

# Parametric Optimization of Series Elastic Actuator for Design and Control of Wearable Robotic Ankle Foot Orthosis

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Ongoing research on wearable rehabilitation robots explores challenges related to actuation and control in human-centric environments. To achieve precise force control and ensure smooth operation of rehabilitation devices, new actuation mechanisms and advanced control methods are continually being analyzed. The task becomes more challenging when the focus is on the human ankle joint. Conventional actuation methods are being replaced by hybrid actuation methods like series elastic actuators to take advantage of both passive and active elements. Selecting parameters for passive elements and choosing control methods remain challenging due to their behavior and limited operational range. This work has been done to investigate the effect of the passive element spring in series elastic actuators and improve their applicability in the rehabilitation domain. Response of the series elastic actuator for torque tracking when subjected to various standard input signals is thoroughly analysed employing conventional Proportional Integral Derivative (PID) control and Robust Integral of Sign of Error (RISE) based advanced control. The emphasis is on understanding how these controls perform when applied to active orthosis for rehabilitation purposes using RMSE and mean error metrics. The PID control stabilizes much more quickly within a time frame of ~0.02 seconds, whereas RISE control for the same input stabilises, taking ~0.48 seconds to start tracking with minimal error. RISE excels for ankle reference inputs, with extremely low RMSE and Mean Error, especially at higher stiffness values. Results obtained from the analysis will aid orthotic designers in designing robotic ankle foot orthosis and implementing control methodology for ankle rehabilitation robots.

**Keyword:** Ankle foot orthosis, Rehabilitation, Robotic, Spring coefficient, Torque control

## Introduction

Robotic rehabilitation devices are gaining popularity these days. Several studies have confirmed that it is as effective as conventional therapy and helps improve the physiotherapy.<sup>1,2</sup> Design of these devices is challenging due to constraints such as limited space, weight, and control. The scenario becomes more complex when targeted joint is human ankle. The ankle joint is one of the most anatomically complex and load-bearing joint.<sup>3</sup> Rehabilitation therapy of ankle joint consists of providing repetitive movements of plantarflexion and dorsiflexion to regain required range of motion. Various wearable robotic devices have been developed and tested for ankle rehabilitation purposes.<sup>4,5</sup> Traditional stiff actuation and classical position control methods developed for industrial applications are not appropriate for robotic rehabilitation applications.<sup>6</sup>

Absence of impedance sensing and adjustment, adaptation to change, and back-drivability are some limitations associated with conventional actuation systems. Involvement of parameters like human dynamics and compliant operation has motivated the application of torque control in such devices.<sup>7</sup> Also, torque control ensures the safety of the individual, keeping the assistance natural.<sup>8</sup> Compliant actuators are replacing stiff actuators where human-robot interaction is involved.<sup>9</sup> These actuators have been developed and improved over decades to overcome the limitations of rigid actuators.<sup>10</sup> Research is focusing on the development of compact, compliant actuators with precise and efficient control.<sup>11,12</sup> The compliant element spring plays a crucial role in determining the overall performance and functionality of the rehabilitation device. Studies examine actuator performance based on configuration, spring placement, operational nature, and control approach.<sup>13,14</sup> The effects of parallel and series elastic element configurations<sup>15</sup> in electric motor-powered

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actuators were investigated. According to the authors, the series configuration outperforms parallel in mimicking the human ankle joint in walking and running. However, the article recommended a double motor-based solution for both gaits. Effects of elastic elements on hydraulic and electric actuators<sup>16</sup> using proportional derivative control were also studied. Authors emphasized component weight-related issues and proposed clutch-based designs for future prototypes. A design based on a four-bar mechanism with a clutch mechanism<sup>17</sup> was further proposed and evaluated. The design uses a motor to stretch the spring, and the spring force is released by a manual trigger during push-off. In addition to the actuator configuration, several new control strategies have been implemented to analyze the operation of series elastic actuators. Proportional-derivative (PD) controller for trajectory tracking<sup>18</sup> was described for an active orthosis activated by a linear motor with a series elastic element. A simulation-based study of clutch spring-based actuators<sup>19</sup> targeting the hip, knee, and ankle joints for a walking assistance application was presented. Another torque control approach<sup>20</sup> using PI control for rehabilitation using a series elastic exoskeleton was implemented. Comparison of PID, PD, Sliding Mode Control (SMC) and adaptive control scheme<sup>21</sup> for SEA based on robust control was analyzed. The paper presented quantitative analysis and comparison based on RMSE and maximum error. Further adaptive sliding mode control<sup>22</sup> applied to active ankle orthosis is analyzed to apply a desired impedance. An improvement in SMC control is achieved to make control continuous and this is done using addition of Robust Integral of Sign of Error (RISE) based control.<sup>23</sup> An application of the more advanced adaptive RISE-based nonlinear controller<sup>24</sup> was also implemented for a knee exoskeleton. The nonlinear control was thoroughly tested in the presence of system uncertainties and external disturbances. RISE-based control has the advantage of being continuous and reducing chatter behaviour,

making it suitable for applications involving electromechanical systems.<sup>25</sup>

