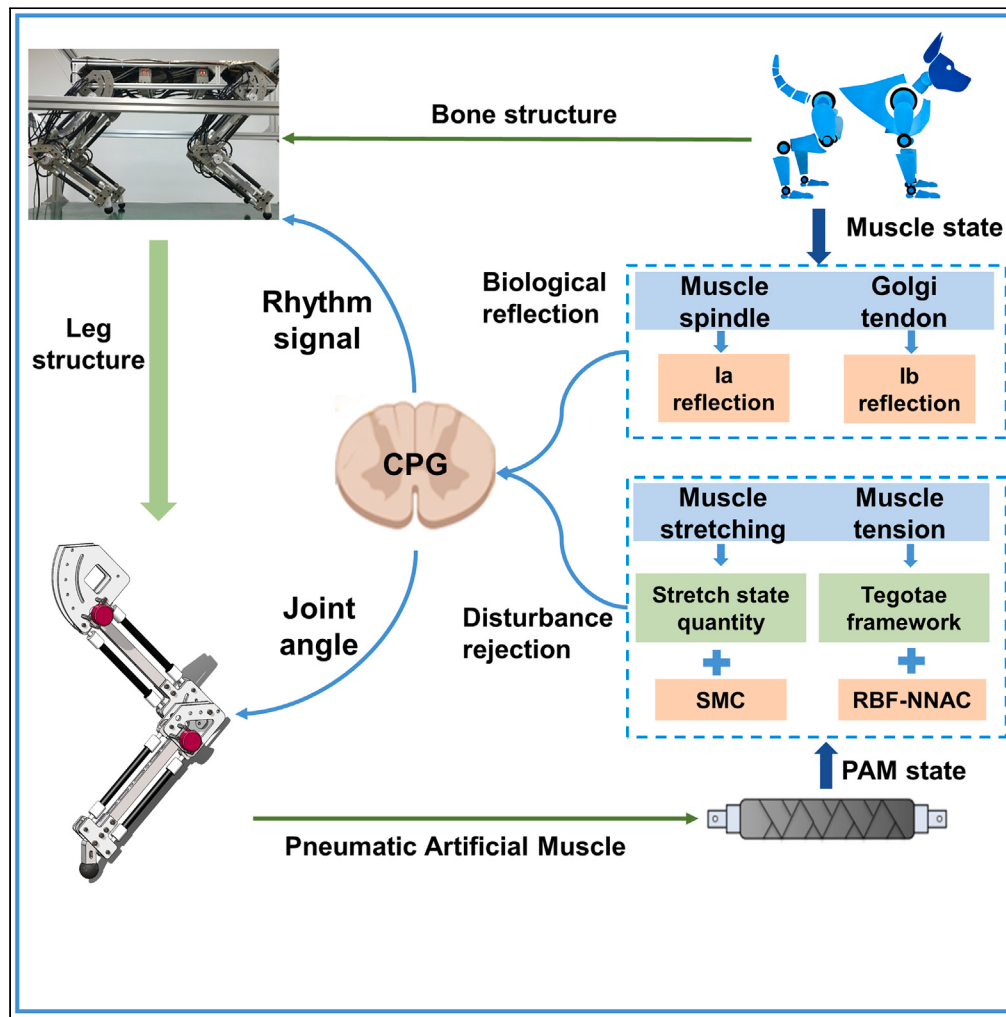


Article

Anti-disturbance control of CPG bionic reflection in pneumatic muscle actuator



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Highlights

Bionic reflex with CPG boosts anti-interference in pneumatic muscle robots

Spindle reflex with SMC reduces hip joint trajectory deviation under impact

CPG-based deep tendon reflex mitigates knee joint blocking forces

Both reflection methods have better performance than several contrast methods

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Article

Anti-disturbance control of CPG bionic reflection in pneumatic muscle actuator

Lina Wang,^{1,2} Zeling Chen,¹ Xiaofeng Wang,¹ and Binrui Wang^{1,2,3,*}

SUMMARY

Addressing the joint control problem of pneumatic muscle-driven robots, this study aims to design a bionic reflex mechanism to enhance the robots' adaptive capacity to various disturbances. Based on the biological reflex mechanism, we developed a spindle reflex and deep tendon reflex control system based on CPG (central pattern generator) to mitigate the sudden impact on the hip joint and the continuous blocking force on the knee joint, respectively. The spindle reflex controller incorporates the fast response of sliding mode control to effectively minimize the trajectory deviation of the hip joint under impact disturbances. The deep tendon reflex controller integrates RBF neural network adaptive control and the Tegotae framework to suppress excessive tension in the knee joint and augment the system's adaptability to the blocking force disturbances. The experimental results confirm that the two reflex mechanisms significantly enhance the robustness and flexibility of the pneumatic muscle-driven robot in motion.

INTRODUCTION

Pneumatic artificial muscle (PAM) is extensively utilized across the domains of restorative health care, intelligent industry, and bionic robot^{1–4} because of its affordable, boasting a superior power-to-weight ratio, and adaptability.^{5–7} The working principle of PAM is based on the change of internal gas pressure, and the power output is realized by adjusting the muscle length.⁸ However, PAM also faces some challenges, including its inherent nonlinear characteristics, dynamic uncertainty caused by gas compressibility, hysteresis, and creep phenomena.^{9–12} These characteristics increase the difficulty of control system design and pose a potential impact on system performance and reliability.

