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# A Co-Simulation Platform for Closed-Loop Evaluation of Human-Exoskeleton Control Strategies

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***Abstract*— Effective control of lower-limb exoskeletons depends on a comprehensive understanding of both human biomechanics and robotic actuation. We present a modular co-simulation framework that couples a physics-based exoskeleton model in Simscape with a musculoskeletal human model in OpenSim. The system supports bidirectional, stepwise interaction: joint angles from the exoskeleton model are sent to OpenSim, which returns corresponding interaction torques for use in the next simulation step. This closed-loop coupling enables the evaluation of assistive control strategies in a physiologically meaningful environment prior to hardware deployment. To demonstrate the framework's utility, we implement the adaptive Central Pattern Generator (CPG) strategy previously established in the literature as a representative case study. The results verify that the co-simulation environment successfully captures the intended closed-loop behavior, such as torque-dependent gait modulation and perturbation recovery. This confirms the platform's efficacy as a versatile tool for testing and refining human-exoskeleton interaction strategies before experimental trials.**

**Keywords: Human-robot interaction; Exoskeleton control; Central Pattern Generator; Musculoskeletal modeling; OpenSim**

## I. Introduction

Active lower-limb exoskeletons hold immense potential for restoring locomotor function in individuals with neurological impairments [1], [2]. However, the transition from theoretical control design to clinical deployment is fraught with challenges. Prototyping experimental controllers directly on human subjects is inherently risky; rehabilitation populations cannot tolerate the instability or erratic torque behavior that often accompanies early-stage testing [3]. Furthermore, hardware iterations are prohibitively expensive and time-consuming. Consequently, high-fidelity simulation is not merely convenient; it is a safety-critical prerequisite for development [4].

Despite this need, standard simulation methodologies often fail to predict real-world performance because they model the human and the robot in isolation. Robotic simulations frequently oversimplify the user as a passive payload or a pre-defined disturbance, neglecting the active, compliant nature of biological muscles. Conversely, biomechanical environments like OpenSim are powerful for analyzing human movement but typically lack the sophisticated sensor noise modeling and control architecture of engineering platforms like MATLAB Simscape [5]. This "decoupled" modeling approach creates a dangerous validation gap: controllers may appear robust in idealized, isolated simulations, yet fail catastrophically when subjected to the complex, coupled dynamics of physical human interaction [6]. To address this limitation, a stepwise torque exchange co-simulation framework is required, one that captures the continuous dynamic exchange between the robot's actuators and the human's musculoskeletal system.

Recent research has attempted to address this through various co-simulation strategies, though limitations remain. For instance, Tali et al. [7] utilized OpenSim Moco to optimize exoskeleton assistance. While their approach leverages detailed musculoskeletal modeling, it is computationally intensive and relies on offline optimization rather than real-time controller adaptation [8]. Similarly, Molz et al. [9] and Pineda-Rico et al. [10] developed co-simulations for upper-limb tasks. However, these frameworks were tailored to static or industrial applications and do not address the dynamic instability inherent in bipedal gait. A critical missing link is a synchronous, real-time framework capable of evaluating bio-inspired adaptive controllers, such as Central Pattern Generators (CPGs) [11], which require immediate physiological feedback to modulate gait patterns.

In this study, we present a modular, bidirectional co-simulation framework that links OpenSim's high-fidelity musculoskeletal human model with a Simscape-based physics model of the Exo-H3 exoskeleton, enabling continuous, stepwise torque exchange between the biological and robotic subsystems. The main contribution of this work is the development and functional verification of this closed-loop co-simulation infrastructure, which allows physiologically realistic interaction dynamics and controller–human feedback to be analyzed within a single computational environment.