Considering the rehabilitation domain, this paper presents a simulation-based approach to analyse the effect of elastic spring stiffness and control algorithms that can be applied to an ankle orthosis for torque tracking. A rotary series elastic actuator with motion in a single plane is considered for modelling robotic ankle orthosis. Proportional Derivative Integral (PID) control and Robust Integral of Sign of Error (RISE) control schemes are selected for simulation purposes to keep future implementations practically feasible. Various standard input signals were used to examine the control response with a change in spring stiffness and input type. Ankle torque trajectory derived from Whittle<sup>26</sup> is also employed as an input for the simulation. The orthosis is assumed to be wearable and designed to align the human ankle and axis of rotation of SEA. The simulation and modelling of ankle orthosis is performed in MATLAB R2022a version. Analysis and comparison based on RMSE and mean square error are presented to highlight the effects of control scheme and spring stiffness. In the beginning, proposed structure and actuator arrangement are discussed. Then the significance of various inputs used are described followed by mathematical representation of system along with system parameters. The remaining sections are dedicated to the findings and observations from the simulation.

## Materials and Methods

Focusing on ankle joint movement a wearable orthosis with rotary series elastic actuator is considered. The axis of rotation of ankle and orthosis are assumed to be aligned to impart desired dorsiflexion and plantarflexion movements. Assuming the wearable active ankle orthosis axis of rotation perfectly aligns with human ankle rotation axis a rotary series elastic actuator simulation approach is shown in Fig. 1. A Simulink model consisting of SEA parameter is developed. The schematic representation of SEA system is shown in Fig. 2, it consists of a

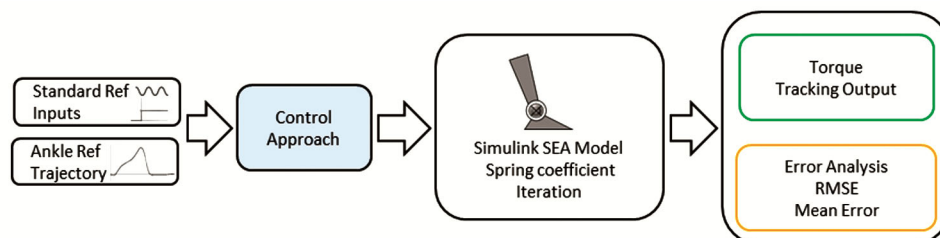


Fig. 1 — Series elastic actuator simulation approach

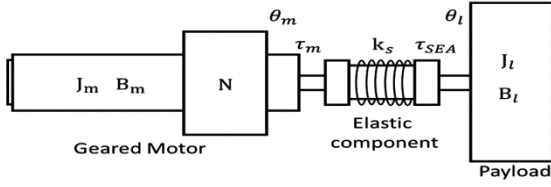


Fig. 2 — Schematic representation of a SEA system for ankle movement

Rotary Series Elastic Actuator (RSEA) with mechanical frame to support ankle and foot. The SEA constitutes of geared brushless motor (make- Maxon) having moment of inertia and damping coefficients represented by  $J_m$  and  $B_m$ . It is the combined inertia of motor and gearbox. Similarly, load inertia and damping is represented by  $J_l$  and  $B_l$  respectively. The spring element is represented by  $k_s$ .

All parameters are transformed into a Simulink model in MATLAB environment. The rotation of geared motor output shaft is assumed to be confined in a range of  $\pm 25^\circ$ . Proposed wearable orthosis allows a single degree of freedom to achieve dorsiflexion ( $25^\circ$ ) and plantarflexion ( $25^\circ$ ) movements. Proportional Integral Derivative (PID) being the most widely acceptable control is selected for simulation analysis compared with nonlinear Robust Integral of Sign of Error (RISE) control.

The core of selecting the controls is to observe the control and actuator capabilities when applied to ankle orthosis in scenarios when input signal and spring coefficient is changed. Both controller gains are tuned to avoid overshoots and ensure stability for a range of system parameters. The controller is required to track the output torque of the series elastic actuator as per the reference signal. Four different reference inputs, sine wave of 0.5 Hz, trapezoidal waveform 0.5 Hz, step signal and sine with perturbation is taken as reference inputs. A chirp signal 0.3 Hz – 2.0 Hz was used to assess the controller's performance in case of input frequency change. In rehabilitation, generally periodic motions are involved, which can be represented by a sinusoidal waveform. The trapezoidal waveform is also selected as an input reference to test hold and move conditions. The purpose of the step signal is to analyse the response to sudden changes and the steady state response. To simulate controller response in presence of disturbances, perturbation with sine input is applied. For both the control approaches fixed amplitude reference input signal of amplitude 5 Nm is used. An input signal derived from the ankle moment of a complete gait cycle is also taken as input to the