In the control system driven by pneumatic muscles, external disturbances, and internal uncertainties pose inevitable challenges. In response to these challenges, researchers have developed a variety of control strategies. Early PID control and sliding mode control (SMC),^{13,14} to the neural network and active disturbance rejection control.¹⁵ In recent years, many researchers have proposed some more powerful control methods. Cai¹⁶ et al. introduced auxiliary signals, which effectively deal with the saturation problem of control input. Through coordinate transformation, the auxiliary signals are integrated into the control design framework. They model all unknown modeling errors and external disturbances as an unknown nonlinear function that satisfies certain bounded conditions and design a parameter estimator to estimate its upper bound to achieve effective suppression of disturbances. Cao¹⁷ et al. proposed an adaptive surrogate-based robust control method for PAM and integrated it with a nonlinear disturbance observer. As the surrogate mass augments, the tracking deviation tends to gradually approach the boundary related to the disturbance estimation error, and enhance the system's efficiency and resilience in the face of unpredictable shocks and disturbances. Vo¹⁸ et al. suggested a responsive finite-duration tracking control strategy that is independent of force sensors, and utilized a force-driven time lag assessment approach to gauge the comprehensive system variability, thereby improving the control accuracy and reducing the chattering effect. However, most studies have the assumption that the collision disturbance or joint resistance disturbance encountered in practical applications is beyond the bound, which may lead to the failure of the control scheme to effectively deal with, and there may be a problem of compensation delay. Takahashi¹⁹ explored the possibility of realizing a biological-like reflection mechanism in a pneumatic muscle robot, and studied the two reflection paths of Ia and Ib, these two types of reflexes are derived from neurophysiology and refer to different types of spinal reflexes. The Ia fiber is mainly related to the muscle spindles in the muscle. When the muscle spindle is stretched, it triggers a rapid contraction reaction. Ib fibers are associated with Golgi tendon organs. When muscle strength reaches a certain threshold, it sends signals to the spinal cord, causing muscle relaxation and preventing excessive force. This kind of reflection mechanism is more suitable for biological principles than simple upper and lower bounds and has strong adaptability, which comes from the joint action of reasonable biological reflection mechanism and nervous system.²⁰ Bionic control mostly adopts a top-down method, which monitors the body or responds to stimuli by adjusting the output of the central pattern generator (CPG). Among them, sensory information is crucial for the formation of reflection mechanisms, but it is not

