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Fall Detection and Prevention in a Lower Limb Exoskeleton Using MuJoCo Simulation

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Exoskeletons are a vital assistive technology for enabling gait in elderly and disabled people. Although there have been some advances in exoskeletons designed for fall protection, further improvements and research are necessary. This paper addresses the issue of fall detection and prevention using exoskeletons. The MuJoCo physics simulator was utilized to develop and test our fall prevention control strategy. The simulation employs a humanoid model coupled with a lower-limb exoskeleton. This single platform integrates gait generation, fall detection, and fall prevention control strategy. The simulation results demonstrate that the system can maintain stable walking, detect disturbances, and prevent falls.

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I. Introduction

Walking stability is important for recovery, and falling can cause serious health problems, especially for the elderly. There are many fall detection strategies of exoskeletons based on Inertial Measurement Units (IMUs) and pressure sensors data, while fall prediction and prevention studies are still lacking. Therefore, this project aims to study fall prevention for lower-limb exoskeletons. Conducting fall prevention studies on real exoskeletons is unsafe and expensive, making simulation an essential choice for strategy evaluation. The main contribution of this work is the development of a dynamic simulation using the Multi-Joint Dynamics with Contact (MuJoCo) physics engine. This simulation unifies a dataset-driven gait, a fall prevention strategy based on Center of Mass (COM) and Zero Moment Point (ZMP) detection, and a capture step mechanism within an integrated exoskeleton humanoid system. To the best of the authors' knowledge, this is the first time the MuJoCo Simulation Environment has been used to investigate fall prevention approaches.

I.I. Literature overview

In [1], the authors applied stable walking control strategies that can resist disturbances. They used a two-level control scheme, including task-space planning, a prioritized stack of tasks, floating-base inverse dynamics, posture control, and joint-level control, achieving a walking speed of 10 cm/s. In our study, we apply the walking and fall prevention control strategies to a humanoid model with exoskeleton in MuJoCo and achieve a higher average walking speed of 0.67 m/s.

II. Material and methods

In this study, we use a humanoid model from an existing MuJoCo model [2], complete the modeling of the lower limb exoskeleton, and bind them together. The exoskeleton has a total of 6 joints for the hips, knees, and ankles, each of which has one degree of freedom in the sagittal plane. To simulate individuals with lower limb disabilities, the active joint torques of the humanoid model's legs were set to zero. It means the lower limb of the humanoid is totally controlled by the exoskeleton that is attached to it. The weight of the exoskeleton is 22.854kg, and the humanoid mass is 62.4kg, resulting in a total combined mass of 85.254kg. The heights of the humanoid and the exoskeleton are 1.71m and 1.09m, respectively. Fig.1 demonstrates the humanoid and designed exoskeleton in the MuJoCo simulation.

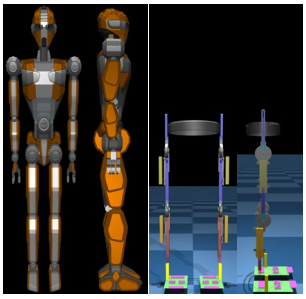


Figure 1: Two views of humanoid and exoskeleton in MuJoCo

After assembling the model, we use a walking dataset [3] to set the walking trajectory. The gait cycle is set as 2.2s, and the simulation frequency is 1000Hz. A PD controller is used to apply the necessary torque to the exoskeleton joints, helping the humanoid-exoskeleton system walk normally and follow the trajectory accurately. However, this controller is not able to maintain stability for more than a few steps.

To assist the humanoid in maintaining stability while walking, we implemented another PID controller and used the COM and the support area, which is defined as the region on the ground enclosed by the contact points of the

foot or feet. To apply this strategy, the difference between the COM and the middle of the support interval of the feet is used to adjust the COM position and to ensure that it remains inside the support area. Using this approach, we achieved stable walking for a longer period.

Then we implemented a fall detection system that monitors COM velocity, acceleration, pitch angle, and ZMP to determine the state. If COM velocity or acceleration reaches a specific threshold or if ZMP is monitored to be outside the support area and the pitch angle exceeds a threshold, the onset of fall will be detected. Furthermore, we employ a low-pass filter to smooth the monitored data, remove the noise, and improve accuracy.

Once an Impending fall is detected, the system activates the capture step strategy. To prevent the fall the leg in the swing phase takes a larger stride to restore dynamic stability. Following that, based on the angle changes of the 6 joints of the exoskeleton (Hips, Knees, and Ankle) and COM, the control system forms a double stance gait and maintains static stability. In other words, the system records the current joint angles and sets them as new targets. Meanwhile, the reference of the pelvis pitch is reset to zero, making the upper body straight.