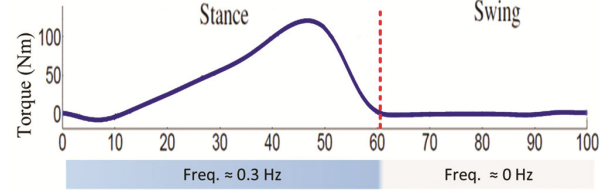


Fig. 3 — Ankle torque characteristics during a complete gait cycle derived from whittle<sup>26</sup>

system. Considering the ankle moment signal, Fig. 3 is obtained from a complete gait cycle in which majority waveform comprises a sinusoidal signal of 0.33 Hz and almost 0 Hz frequency during the rest of time. To study the effects of frequency variations and steady state error, chirp signal of frequency range from 0.3Hz to 2.0Hz and step signal is used.

The performance of SEA is tested based on RMSE and mean error in torque tracking. The torques involved in a series elastic actuator are given by expression for motor, spring and load system as given by following equations:

$$J_m \ddot{\theta}_m + B_m \dot{\theta}_m = \tau_k - N^{-1} \tau_{out} \quad \dots (1)$$

$$J_m \ddot{\theta}_m + B_m \dot{\theta}_m = \tau_{out} + \tau_{ext} \quad \dots (2)$$

$$\tau_s = k_s (\theta_m - \theta_l) \quad \dots (3)$$

Load side and motor side dynamics are represented by Eqs (1, 2), whereas the spring dynamics is given by Eq. (3), where,  $\theta_m$  and  $\theta_l$  are motor and load positions, respectively.  $\theta_s$  is the new rotation in spring element given by  $\theta_m - \theta_l$ . Motor torque and torque spring are represented by  $\tau_m$  and  $\tau_s$  respectively. The output torque observable at the load is  $\tau$  and external disturbance is represented by  $\tau_{ext}$ . These three systems are constrained by the gear ratio  $N$ . The force can be calculated using spring deflection given by the expression in Eq. (3). The objective is to ensure that the series elastic actuator in design can track the input reference for torque.

#### Control Methods and Configuration for Dynamic Simulation

To compare the performance of two controllers, a range of spring coefficients with stiffness values ( $k_s = 5, 10, 15, 20$ ) are selected. As the actuator and ankle axis are assumed to be aligned in ankle orthosis it is believed that the torque generated at the load end in simulation resembles the torque at ankle joint. The series elastic actuator parameters used for simulation are listed in Table 1.

#### PID Controller

PID controller given by Eq. (4) is tuned using the MATLAB *pidtune* tool. The gains  $k_p$  and  $k_d$  are

adjusted to achieve stable operation of the controller for a given range of spring coefficients ( $k_s$ ).

$$u_{pid}(t) = k_p e(t) + k_i \int_0^t e(t) + k_d \frac{de(t)}{dt} \quad \dots (4)$$

A block diagram representation of PID controller is shown in Fig. 4 below.

The control gains are adjusted to compensate for all ranges of spring values. For simulation, the proportion gain ( $k_p$ ), integral gain ( $k_i$ ) and derivative gain ( $k_d$ ) are set to 1.891, 1.012 and 0.00998, respectively. The effect on torque tracking is studied in simulation using a set of spring stiffness ( $k_s$ ) values.

#### RISE Controller

RISE control structure is a non-linear control. It is a control strategy with differentiable high-gain feedback and contains an integral *signum* function in the controller for smooth bounded disturbances. The controller shown in Fig. 5 given by Eq. (5) is used as a tracking controller.

$$u_{rise}(t) = K_r \int_0^t \text{sgn}(e(t)) + \alpha e(t) + \beta \frac{de(t)}{dt} \quad \dots (5)$$

where,  $u(t)$  is the control output,  $e(t)$  refers to error, the difference between the setpoint and the process variable.  $K_r$  is the gain for the signum term, ensuring robust convergence.  $\alpha$  and  $\beta$  are proportional and derivative gains, affecting the response to the current error and rate of change of error respectively. For simulation purpose gains used for RISE control are given as  $K_r = 0.4$ ,  $\alpha = 0.6$  and  $\beta = 0.004$ .

