Plantar Force Prior-Guided Parameter Optimization for Adaptive Control of Wearable Knee Exoskeletons

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Abstract— Wearable knee exoskeletons have shown potential for assisting individuals with lower-limb mobility limitations. However, existing adaptive controllers mainly rely on robot-side sensing signals and often neglect the wearer's biomechanical responses. To address this limitation, this work proposes a plantar-force-prior-guided parameter optimization framework for adaptive control of wearable knee exoskeletons. A shoe-integrated plantar-force sensing system is developed to capture bilateral foot-ground interaction information. Based on the measured plantar force, a symmetry metric is designed to evaluate load distribution between the two lower limbs and is further used to optimize high-level assistance parameters, including torque amplitude, activation timing, and torque profile shape. Human-subject experiments demonstrate that the proposed framework can improve plantar-force balance, reduce gait asymmetry, and promote more coordinated weight transfer during walking.

I. INTRODUCTION

The human knee plays a central biomechanical role in lower-extremity support, shock absorption, weight transfer, and functional locomotion in daily life [1], [2]. By providing task-dependent assistive torque at the knee joint, wearable knee exoskeletons can directly modulate load sharing, support-phase mechanics, and weight-transfer behavior, thereby influencing the wearer's biomechanical performance during locomotion [3]. Therefore, it is necessary to design adaptive controllers of the exoskeletons that can accommodate diverse locomotion scenarios and provide appropriate assistance under varying biomechanical demands.

To realize adaptive control of wearable knee exoskeletons, a key challenge is to accurately infer the wearer's locomotion intention and translate it into appropriate assistive control parameters. Previous studies have explored electromyography (EMG)-based intention recognition, as EMG signals can directly reflect neuromuscular activation patterns [4], [5]. However, EMG-based methods often require additional sensing equipment, which may increase system complexity, device size, calibration burden, and donning difficulty. To enhance practicality and support real-world deployment, recent studies have increasingly relied on onboard sensors, such as inertial measurement units (IMUs) [6], [7], joint encoders, and joint torque sensors, to estimate locomotion intention from information already available in the exoskeleton system. Although these sensor-driven approaches enable adaptive assistance across diverse locomotion scenarios, they do not necessarily ensure that the resulting controller parameters are biomechanically appropriate for different users, tasks, and load conditions. Therefore, incorporating biomechanical priors into controller parameter optimization is essential for improving the adaptability, robustness, and human compatibility of wearable knee exoskeletons.

To overcome the above limitation, this work proposes a parameter optimization framework for the exoskeleton controller by further leveraging human biomechanical information. Specifically, we develop a force sensor that can be integrated into the wearer's sports shoes to capture plantar force information. The bilateral symmetry of plantar force is essential for assessing gait balance and load distribution between the lower limbs. Maintaining such symmetry is particularly desirable for wearable knee exoskeletons, as asymmetric plantar force may indicate unbalanced assistance, abnormal gait patterns, or insufficient coordination between the human wearer and the exoskeleton. Accordingly, this work designs an asymmetry evaluation metric based on bilateral plantar force, which is further used as feedback to adjust the controller parameters. For the basic controller, IMUs and joint torque sensors mounted on the robot are still employed to predict the wearer's locomotion intention. Finally, the proposed framework enables customized controller parameter optimization for different users across diverse locomotion scenarios.

The main contributation of this work include:

- We develop a shoe-integrated plantar-force sensing system to acquire biomechanical information from the wearer during different locomotion scenarios.
- We propose a bilateral plantar-force asymmetry metric to evaluate gait balance and load distribution, and further incorporate this metric as feedback for adaptive controller parameter optimization.
- We conduct experiments with human participants across multiple locomotion scenarios to demonstrate the feasibility and effectiveness of the proposed framework on a wearable knee exoskeleton.

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II. System Description and Controller

A. System Description

In this work, the applied knee exoskeleton platform employed is a lightweight wearable knee exoskeleton with a total mass of 2.55 kg, capable of providing 0–11 Nm of assistive torque, a peak power output of 96 W, and an operating endurance of 4–6 h. The hardware system integrates a mechanical frame, knee actuation modules, a central control unit, and a locomotion sensing suite. This compact and integrated design enables adaptive assistance across diverse locomotion scenarios, including level-ground walking, ramp ambulation, and stair negotiation.