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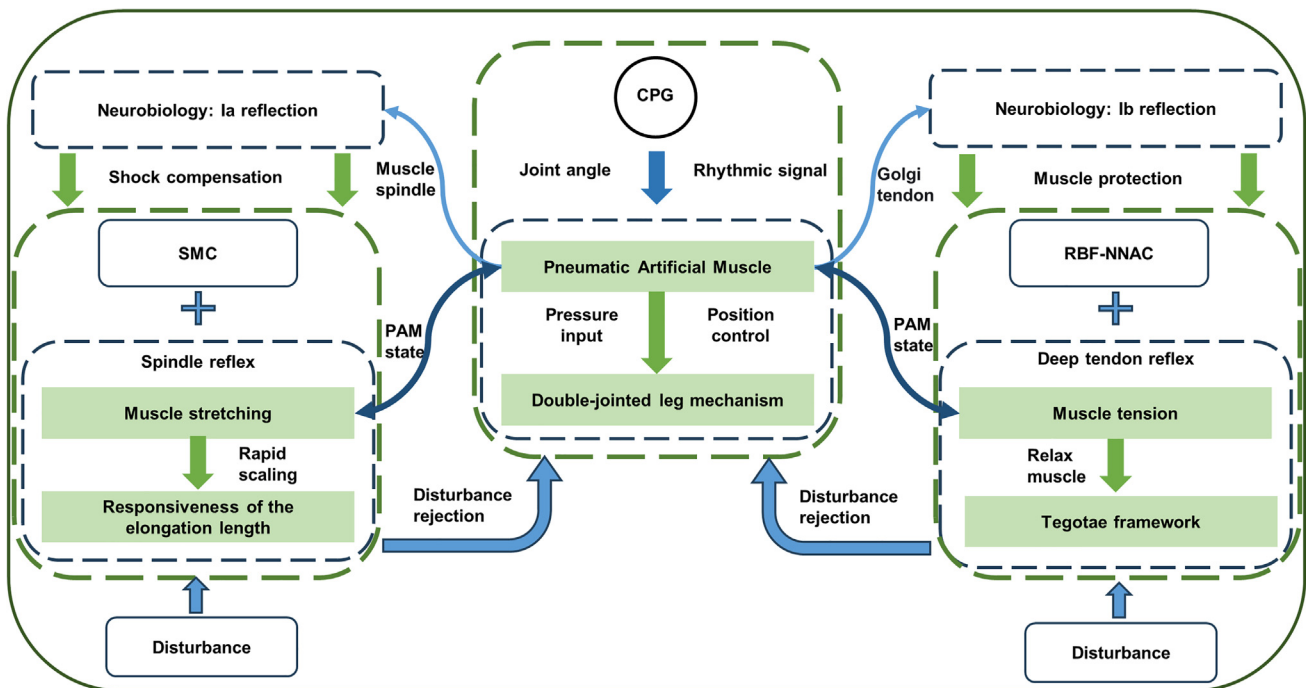


Figure 1. CPG bionic reflection control chart

easy to quickly integrate it into the control architecture.²¹ Owaki²² proposed the concept of the Tegotae method, it describes the degree of matching between the expected action and the perceived response. In robotics, the Tegotae method is used to measure the consistency between the expected motion instructions issued by the controller and the sensory information received based on the motion generated by the controller. This method is applied to the design of local controllers for robots, especially in the CPG-based walking model, Owaki studied the integration mechanism of bionic morphology, bionic structure, and bionic function, and had the guiding idea of designing a sensory feedback mechanism.

In this paper, the double-joint leg mechanism driven by the pneumatic muscle is designated as the subject, relying on the principle of biological bionics, aiming to compensate for the adverse effects caused by interference. As shown in Figure 1. In the proposed scheme, based on the different characteristics of Ia reflection and Ib reflection, two reflection disturbance suppression mechanisms of spindle reflex and deep tendon reflex are designed to adjust the trajectory tracking effect of the joint. According to the fast response ability of SMC and the adaptive learning generalization ability of RBF neural network adaptive control (RBF-NNAC), the spindle reflex and SMC methods are combined, respectively. Aiming at the telescopic reaction of the pneumatic muscle, the CPG external spindle reflex model is designed to

