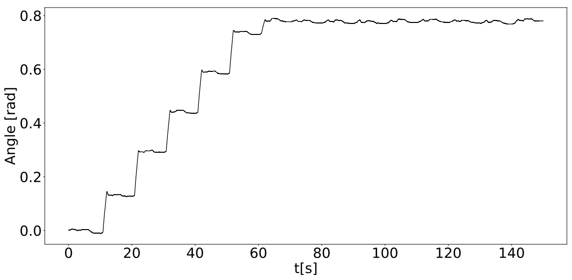

Fig. 8. CS3 - Yaw of the robot's base with respect to the initial conditions during the tracking of the curved path. After a first, straight step, the robot curves at a constant rate each step, accounting for the assigned radius of the curve, until it reaches the desired angle.

D. Discussion

The mechanical structure of the robot demonstrates that, even with a minimal number of DoFs, it can effectively traverse 2D space. This minimalist design contributes to a low Cost of Transport (CoT) of 0.584. Recall that the cost of transport can be defined as the ratio between the total energy expended by the motors and the product between the total weight and the total distance $CoT = \frac{E}{mgd}$, and is an index of the efficiency of locomotion [16]. This results significantly lower compared to [13], but almost three times higher than [14], which however plans locomotion by optimizing CoT.

As discussed in III-C, the robot's sagittal movement (*i.e.*, the two flexion/extension joints) and its angular movement around the vertical axis operate independently. However, in the absence of feedback, mechanical uncertainties cause the robot to deviate from its intended path. Notably, the ankle actuation system effectively compensates for yaw errors and enables the robot to follow curved trajectories. However, given the incapability of the robot to sense absolute orientation, it is possible for the robot to follow a wrong path, which could be fixed with the addition of magnetometer data to the Madgwick filter.

V. Conclusions and Future Works

This paper presents a compact biped robot capable of performing 2D locomotion on flat surfaces. The innovative design leverages external legs as a pair of crutches to enhance stability and efficiency during walking.

A promising direction for future research is to make the biped untethered, enabling it to carry its energy source while performing locomotion tasks. The robot's low COT, demonstrated in this preliminary work, underscores its energy efficiency and supports this objective. Another potential avenue for exploration is enabling the robot to climb stairs, which would require modifications to its kinematic structure, such as increasing the length of the internal leg.

To enhance the walker's adaptability to varying terrain conditions, a low-level controller based on learning approaches will be developed, leveraging the capabilities of physics-based simulation engines. Bridging the gap between simulation and reality will involve massive parallelization of the learning stages to optimize performance.

VI. Acknowledgment

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