As shown in the figure 1, the device is a lightweight wearable knee exoskeleton system mainly composed of shoulder straps, fastening straps, thigh links, shank links, assistive knee joint modules, and a waist-mounted controller with a lithium battery. The overall structure adopts an ergonomic wearable design, and the device is securely attached to the user through multiple fixation points at the shoulders and legs, ensuring both wearing comfort and efficient transmission of assistive torque.

The assistive joint modules are positioned near the knee joints to provide support during knee motion. The thigh and shank links serve as the primary load-bearing and connecting components, enabling mechanical coupling between the exoskeleton and the lower limbs. The shoulder straps and fastening straps are used for suspension and fixation, while the controller and lithium battery are integrated at the waist to reduce distal leg loading and improve portability and endurance. With its compact and lightweight design, the device can provide adaptive knee assistance across various locomotion scenarios, including level-ground walking, ramp ambulation, and stair negotiation.

B. Adaptive Control of the Wearable Knee Exoskeleton

The wearable knee exoskeleton is controlled by an adaptive controller that generates the desired knee assistive torque according to the wearer's real-time motion state. The sensory state of the system is defined as

$$\mathbf{x}(t) = [\theta_k(t), \dot{\theta}_k(t), \tau_k(t), \mathbf{a}_{\text{imu}}(t), \boldsymbol{\omega}_{\text{imu}}(t)]^T, \quad (1)$$

where $\theta_k(t)$, $\dot{\theta}_k(t)$, and $\tau_k(t)$ denote the knee joint angle, angular velocity, and measured joint torque, respectively. $\mathbf{a}_{\text{imu}}(t)$ and $\boldsymbol{\omega}_{\text{imu}}(t)$ are the linear acceleration and angular velocity measured by the IMUs.

A normalized motion progression variable is estimated from the sensory state:

$$z(t) = h(\mathbf{x}(t)), \quad z(t) \in [0, 1], \quad (2)$$

where $z(t)$ represents the normalized progression of the current movement.

The desired assistive torque is formulated as

$$\tau_d(t; \boldsymbol{\Theta}) = A\, w(z(t); z_{\text{on}}, z_{\text{off}})\, f(z(t); \boldsymbol{\beta}), \quad (3)$$

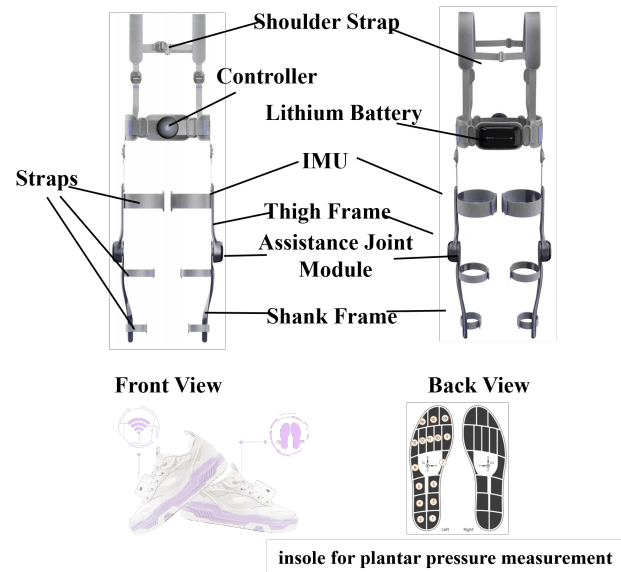

Fig. 1. Prototype overview of the wearable knee exoskeleton system with a shoe-integrated plantar-pressure acquisition device for post hoc gait evaluation.

where A denotes the torque amplitude, $w(z(t); z_{\text{on}}, z_{\text{off}})$ is the assistance activation window, and $f(z(t); \boldsymbol{\beta})$ is the normalized torque profile. The controller parameter vector is defined as

$$\boldsymbol{\Theta} = [A, z_{\text{on}}, z_{\text{off}}, \boldsymbol{\beta}^T]^T. \quad (4)$$

The activation window is expressed as

$$w(z; z_{\text{on}}, z_{\text{off}}) = \frac{1}{2}\left[\tanh(k(z - z_{\text{on}})) - \tanh(k(z - z_{\text{off}}))\right], \quad (5)$$

where z_{on} and z_{off} represent the onset and offset timing of assistance, and k determines the smoothness of activation.