Table 1 — System parameters for simulation

Parameter	Value
Motor Inertia ( $J_m$ )	5.3400e-6 kg·m <sup>2</sup>
Motor damping ( $B_m$ )	4.6146e-6 Nm·s/rad
Load Inertia ( $J_l$ )	0.0218 kg·m <sup>2</sup>
Load damping ( $B_l$ )	0.4832 Nm·s/rad
Gear Ratio ( $N_m$ )	20
Spring Coefficient ( $K_s$ )	[5, 10, 15, 20] N-m/rad

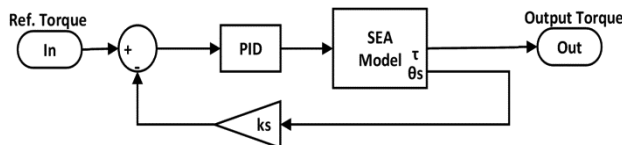


Fig. 4 — PID Controller for ankle orthosis actuator

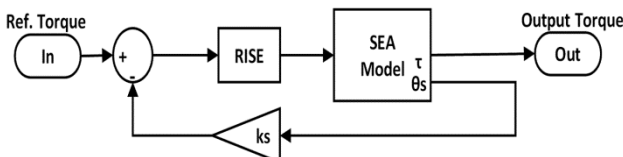


Fig. 5 — RISE base control of ankle orthosis

The stability of the controller is ensured to handle bounded input for all values of spring coefficients used for simulation purposes.

Two commonly used evaluation metrics, viz. RMSE, and Mean error, analyzes the performance of controllers. RMSE values indicate the overall tracking accuracy, with lower values representing better performance and the Mean error reflects the average deviation from the desired trajectory, where smaller values indicate better steady-state performance.

#### Results and Discussion

The parametric optimization of a Series Elastic Actuator (SEA) for a wearable robotic Ankle-Foot Orthosis (AFO) was investigated by evaluating two control strategies viz. Proportional-Integral-Derivative (PID) and Robust Integral of the Sign of the Error (RISE). Simulation was performed across six input types (Sine, Step, Trapezoidal, Chirp, Perturbation, and Ankle Reference) at spring stiffness values of  $k_s = 5, 10, 15,$  and  $20$  N-m/rad. Performance was assessed using Root Mean Square Error (RMSE) and Mean error to quantify tracking accuracy and average deviation, respectively, with a focus on optimizing SEA stiffness and controller design for effective torque tracking in ankle orthosis. The results highlight the influence of stiffness on controller performance and provide insights into their suitability for AFO applications.

The PID controller demonstrated stable performance, with RMSE values ranging from 0.0183 (Ankle Ref.) to 0.0855 (Trapezoidal,  $k_s = 5$ ) and Mean errors from 0.0112 (Ankle Ref.) to 0.0577 (Trapezoidal). RMSE for PID improved marginally with increasing stiffness for most inputs, except Ankle Ref., which remained constant, indicating robustness but limited adaptability to system dynamics. Conversely, the RISE controller exhibited superior precision, particularly for Ankle Ref., where RMSE decreased from 0.0026 ( $k_s = 5$ ) to 0.0005 ( $k_s = 20$ ), and Mean error dropped from 0.0023 to 0.0005. Observed simulation values for various input signals corresponding to spring stiffness range are given in Table 2.

RISE also showed consistent RMSE and Mean error reductions with higher stiffness for Sine, Step, and Perturbation inputs, but struggled with Trapezoidal (RMSE: 0.1144–0.1226) and Chirp (RMSE: 0.1158–0.1315) inputs, where PID outperformed it.

Better torque control can be achieved using PID control for actions that involve hold and move like

Table 2 — RMSE and Mean Error comparison for different inputs

Controller	Input	Spring stiffness							
		$k_s=5$		$k_s=10$		$k_s=15$		$k_s=20$	
		RMSE	Mean	RMSE	Mean	RMSE	Mean	RMSE	Mean
PID	Sine	0.0706	0.0448	0.0682	0.0449	0.0673	0.0449	0.0667	0.0449
	Step	0.0595	0.0203	0.0558	0.0204	0.0538	0.0203	0.0519	0.0201
	Trapezoidal	0.0855	0.0574	0.0826	0.0576	0.0815	0.0576	0.0808	0.0577
	Chirp	0.0707	0.0454	0.0687	0.0459	0.0679	0.0461	0.0674	0.0462
	Perturbation	0.0708	0.0448	0.0684	0.0449	0.0675	0.0449	0.0669	0.0449
	Ankle Ref.	0.0183	0.0112	0.0183	0.0112	0.0183	0.0112	0.0183	0.0112
RISE	Sine	0.0743	0.0129	0.0680	0.0114	0.0661	0.0111	0.0652	0.0109
	Step	0.0734	0.0141	0.0651	0.0115	0.0627	0.0113	0.0616	0.0113
	Trapezoidal	0.1226	0.0688	0.1174	0.0678	0.1156	0.0671	0.1144	0.0665
	Chirp	0.1158	0.0390	0.1315	0.0370	0.1274	0.0355	0.1256	0.0356
	Perturbation	0.0749	0.0137	0.0690	0.0124	0.0672	0.0120	0.0663	0.0118
	Ankle Ref.	0.0026	0.0023	0.0012	0.0011	0.0007	0.0006	0.0006	0.0005