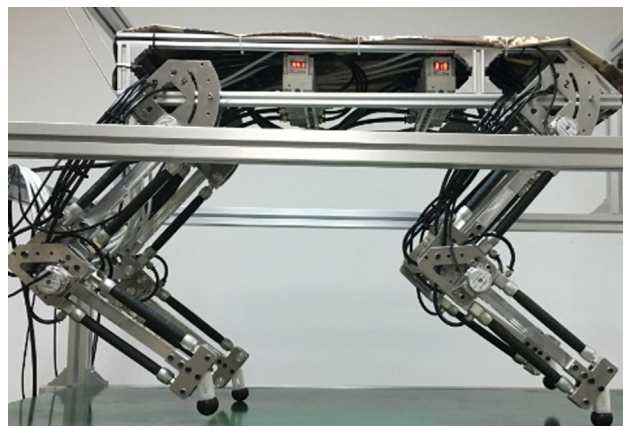


Figure 2. The engineered PAM quadrupedal robot

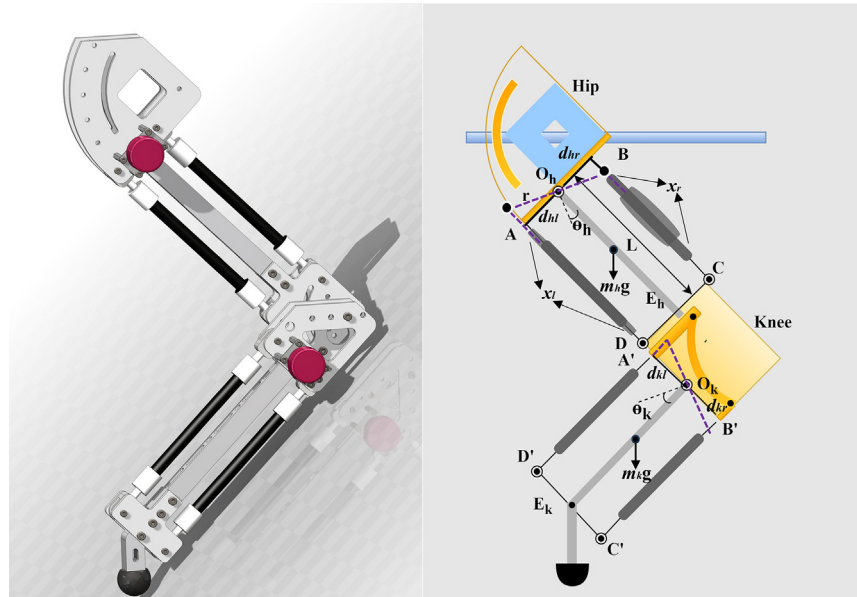


Figure 3. Single-leg structure model and schematic diagram

compensate for the disturbance. Combined with the deep tendon reflex and RBF-NNAC method, the deep tendon reflex pathway of CPG internal feedback was designed according to Tegotae framework to regulate the excessive tension of pneumatic muscles.

PNEUMATIC MUSCLE TWO-JOINT LEG MODEL

The pneumatic muscle quadruped robot imitating a German shepherd dog has been developed,²³ as shown in Figure 2. The leg mechanism features an open-chain design. The streamlined illustration of the individual leg apparatus is presented in Figure 3.

In the figure, h denotes the hip joint, k signifies the knee joint, the length of the thigh bone $O_h E_h$ and the calf bone $O_k E_k$ is L , and r indicates the distance from the PAM's attachment points to its central axis, the purple line in the figure shows the connection axis between the pneumatic muscle and the joint. d_{hl} and d_{hr} are the distances from the muscle's axis to the rotation axis during hip movement, that's the distance from O_h to AD and from O_h to BC, d_{kl} and d_{kr} are the respective distances during knee movement, that's the distance from O_k to A'D' and from O_k to B'C', subscripts l and r distinguish between the left and right PAM. The PAM model adopts a three-element model.