The torque profile is parameterized by a set of basis functions:

$$f(z; \boldsymbol{\beta}) = \sum_{i=1}^{N} \beta_i B_i(z), \quad (6)$$

where $B_i(z)$ denotes the i-th basis function, and β_i is the corresponding shape parameter.

To evaluate the bilateral plantar-force symmetry, the force asymmetry index is defined as

$$\eta(t) = \frac{|F_L(t) - F_R(t)|}{F_L(t) + F_R(t) + \varepsilon}, \quad (7)$$

where $F_L(t)$ and $F_R(t)$ are the plantar forces of the left and right feet, respectively, and ε is a small positive constant used to avoid numerical singularity.

The optimization objective is then defined as

$$J(\boldsymbol{\Theta}) = \frac{1}{T}\int_0^T \eta^2(t)\, dt + \lambda \|\boldsymbol{\Theta} - \boldsymbol{\Theta}_0\|^2, \quad (8)$$

where the first term minimizes bilateral plantar-force asymmetry, and the second term regularizes the optimized parameters with respect to the initial parameter set $\mathbf{\Theta}_0$.

The optimized controller parameters are obtained by

$$\mathbf{\Theta}^* = \arg\min_{\mathbf{\Theta}\in\Omega} J(\mathbf{\Theta}), \tag{9}$$

where Ω denotes the feasible parameter space.

The reference torque generated by the optimized adaptive controller is tracked by a low-level torque controller:

$$e_\tau(t) = \tau_d(t;\mathbf{\Theta}^*) - \tau_{\text{act}}(t), \tag{10}$$

$$u(t) = K_p e_\tau(t) + K_i \int e_\tau(t)dt + K_d \dot{e}_\tau(t), \tag{11}$$

where $\tau_{\text{act}}(t)$ is the actual output torque, $u(t)$ is the actuator command, and K_p, K_i, and K_d are the low-level torque tracking gains.

Thus, the proposed adaptive control framework optimizes the high-level assistance parameters $\mathbf{\Theta}$, including the torque amplitude A, assistance timing parameters z_{on} and z_{off}, and torque profile shape parameters $\boldsymbol{\beta}$, while the low-level torque controller is used only for reference torque tracking. Importantly, in this work, K_p, K_i, and K_d are kept fixed to ensure stable torque tracking, while the proposed optimization focuses on the high-level assistance parameters $\mathbf{\Theta}$.

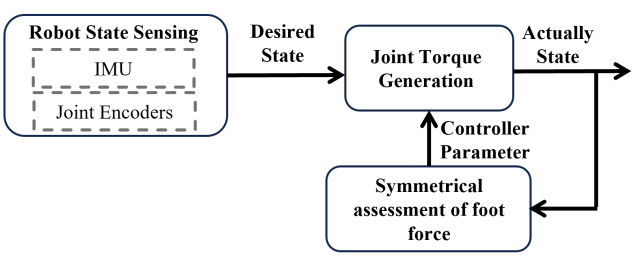

Fig. 2. Overall framework for parameter optimization of the adaptive exoskeleton controller.

C. Symmetry Evaluation for Parameter Optimization

To provide biomechanical feedback for controller parameter optimization, this work evaluates the bilateral symmetry of plantar force between the left and right feet. The basic assumption is that an appropriate assistance strategy should not introduce excessive load imbalance between the two lower limbs. Therefore, plantar-force symmetry is used as an evaluation criterion to guide the optimization of the high-level assistance parameters of the exoskeleton controller.