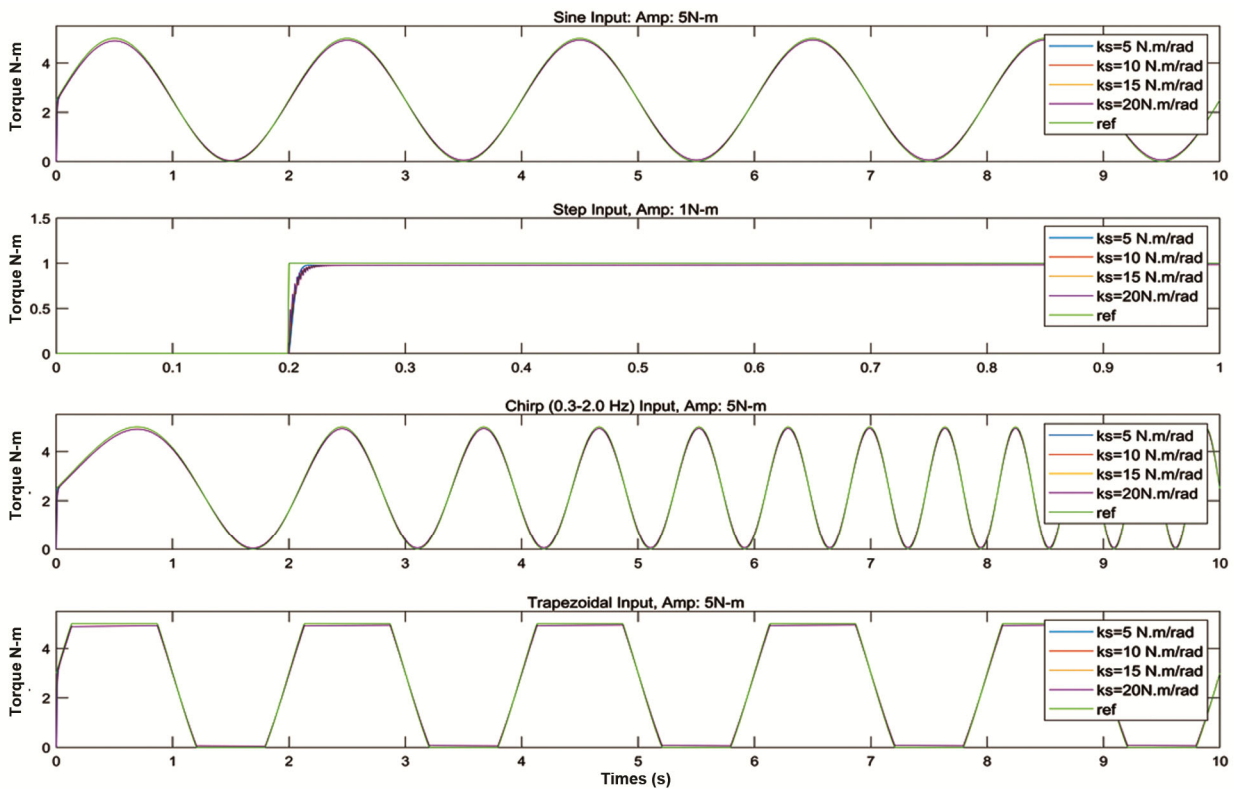


Fig. 6 — Input torque tracking PID control

movements, whereas actions linked with continuously changing applied torque, RISE control is more suitable. Plots in Fig. 6 shows torque tracking for different input types for PID control and Fig. 7 represents the error in torque tracking. Similarly, in plots in Fig. 8 and Fig. 9, RISE controller response for selected inputs with varying spring coefficients is shown.

The RISE controller demonstrated greater sensitivity to spring stiffness, generally achieving lower errors at higher  $k_s$  values, except for the Chirp input. The superior performance of RISE for Ankle Ref. suggests its suitability for biomechanical applications, such as prosthetic or exoskeleton control, where precise tracking of reference trajectories is critical. Conversely, PID's robustness for Trapezoidal and Chirp inputs