To illustrate the functionality of the platform, we implement the adaptive CPG control architecture previously proposed by Sharifi et al. [11] as a representative case study. The purpose of this implementation is not to introduce, validate, or compare a new control strategy, but to show that the co-simulation framework can reproduce known and expected closed-loop behaviors of an established bio-inspired controller when it is embedded in a coupled human–exoskeleton model. No claim is made regarding novelty or superiority of

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Fig. 1. The Exo-H3 Exoskeleton, a lower limb wearable robotic exoskeleton device designed by Technaid S.L.

the controller itself; the scientific focus of this paper is the co-simulation methodology.

## II. Materials and Methods

### A. Exo-H3 Lower Limb Exoskeleton

The robotic device used in this study is the Exo-H3 lower-limb exoskeleton (Technaid S.L., Madrid, Spain), a fully actuated wearable system designed specifically for research and rehabilitation applications [12]. The Exo-H3 features six powered degrees of freedom (hip, knee, and ankle flexion/extension for both limbs), driven by independent DC motors coupled with harmonic drive gears. This configuration allows for high-torque assistance (up to 40 Nm peak) while maintaining a lightweight form factor (approx. 17 kg including batteries) suitable for overground gait training [12], [13]. Integrated distributed sensors, including absolute encoders, interaction torque sensors at each joint, and footswitch pressure sensors, enable precise real-time monitoring of the user's kinematic and kinetic state [12]–[14]. Recent validation studies have confirmed the device's utility in developing advanced control architectures, such as human-in-the-loop optimization and adaptive assistance strategies, by providing reliable low-level torque control and open-architecture communication via CAN bus and Wi-Fi [13].

In our simulation framework, we replicated the Exo-H3 structure and sensor layout within Simscape Multibody using the 3D model provided by Technaid. This ensures that the simulated exoskeleton accurately reflects the behavior of the real device, including its joint constraints, mass distribution, and actuator limits.

### B. Equations of Motion and Coupling

The coupled human-exoskeleton system is modeled using simplified rigid-body dynamics, where both subsystems contribute to joint-level motion and share the same kinematic trajectory due to the rigid mechanical interface. The equation of motion for the human is:

$$M_h(\theta)\ddot{\theta}_h + C_h(\theta,\dot{\theta})\dot{\theta}_h + G_h(\theta) = -\tau_{CNS} + \tau_{int} \tag{1}$$

Here $\theta_h$ represents the human joint angles, $M_h$ is the mass matrix, $C_h$ accounts for Coriolis and centrifugal forces, $G_h$ is the gravitational torque, $\tau_{CNS}$ is the biologically generated torque from the central nervous system (CNS), and $\tau_{int}$ is the interaction torque applied by the exoskeleton. The exoskeleton model, implemented in Simscape, follows a similar structure:

$$M_r(\theta)\ddot{\theta}_r + C_r(\theta,\dot{\theta})\dot{\theta}_r + G_r(\theta) = \tau_{motor} - \tau_{int} \tag{2}$$

In this expression, $\theta_r$ represents the exoskeleton joint angles (assumed to match $\theta_h$ due to rigid coupling), and $\tau_{motor}$ is the actuator torque applied by the exoskeleton controller. Assuming perfect alignment and rigid coupling (i.e., $\theta_h = \theta_r = \theta$), the two equations can be combined into a single unified dynamic relationship:

$$\tau_{CNS} + (M_h - M_r)\ddot{\theta} + (C_h - C_r)\dot{\theta} + (G_h - G_r) = \tau_{motor} \tag{3}$$

This formulation serves as the basis for determining how the controller must generate actuation commands to maintain coordinated and efficient movement between the user and the robotic system. The interaction torque $\tau_{int}$ acts as a critical coupling term exchanged between OpenSim and Simscape at each co-simulation step.

### C. Central Pattern Generator (CPG) Control

To verify the closed-loop capabilities of the co-simulation, we adopted the adaptive CPG framework originally developed by Sharifi et al. [11]. This controller was selected as a test case because it requires real-time modulation of gait parameters in response to human-exoskeleton interaction torque and energy. This biologically inspired structure enables synchronized rhythmic motion across joints and supports adjustment of gait features such as frequency, amplitude, and equilibrium point.