The plantar force of each foot is obtained from the shoe-integrated force sensing device. For the left and right feet, the total plantar forces are calculated as

$$F_L(t) = \sum_{i=1}^{N_L} f_{L,i}(t), \tag{12}$$

$$F_R(t) = \sum_{i=1}^{N_R} f_{R,i}(t), \tag{13}$$

where $f_{L,i}(t)$ and $f_{R,i}(t)$ denote the force measured by the i-th sensing unit under the left and right feet, respectively. N_L and N_R are the numbers of sensing units in the left and right shoes.

To reduce the influence of different body weights and sensor scale variations, the measured plantar forces are normalized as

$$\bar{F}_L(t) = \frac{F_L(t)}{F_L(t) + F_R(t) + \varepsilon}, \tag{14}$$

$$\bar{F}_R(t) = \frac{F_R(t)}{F_L(t) + F_R(t) + \varepsilon}, \tag{15}$$

where ε is a small positive constant used to avoid numerical singularity.

The instantaneous plantar-force asymmetry is defined as

$$\eta(t) = \frac{|F_L(t) - F_R(t)|}{F_L(t) + F_R(t) + \varepsilon}. \tag{16}$$

A smaller value of $\eta(t)$ indicates better bilateral plantar-force symmetry. When the plantar forces of the two feet are identical, $\eta(t) = 0$, which represents perfect symmetry. A larger value of $\eta(t)$ indicates a greater load imbalance between the two lower limbs.

For parameter optimization, the symmetry metric is further evaluated over a complete motion period. The average plantar-force asymmetry is defined as

$$J_{\text{sym}} = \frac{1}{T}\int_0^T \eta^2(t)\,dt, \tag{17}$$

where T denotes the duration of the evaluated motion segment. This metric reflects the overall degree of bilateral plantar-force imbalance during the movement.

In addition to the instantaneous force difference, the plantar-force impulse of each foot is also considered to evaluate the accumulated load distribution. The impulses of the left and right feet are defined as

$$I_L = \int_0^T F_L(t)\,dt, \tag{18}$$

$$I_R = \int_0^T F_R(t)\,dt. \tag{19}$$

The impulse-based asymmetry index is then calculated as

$$J_{\text{imp}} = \frac{|I_L - I_R|}{I_L + I_R + \varepsilon}. \tag{20}$$

This metric evaluates whether the total load borne by the two lower limbs is balanced over the entire motion period.

Finally, the overall symmetry evaluation function is defined as

$$J_{\text{asy}} = \lambda_1 J_{\text{sym}} + \lambda_2 J_{\text{imp}}, \tag{21}$$

where λ_1 and λ_2 are weighting coefficients. J_{sym} evaluates the time-varying plantar-force asymmetry, while J_{imp}

evaluates the accumulated load asymmetry between the two lower limbs.

The proposed symmetry evaluation metric is used as feedback for optimizing the controller parameters. Given the high-level assistance parameter vector

$$\boldsymbol{\Theta} = [A, z_{\text{on}}, z_{\text{off}}, \boldsymbol{\beta}^T]^T, \tag{22}$$

the parameter optimization problem is formulated as

$$\boldsymbol{\Theta}^* = \arg\min_{\boldsymbol{\Theta}\in\Omega} \left(J_{\text{asy}}(\boldsymbol{\Theta}) + \lambda_\Theta \|\boldsymbol{\Theta} - \boldsymbol{\Theta}_0\|^2 \right), \tag{23}$$

where $\boldsymbol{\Theta}^*$ denotes the optimized controller parameters, $\boldsymbol{\Theta}_0$ is the initial parameter set, Ω is the feasible parameter space, and λ_Θ is a regularization coefficient. The regularization term prevents excessive parameter variation and ensures that the optimized assistance profile remains smooth and physically reasonable.

Through this formulation, the plantar-force symmetry metric provides quantitative biomechanical feedback for the adaptive controller. By minimizing J_{asy}, the controller parameters are adjusted to reduce bilateral load imbalance and improve the coordination between the wearer and the wearable knee exoskeleton.