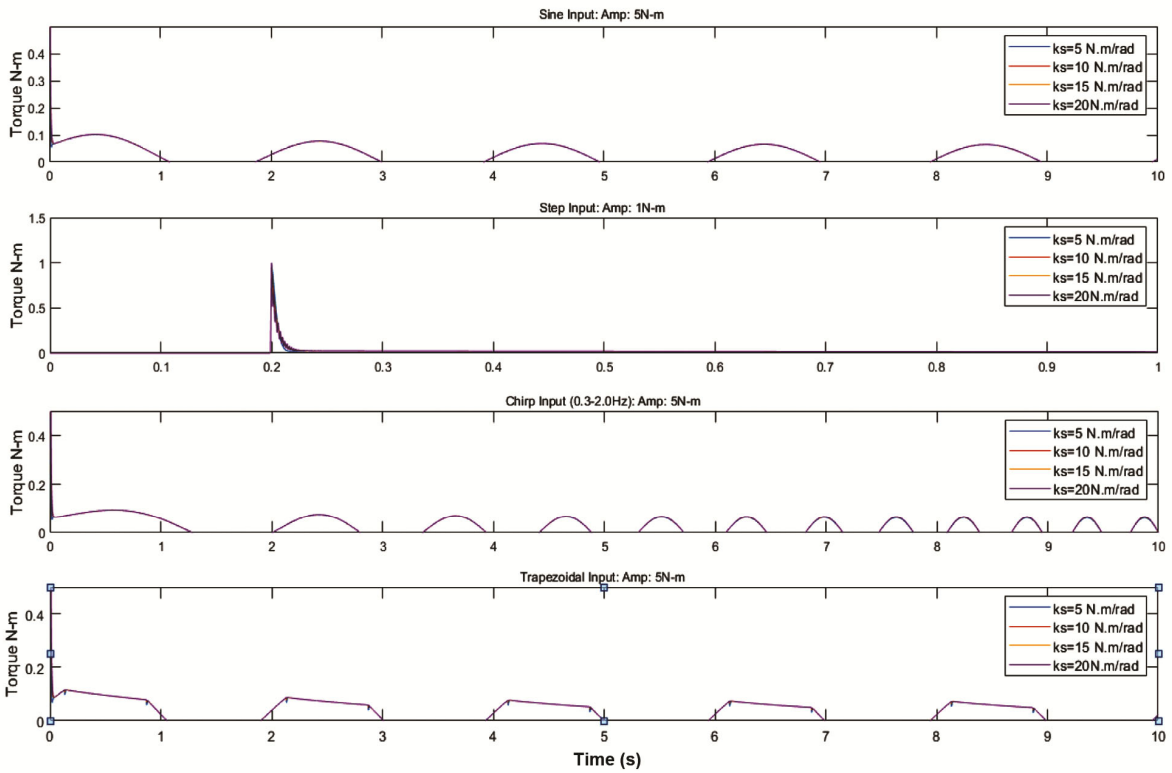


Fig. 7 — Torque tracking error (PID)