The hip joint's length corresponds to the span from point O_h and O_k , denoted by l_h ; the knee joint's length is the span from point O_k to E_k , denoted by l_k . The bilateral contraction span of the hip and knee joints' pneumatic muscles is denoted by x_l and x_r . The respective equivalent masses for the hip and knee joints are labeled as m_h and m_k . The model is expressed in the form of Equation 1:

$$\tau = D(\theta)\ddot{\theta} + C(\theta, \dot{\theta}) + f(\theta) \quad (\text{Equation 1})$$

$$\text{Where, } D = \begin{bmatrix} (m_h + m_k)l_h^2 + m_k l_k^2 + & m_k l_k^2 + m_k l_h l_k \sin \theta_k \\ 2m_k l_h l_k \sin \theta_k & m_k l_k^2 + m_k l_h l_k \sin \theta_k \\ m_k l_k^2 + m_k l_h l_k \sin \theta_k & m_k l_k^2 \end{bmatrix}$$

$$C = \begin{bmatrix} 2m_k l_h l_k \dot{\theta}_h \dot{\theta}_k \cos \theta_k + m_k l_h l_k \dot{\theta}_k^2 \cos \theta_k \\ -m_k l_h l_k \dot{\theta}_h^2 \cos \theta_k \end{bmatrix}$$

$$f = \begin{bmatrix} (m_h + m_k)g l_h \sin(\theta_h + \pi/4) + \\ m_k g l_k \sin(\theta_h + \theta_k - \pi/4) \\ m_k g l_k \sin(\theta_h + \theta_k - \pi/4) \end{bmatrix}, \theta_h \text{ and } \theta_k \text{ are the swing angles of the hip and knee joints, respectively.}$$

CONTROLLER DESIGN

The spindle between muscle fibers is extremely sensitive to changes in muscle length, and its rapid response mechanism is crucial for motion control. The deep tendon reflex, triggered by the tendon organ in the tendon, responds to changes in muscle tension and forms a negative feedback mechanism to maintain the stability of muscle tension.²⁴ In biological kinematics, the hip joint occupies a larger value in gait, while