III. Evaluation

A. Experiment Setup

To evaluate the effectiveness of the proposed parameter optimization framework, we implemented the adaptive control framework on the wearable knee exoskeleton and optimized the high-level assistance parameters using plantar-force-based biomechanical feedback. The initial adaptive control parameters were first applied to generate the baseline assistive torque profile. Then, the proposed optimization method was used to adjust the assistance parameters, including the torque amplitude, assistance timing, and torque profile shape.

The experiment was conducted with one participant(Fig. 3) using the proposed wearable knee exoskeleton. After a brief familiarization period, the participant performed level-ground walking trials under two controller settings: adaptive control with the initial parameter set $\boldsymbol{\Theta}_0$, and adaptive control with the optimized parameter set $\boldsymbol{\Theta}^*$. For each setting, three successful walking trials were collected and used for subsequent analysis.

The primary evaluation metric was the bilateral plantar-force balance between the left and right feet. The plantar-force asymmetry was calculated as

$$\eta(t) = \frac{|F_L(t) - F_R(t)|}{F_L(t) + F_R(t) + \varepsilon}, \tag{24}$$

where $F_L(t)$ and $F_R(t)$ denote the total plantar forces of the left and right feet, respectively, and ε is a small positive constant used to avoid numerical singularity. A smaller $\eta(t)$ indicates better bilateral plantar-force balance and more symmetric load distribution.

By comparing the plantar-force balance before and after parameter optimization, this experiment aimed to verify whether the proposed framework can improve the adaptive assistance strategy of the exoskeleton and reduce bilateral load imbalance from the wearer's biomechanical perspective.

Fig. 3. Experimental procedure of the human-subject validation.

B. Results and Discussion

Fig. 4 summarizes the changes in spatiotemporal gait characteristics, bilateral symmetry, and weight-transfer coordination under the no-wear (NW) and wear (W) conditions. Overall, the results indicate that wearing the exoskeleton improved gait organization by reducing excessive double-support duration, decreasing bilateral temporal asymmetry, and promoting a more coordinated plantar-pressure transfer pattern.

As shown in Fig. 4(a1), the single-support time of both the left and right sides showed a decreasing trend under the W condition compared with the NW condition. However, the differences were not statistically significant, suggesting that exoskeleton assistance did not cause a significant unilateral alteration in single-limb support duration. In contrast, the bilateral support phase was significantly reduced under the W condition, as shown in Fig. 4(a2). Since a prolonged bilateral support phase is often associated with cautious walking, delayed weight transfer, and reduced gait confidence, this reduction suggests that the exoskeleton assistance may facilitate a smoother transition of body weight between the two lower limbs.

C. Discussion

The symmetry-related results are presented in Fig. 4(b1)–(b2). Both the stance-time ASI and single-support ASI were significantly reduced under the W condition, indicating that the temporal difference between the left and right limbs became smaller when the participant walked with the exoskeleton. This result suggests that the assistance provided by the exoskeleton