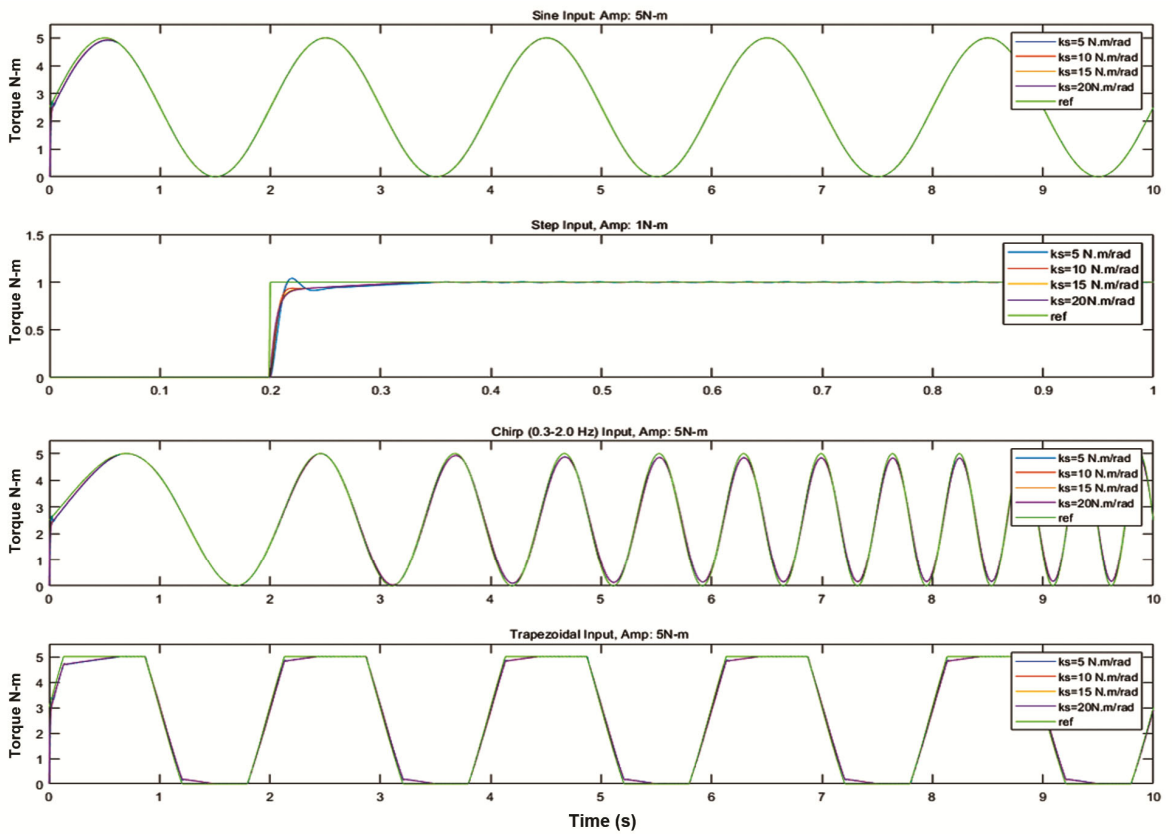


Fig. 8 — Torque tracking in RISE control

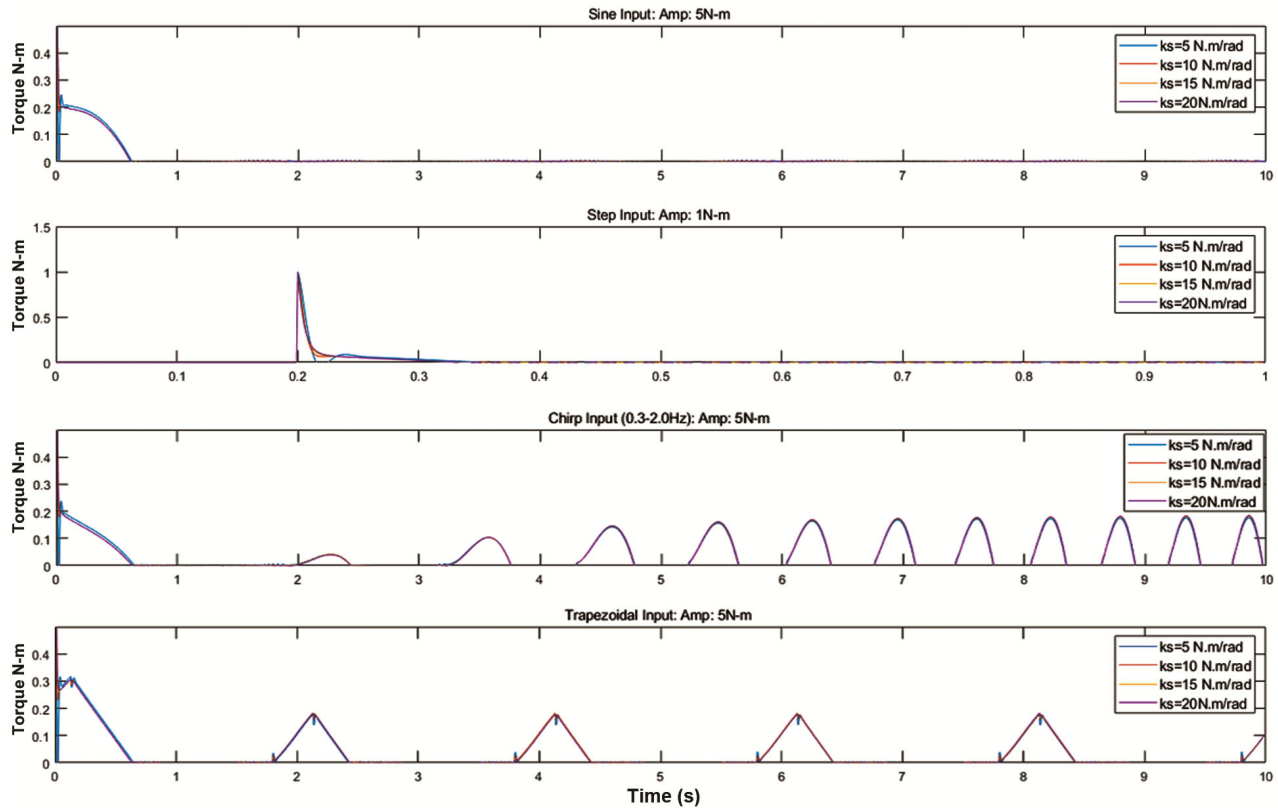


Fig. 9 — Error in torque tracking (RISE)