To enable autonomous adaptation, we define two interaction metrics based on the estimated interaction torque $\hat{\tau}_{int}$: the interaction energy $E_i(t)$ and the time-integral of torque $T_i(t)$. For each joint $i$, these are calculated as [11]:

$$E_i(t) = \int_0^t \mathrm{dz}(\hat{\tau}_{int,i}(\zeta))\dot{q}_i(\zeta)d\zeta \tag{4}$$

$$T_i(t) = \int_0^t \mathrm{dz}(\hat{\tau}_{int,i}(\zeta))d\zeta \tag{5}$$

where $\mathrm{dz}(\cdot)$ is a dead-zone function used to filter out negligible interaction torques. These metrics drive the adaptation of the CPG parameters. The dynamics for the overall frequency $\omega$, joint amplitude $\rho_i$, and equilibrium position $\xi_i$ are governed by the following coupled differential equations [11]:

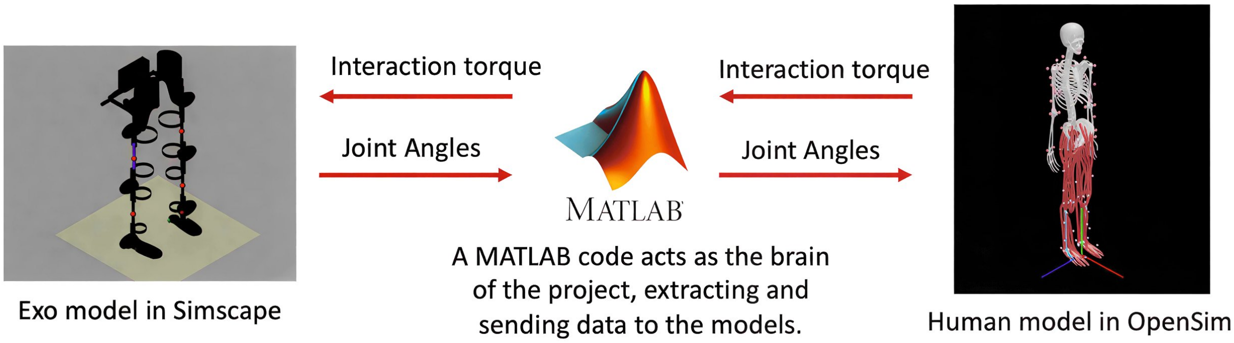


Fig. 2. Overview of the modular co-simulation framework. A custom MATLAB script manages bidirectional communication between the Simscape-based exoskeleton model (left) and the OpenSim musculoskeletal human model (right). Joint angles are transmitted from the exoskeleton to OpenSim for inverse dynamics analysis, and the resulting interaction torques are sent back to Simscape to actuate the exoskeleton. This architecture enables closed-loop simulation of human-exoskeleton interaction.

$$\dot{\omega} = \gamma_\omega \left( \frac{\gamma_\omega}{4}(\Omega_0 + \sum_{k=1}^{n} \psi_k E_k - \omega) - \dot{\omega} \right) \tag{6}$$

$$\dot{\rho}_i = \gamma_\rho \left( \frac{\gamma_\rho}{4}(A_{\rho_i} + \lambda_i E_i - \rho_i) - \dot{\rho}_i \right) + B_\rho(\rho_i) \tag{7}$$

$$\dot{\xi}_i = \gamma_\xi \left( \frac{\gamma_\xi}{4}(A_{\xi_i} + \beta_i T_i - \xi_i) - \dot{\xi}_i \right) + B_\xi(\xi_i) \tag{8}$$

where $\gamma_\omega, \gamma_\rho, \gamma_\xi$ are convergence gains; $\psi_k, \lambda_i, \beta_i$ are sensitivity factors determining the user's authority over the gait; and $\Omega_0, A_{\rho_i}, A_{\xi_i}$ represent the nominal gait parameters. The terms $B_\rho$ and $B_\xi$ represent logarithmic barrier functions defined in [11] that prevent the amplitude and equilibrium positions from exceeding safe biomechanical limits. Finally, the synchronized phase $\phi_i$ updates according to $\dot{\phi}_i = \omega + \sum \eta_{ij} \sin(\phi_i - \phi_j - \Delta\phi_{ij})$.