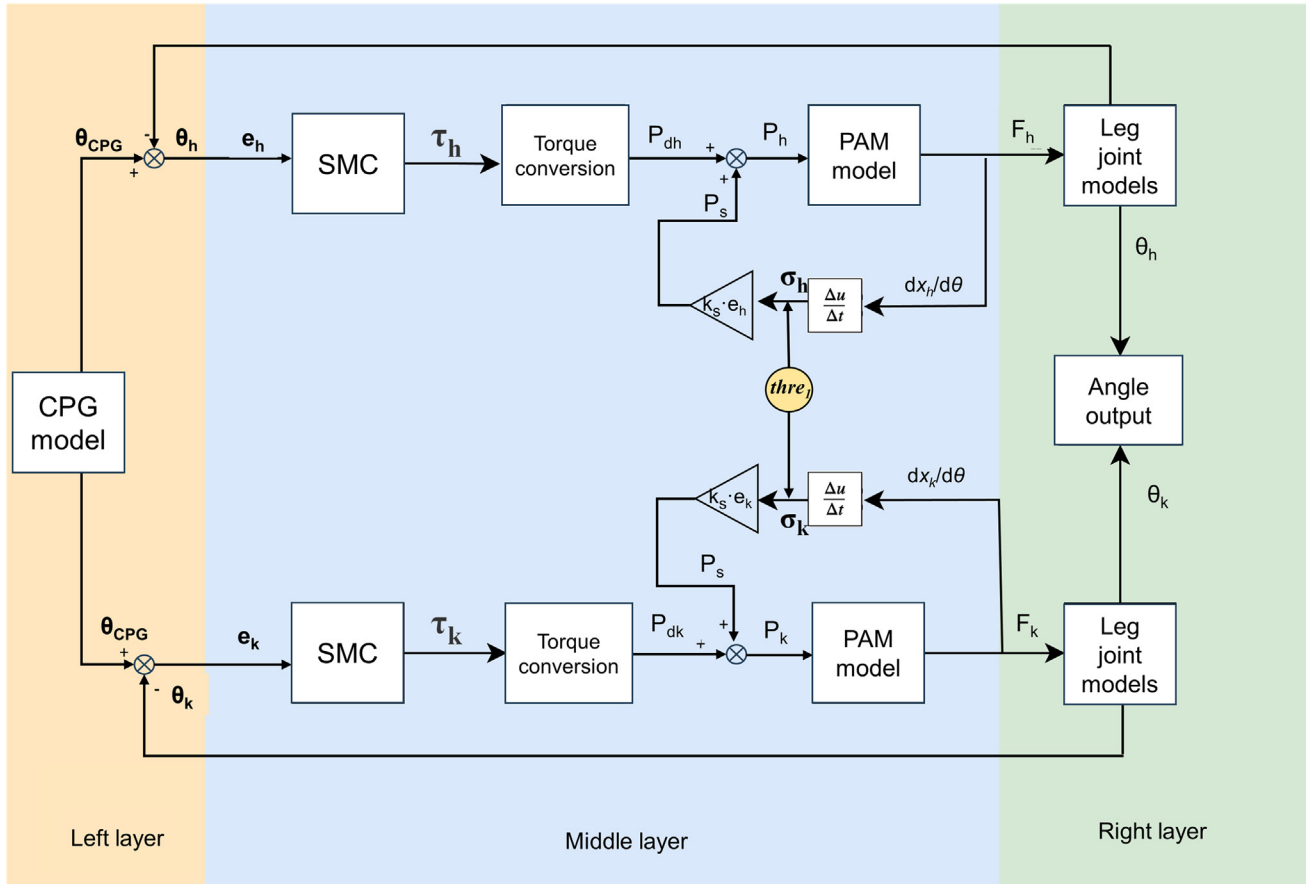


Figure 4. Model of spindle reflector controller

the knee joint frequently participates in tendon reflex, such as the knee bounce reflex.²⁵ Therefore, the spindle reflex pathway is designed for the hip joint of the pneumatic muscle leg mechanism, and the deep tendon reflex pathway is designed for the knee joint.

Construction of CPG control network

The CPG network functions as a system of interconnected nonlinear oscillators, forming a distributed configuration. It can realize the occurrence of rhythmic signals generated by phase synchronization and alter the oscillator coupling to produce spatiotemporal sequences with varying phase relationships, thereby enabling diverse motion patterns.²⁶ In this section, the Hopf oscillator is employed to develop the CPG framework, and the model formulation of adding the feedback term is as follows:

$$\left\{ \begin{array}{l} \begin{bmatrix} \dot{\gamma}_i \\ \dot{\lambda}_i \end{bmatrix} = \begin{bmatrix} \alpha(\mu - r_i^2) & -\omega_i \\ \omega_i & \alpha(\mu - r_i^2) \end{bmatrix} \begin{bmatrix} \gamma_i + feed_{\gamma_i} \\ \lambda_i + feed_{\lambda_i} \end{bmatrix} + \sum_{j=1}^4 R(\theta_j^i) \begin{bmatrix} \gamma_j \\ \lambda_j \end{bmatrix} \\ r_i^2 = (\gamma_i + feed_{\gamma_i})^2 + (\lambda_i + feed_{\lambda_i})^2 \\ \omega = \frac{\omega_{st}}{e^{-a(\lambda_i + feed_{\lambda_i})} + 1} + \frac{\omega_{sw}}{e^{a(\lambda_i + feed_{\lambda_i})} + 1} \\ \omega_{st} = \frac{1 - \beta}{\beta} \omega_{sw} \\ \theta_{hi} = \gamma_i \\ \theta_{ki} = \begin{cases} -\text{sgn}(\psi) \frac{A_k}{A_h} (\lambda_i + feed_{\lambda_i}) + feed_{\lambda_i}, & \lambda_i \leq feed_{\lambda_i} \\ feed_{\lambda_i}, & \lambda_i > feed_{\lambda_i} \end{cases} \end{array} \right. \quad (\text{Equation 2})$$