III. Results and discussion

Fig. 2 shows the actual and target angles of 3 joints of the left leg. The plot shows stable and smooth tracking with smaller errors for the hip and knee joints, while the ankle joints exhibit larger fluctuations due to ground contact. This tracking indicates that the control is effective and provides a stable reference baseline for the normal walking state.

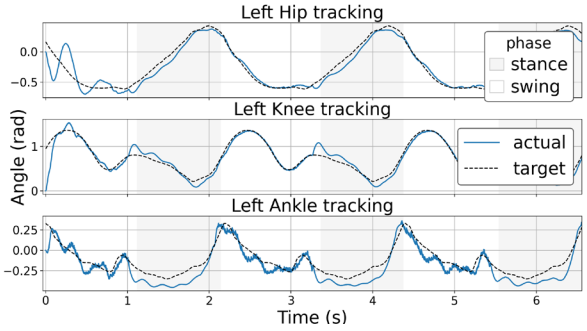


Figure 2: Joint tracking reference and actual angles produced by exoskeleton for hip, knee, and ankle of the left leg.

During normal walking, the mean tracking error remained within 0.04–0.06 rad. After disturbance, a temporary increase of up to 0.1 rad was observed, followed by rapid convergence, indicating control stability.

To validate our approach, a perturbation force of up to 275 N is applied to the waist in the walking direction and opposite direction, for a duration of 0.25 s to 0.85 s, starting across the gait cycle using a coarse step of 0.1 s and refined to 0.01 s around sensitive phases. This demonstrates a broad robustness range of the proposed fall prevention strategy. Fig.3 shows the actual pelvis pitch angle. As it is shown in the figure, when this angle goes over the threshold, the system detects the onset of fall. In our scenario, where the perturbation starts at 4.5 s after the initiation of the first step, pelvis pitch angle reaches the threshold of 0.06 rad at the point of 4.58 s, which is an indicator for fall detection.

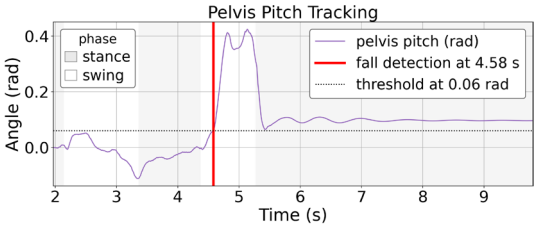


Figure 3: COM velocity and acceleration relative to pelvis position.

After the onset of fall is detected at 4.58 s, the capture step activates and attempts to step further forward. The difference between COM and the center of the support interval is calculated to apply additional hip and ankle torques to generate a larger step forward. The knee is extended to ensure proper foot placement ahead of COM. When the swing leg touches the ground, the system enters a double stance phase and switches to balance mode. This process redirects COM back into the support interval and prevents the fall. As shown in Fig. 4, the system becomes stable after the disturbance, demonstrating the effectiveness of the fall prevention strategy.

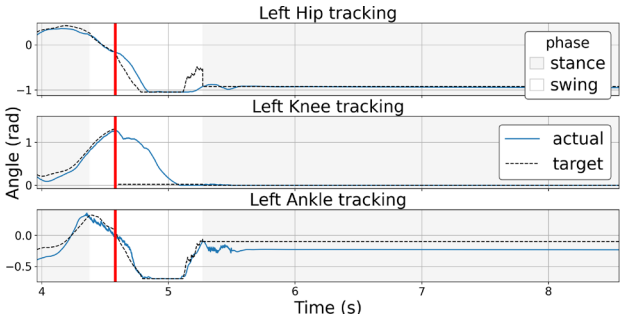


Figure 4: Joint tracking of the left leg after disturbance and subsequent stabilization.

Our model-driven approach achieves a detection latency of 0.19 ± 0.10 s, which outperforms the 0.5 s latency reported in a deep learning-based system in [4]. Furthermore, our system ensures comprehensive stability. It reaches a swing-leg touchdown at 0.2 ± 0.1 s and restores full gait equilibrium within 1.5 ± 0.3 s.

We build an effective simulation system, integrating gait, stability, fall detection, and prevention of a humanoid with an exoskeleton. This platform can test the fall prevention strategy in a safe and controllable environment. However, there are still differences between the model and the real human body and exoskeleton. Future validation is required with more complex models, introducing more diverse disturbance scenarios.

Author's Statement

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