Using these updated parameters, the high-level CPG control generates the joint reference trajectory $q_{ri}(t)$ for each joint $i$ using a time-varying Fourier series expansion:

$$q_{ri}(t) = \xi_i(t) + \rho_i(t) \sum_{l=1}^{S} (c_{il} \cos(l\phi_i(t)) + d_{il} \sin(l\phi_i(t))) \tag{9}$$

Where the Fourier coefficients $c_{il}$ and $d_{il}$ are extracted from gait data and remain fixed. Each parameter $(\xi, \rho, \phi)$ evolves dynamically in response to joint interactions as defined in (II-C). The adaptability of this method and its mathematical formulation are drawn from the work of Sharifi et al. [11], who demonstrated that this approach enables flexible gait shaping and energy-efficient control when applied to wearable robotic systems. We adopt and replicate their structure for CPG dynamics in our framework.

### D. Co-Simulation Framework

The exoskeleton model was developed in MATLAB Simscape Multibody (MATLAB 2024b, The MathWorks Inc., USA) and includes six actuated revolute joints, representing the hip, knee, and ankle for both the left and right limbs. The OpenSim (version 4.3) human model used in this study is the Full-Body Musculoskeletal model provided by Rajagopal et al. [15], which includes muscle-actuated joints and outputs joint torques for biomechanical analysis. An interface was implemented in MATLAB as shown in Fig. 2 to facilitate communication. At each simulation timestep, the exoskeleton's joint angles $\theta$ are passed to OpenSim, which computes the joint torques $\tau_{int}$ that would result from the same angles applied to the human. This interaction torque is then applied back to the exoskeleton in Simscape. The communication step proceeds as follows:

- Simscape computes $\theta$, the current joint angles of the exoskeleton.
- $\theta$ is passed to OpenSim as input in the format of a motion (.mot) file.
- OpenSim runs an inverse dynamics step to compute the interaction torque $\tau_{int}$.
- The summation of $\tau_{motor}$ generated from CPG and $\tau_{int}$ is returned to Simscape.
- The adaptive CPG updates its output based on the $\tau_{int}$ torque feedback, and the process repeats at the next timestep.

Ground contact dynamics are resolved exclusively within the Simscape Multibody environment using a spatial contact force model between the exoskeleton's feet and the ground plane. Consequently, the OpenSim model operates in a kinematic-driven inverse dynamics mode, receiving joint trajectories to compute the biological inertial and gravitational moments without requiring redundant ground reaction force inputs.

To handle the co-simulation synchronization, a 'stop-and-wait' protocol is employed. At each discrete time step ($dt$), the Simscape solver pauses execution to exchange state data with OpenSim. The computed interaction torque is then applied as a Zero-Order Hold (ZOH) input for the subsequent integration interval, eliminating variable communication latency and ensuring temporal consistency between the domains.

### E. Implementation and Reproducibility Details

To ensure the reproducibility of the reported results, the computational framework and parameter settings are detailed below.

*1) Simulation Setup:* The co-simulation was orchestrated in MATLAB (R2024b) with a discrete communication interval of 0.1 s. While the high-level exchange of joint angles and interaction torques occurred at this 10 Hz rate, the internal Simscape Multibody solver was configured to use a stiff/NDF ode15s solver with a maximum relative tolerance of $1e-3$ to ensure numerical stability of the rigid body dynamics. The simulation spanned a total duration of 20.0 s, capturing approximately three complete gait cycles following an initial stabilization period. While the 0.1 s communication interval is sufficient for rhythmic gait analysis and stable numerical synchronization, it may limit the evaluation of high-frequency reflex-based controllers or sudden impact dynamics.