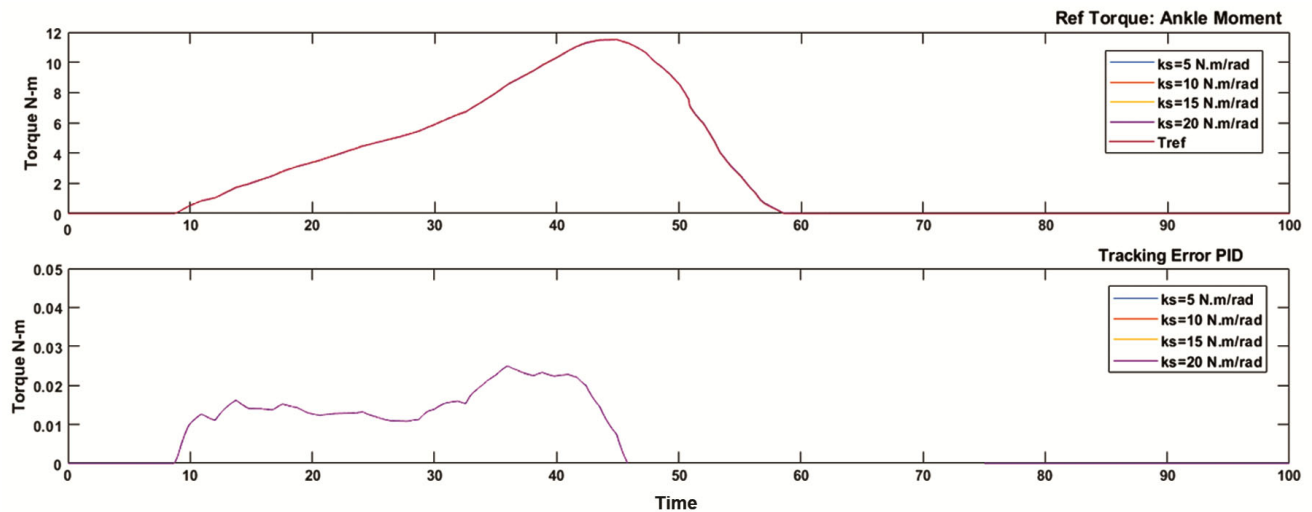


Fig. 10 — Ankle reference tracking and error (PID): (a) Ref Torque-Ankle moment, (b) Tracking error PID

makes it preferable for systems with unpredictable or complex. The findings align with existing literature on similar control strategies for series elastic actuators,<sup>23</sup> though direct comparisons are challenging due to differences in system configurations and methodologies. The significance of the ankle reference

trajectory is more as it is related to the gait. Simulation results for both control approaches are presented in Fig. 10 and Fig. 11 input is significant for ankle orthosis applications and is applied, as it likely represents a trajectory mimicking human ankle motion.

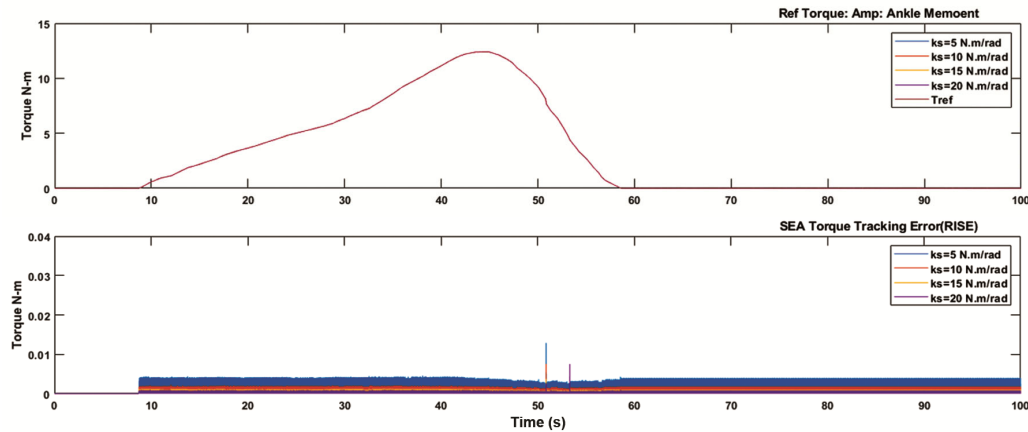


Fig. 11 — Ankle reference tracking and error (RISE): (a) Ref Torque-Amp-Ankle moment, (b) Torque tracking error

## Conclusions

The parametric optimization of the SEA for a wearable robotic AFO reveals that RISE offers superior precision for ankle motion tracking, particularly at higher stiffness ( $k_s = 20$ ), achieving near-zero errors for Ankle Ref. (RMSE: 0.0006, Mean: 0.0005), making it ideal for applications requiring high-fidelity control, such as assisting natural gait in ankle orthosis users. PID, while less precise, provides robust and stable performance across diverse inputs, particularly for complex trajectories like Trapezoidal and Chirp, which are relevant for dynamic gait conditions. Increased stiffness of the spring is associated with the amount of torque it can deliver or withstand. Considering the results, it stipulates RISE control for the ankle joint when the torque requirement is high and the ref trajectory resembles natural gait. Considering another perspective, it also promotes the use of PID-based control for training and exercise purposes, typically starting with lower torque applications and RISE control for assistance. Future work should focus on developing hybrid PID-RISE controllers to combine stability and precision. Optimizing RISE for challenging inputs like Chirp and validating these results in physical AFO prototypes to ensure real-world efficacy. The concept of variable stiffness is another aspect that needs attention in the future. Integrating variable stiffness actuators substantially increases their usability in rehabilitation and augmentation applications.

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