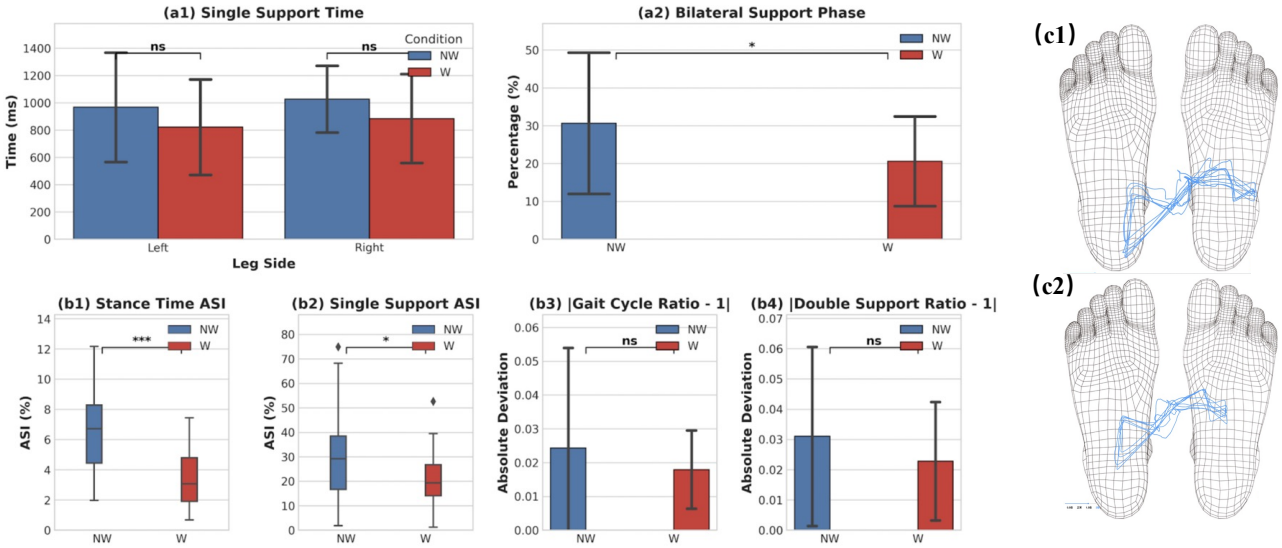

Fig. 4. Spatiotemporal gait parameters, symmetry-related indices, and coordination-related changes under the no-wear (NW) and exoskeleton-wear (W) conditions. (a1) Comparison of single-support time between the NW and W conditions for the left and right sides. (a2) Comparison of the bilateral support phase between the NW and W conditions. (b1) Comparison of the stance-time Asymmetry Index (ASI) between the NW and W conditions. (b2) Comparison of the single-support ASI between the NW and W conditions. (b3) Comparison of the absolute deviation of the gait-cycle ratio from the ideal coordinated pattern under the NW and W conditions. (b4) Comparison of the absolute deviation of the double-support ratio from the ideal coordinated pattern under the NW and W conditions. (c1)–(c2) Representative bilateral Center of Pressure (COP) trajectories under the NW and W conditions. Statistical significance is denoted by $^*p < 0.05$, $^{***}p < 0.001$, and ns for not significant.

helped improve bilateral gait symmetry and reduced the imbalance between the two lower limbs. In addition, Fig. 4(b3)–(b4) show that the deviations of the gait-cycle ratio and double-support ratio from the ideal coordinated pattern were also lower under the W condition, although the differences were not statistically significant. These results further indicate a trend toward improved temporal coordination during assisted walking.

The representative bilateral COP trajectories in Fig. 4(c1)–(c2) provide qualitative evidence of the changes in plantar-pressure transfer. Under the NW condition, the COP trajectory showed a more scattered and less organized pattern, reflecting unstable weight transfer between the two feet. In comparison, the COP trajectory under the W condition became more continuous and concentrated, suggesting that the exoskeleton assistance promoted a more stable and coordinated transfer of plantar pressure during walking.

Taken together, the significant reduction in bilateral support phase, the decrease in stance-time and single-support ASI, and the more organized COP trajectory pattern demonstrate that the exoskeleton can improve gait balance and bilateral coordination. These findings also support the effectiveness of using plantar-force-related symmetry metrics as biomechanical indicators for evaluating exoskeleton assistance.

IV. CONCLUSIONS

This study presented a controller parameter optimization method for a wearable knee exoskeleton. Specifically, the proposed method was developed within a human-centric assistance framework that integrates wearer-state sensing, locomotion mode recognition, assistance generation, and post hoc biomechanical evaluation. Rather than focusing on detailed controller design, this work emphasized the use of human-centered biomechanical metrics to evaluate the effects of exoskeleton assistance on the wearer. In particular, plantar-pressure-related metrics were used to assess gait symmetry and weight-transfer characteristics under exoskeleton assistance. Human-subject experiments were conducted to validate the feasibility of the proposed parameter optimization method. The experimental results demonstrated that the optimized assistance strategy improved plantar-force balance, reduced gait asymmetry, and promoted more organized weight transfer during walking.

However, the current validation is limited by the single-subject design and the preliminary level-ground walking evaluation. Future work will expand the study to additional participants, more locomotion scenarios, and more comprehensive biomechanical analyses.

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