*2) Computational Environment:* All simulations were performed on a workstation equipped with an Intel Core i9-10900X processor and 32 GB of RAM, running on Windows 11. The average wall-clock time for a full 20-second simulation was approximately 1407 seconds, corresponding to a real-time factor of roughly 0.01. The primary computational bottleneck in this framework is the OpenSim inverse dynamics solver, which is not natively optimized for high-speed, iterative calculations. While the Simscape physics engine and the communication interface introduce minor delays, the OpenSim calculations dominate the processing time. Future work aimed at runtime reduction may explore surrogate modeling or simplified musculoskeletal representations to accelerate this step.

*3) Control and Perturbation Parameters:* The nominal gait trajectories were generated using a Fourier series expansion with coefficients derived from the adaptive CPG framework established by Sharifi et al. [11]. The nominal stride frequency was set to 0.2 Hz ($\omega_0 \approx 1.26$ rad/s), with joint-specific equilibrium and amplitude parameters tuned to match healthy kinematic profiles. To evaluate controller robustness, a destabilizing perturbation was modeled as a step decrease of 20 Nm applied to the right hip actuator. This disturbance was injected for a duration of 0.5 s (from $t = 13.0$ s to $t = 13.5$ s), simulating a sudden, transient loss of assistive torque.

## III. Results

The results are presented to functionally verify the proposed co-simulation infrastructure, rather than to establish new performance claims for the implemented controller. This section reports the outcomes obtained using the proposed bidirectional co-simulation framework, which couples a Simscape-based exoskeleton model with an OpenSim musculoskeletal human model and includes an adaptive CPG as a representative closed-loop controller. The aim of these results is to show that the simulation environment can support online trajectory generation, torque-based adaptation, and stable interaction under both nominal and perturbed conditions, and that it can reproduce closed-loop behaviors that are already known from previous studies.

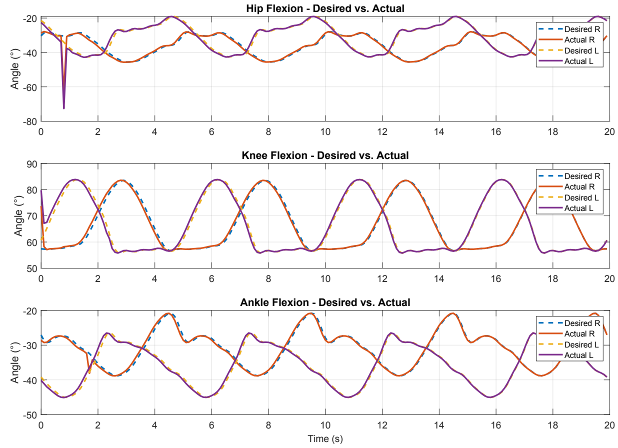


Fig. 3. Joint angle tracking performance for right and left lower-limb joints over a 20-second simulation. Desired trajectories generated by the adaptive CPG controller (dashed lines) are compared against actual joint angles measured from the Simscape exoskeleton model (solid lines) for hip, knee, and ankle flexion. The results demonstrate accurate trajectory tracking and consistent rhythmic motion across joints.

### A. Joint Trajectory Tracking

Tracking performance was evaluated by comparing joint angles computed in Simscape with the reference trajectories generated by the CPG. As shown in Fig. 3, close agreement is observed for all right lower-limb joints. The initial spike observed in the hip joint angle is caused by the exoskeleton model settling under gravity while being stabilized by the pelvis constraint. Once the system becomes stable, trajectory tracking becomes accurate. The Root Mean Square Error (RMSE) remained below 0.10 rad for all joints, indicating that the co-simulation framework can consistently synchronize the musculoskeletal and exoskeleton models while executing rhythmic trajectories generated online.

### B. Interaction Torque Reduction Through Adaptation

To examine whether the co-simulation platform can reproduce known transparency-related trends of adaptive gait controllers, joint interaction torques were analyzed before and after enabling adaptive feedback. Fig. 4 shows reductions in both peak and mean torque values, particularly at the right hip. These trends, reproduced by the co-simulation, are consistent with behaviors previously reported for adaptive CPG-based assistance.

The RMS values in Table I indicate that interaction torque decreased in most joints, with the largest reduction at the right hip (6.55%). The total torque effort across all joints decreased by 6.2%. In this study, these reductions are not interpreted as new performance improvements of the controller. Instead, they demonstrate that the proposed co-simulation environment is able to reproduce known relationships between adaptive control and interaction torque within a coupled human–exoskeleton model.

### C. Perturbation Response in Closed-Loop Co-Simulation

To further evaluate the stability of the closed-loop co-simulation, a 20 Nm external torque perturbation was applied

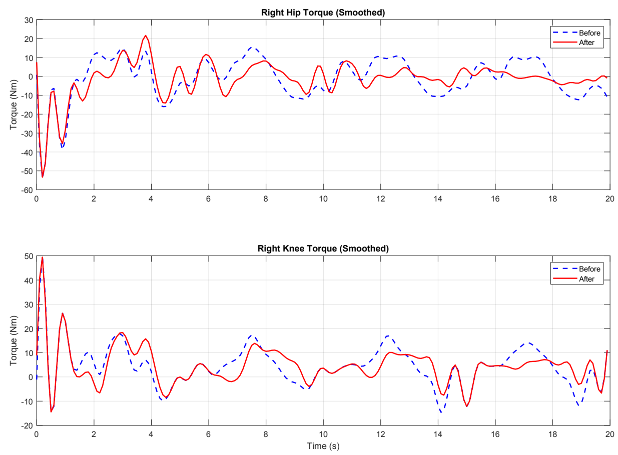


Fig. 4. Joint interaction torques at the right hip (top) and right knee (bottom) before (dashed blue) and after (solid red) enabling adaptive feedback over a 20-second simulation. The co-simulation reproduces the expected reduction in interaction torque magnitudes, indicating improved efficiency in joint-level assistance.

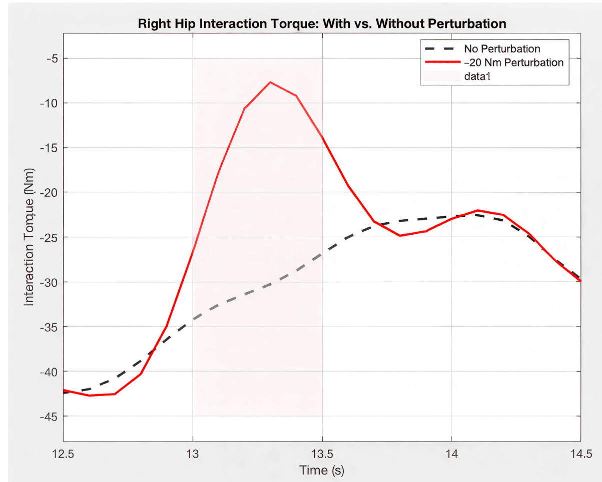


Fig. 5. Interaction torque at the right hip with (red) and without (black dashed) a 20 *Nm* external torque perturbation applied between 13.0–13.5 *s* (shaded). The perturbed case shows a sharp deviation followed by rapid convergence, demonstrating system robustness.

TABLE I
ROOT MEAN SQUARE (RMS) JOINT TORQUE VALUES BEFORE AND AFTER ENABLING ADAPTIVE FEEDBACK

| Joint | Before (Nm) | After (Nm) | Reduction (%) |
|---|---|---|---|
| Right Hip | 14.81 | 13.84 | **6.55%** |
| Left Hip | 13.50 | 13.45 | 0.37% |
| Right Knee | 16.49 | 16.17 | 1.94% |
| Left Knee | 17.75 | 17.33 | 2.37% |
| Right Ankle | 9.73 | 9.73 | 0.00% |
| Left Ankle | 10.64 | 10.65 | -0.09% |

at the right hip between 13.0 and 13.5 s. As shown in Fig. 5, the perturbation caused a transient increase in interaction torque, followed by a smooth return to the nominal profile.

This response reflects the expected adaptive dynamics of the implemented CPG when operating inside the bidirectionally coupled musculoskeletal–robotic system. The observed convergence indicates that the proposed torque-exchange architecture and numerical synchronization between OpenSim and Simscape can maintain stable closed-loop behavior under external disturbances.

## IV. DISCUSSION

The results show that the proposed co-simulation platform provides stable closed-loop operation with continuous bidirectional exchange of torques and states between a high-fidelity musculoskeletal model and a physics-based exoskeleton model. The generation of rhythmic gait, accurate tracking, and bounded response to perturbations indicate that the framework can reproduce coupled human–robot dynamics that are not captured in decoupled simulations. Compared to existing Moco-based offline optimizations and static upper-limb models, the primary advantage of this framework is its capacity for continuous, bidirectional torque exchange during dynamic bipedal gait without relying on pre-computed trajectories.

Within this environment, previously reported behaviors of the adaptive CPG controller were reproduced. For example, the reduction in global interaction torque shown in Table I, including the 6.55% decrease at the right hip, is consistent with trends reported in earlier experimental and simulation studies [16], [17]. In this work, these observations are not treated as new findings on controller performance. They are used to show that the co-simulation framework can express known transparency-related effects when an established controller is embedded in a coupled human–exoskeleton model [18], [19].

Similarly, the recovery after a 20 Nm perturbation (Fig. 5) should be understood as a functional verification of the bidirectional simulation pipeline, rather than as evidence of superior robustness of the controller. The observed transient and convergence behavior indicate that the platform can reproduce expected adaptive responses under physiologically realistic inertia and loading conditions.

It should be noted that assuming rigid human-exoskeleton coupling and resolving ground reaction forces solely within Simscape streamlines computation, but omits physical interface compliance. This simplification may lead to an overestimation of torque transfer efficiency, which should be considered when translating these specific interaction torques to hardware.

Importantly, the main contribution of this work lies in the evaluation methodology, not in the specific control law. The adaptive CPG controller is intentionally adopted from prior literature to demonstrate the controller-agnostic nature of the proposed co-simulation framework.

Overall, the results confirm that the proposed platform can reliably reproduce known closed-loop behaviors of existing control laws, supporting its role as a controller-agnostic test environment for human–exoskeleton interaction studies.

## V. CONCLUSION

This paper presents a modular bidirectional co-simulation platform that couples a Simscape-based exoskeleton model with an OpenSim musculoskeletal human model through continuous torque exchange. The main contribution is the development and functional verification of this closed-loop simulation infrastructure, which enables physiologically meaningful interaction dynamics within a unified computational framework.

An adaptive CPG controller previously reported in the literature was implemented only as a representative case study to demonstrate the capabilities of the platform. The reproduction of expected torque-reduction trends and stable responses to external perturbations confirms that the co-simulation environment can capture known closed-loop behaviors of established controllers. No claim is made regarding the novelty or superiority of the control strategy itself. Accordingly, the primary outcome of this study is a reusable simulation platform for analyzing human–exoskeleton interaction, rather than the development of a new gait control strategy.

The proposed framework is therefore intended as a controller-agnostic simulation tool for future research on human–exoskeleton control. Future work will extend the platform with more detailed ground contact models, muscle-level feedback, and EMG-informed adaptation to support the simulation of persons with neurological injuries. By incorporating user-specific musculoskeletal parameters, such as altered force-length relationships or activation delays, the platform's utility for rehabilitation-oriented controller development will be further enhanced. [1].

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