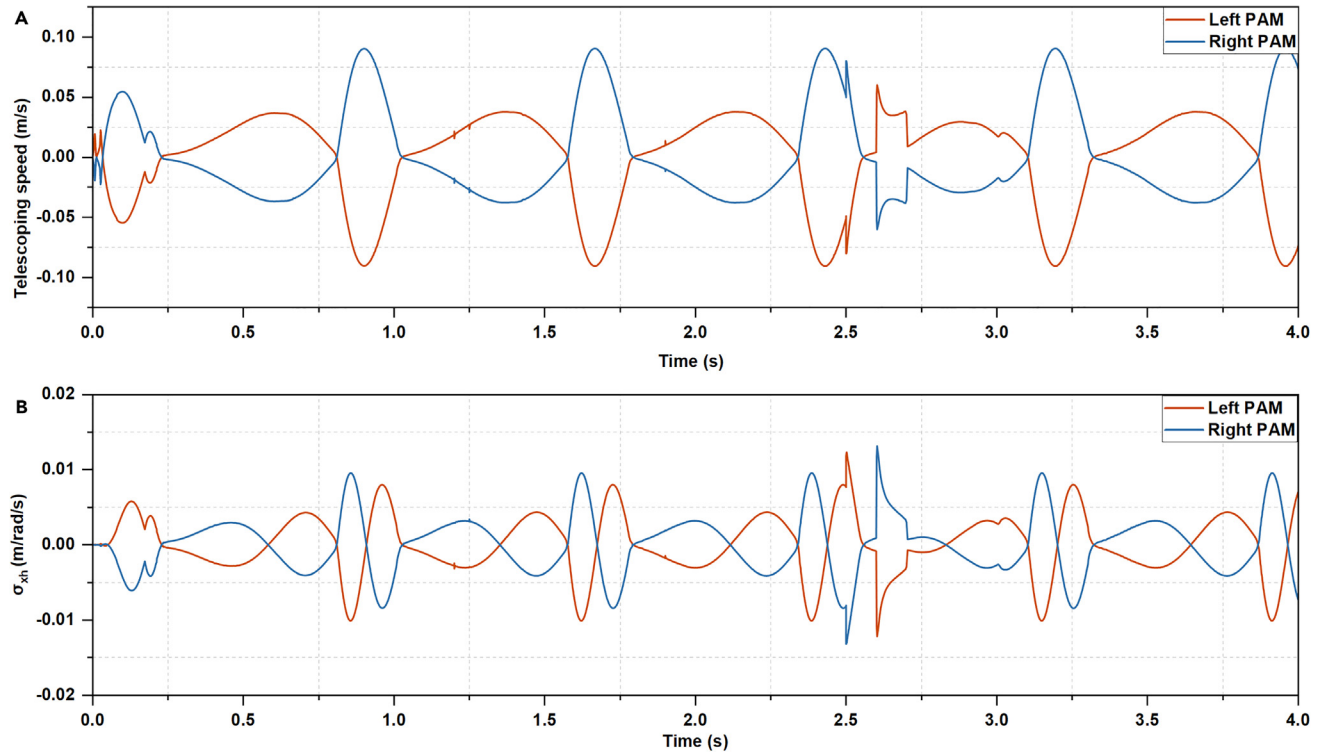


Figure 5. Comparison of PAM telescoping speed and σ_h
(A) Comparison of PAM telescoping speed on both side.
(B) Comparison of σ_h .

Where, γ and λ are state variables, $r^2 = \gamma^2 + \lambda^2$, α is the speed of the oscillator converging to the limit cycle, μ is the square of the amplitude of the oscillator, $feed_{\gamma i}$ is the feedback input of γ , $feed_{\lambda i}$ is the feedback input of λ , ω_{st} is the support phase frequency, ω_{sw} is the swing phase frequency, β is the load factor, A_h and A_k are the amplitudes for the hip and knee joints, this equation describes how each joint responds to internal dynamics, coupling effects, and external feedback to produce rhythm signals that output control signals for the leg joints.

Spindle reflection controller design

As shown in Figure 4, the controller hierarchy diagram of the spindle reflex pathway shows three main levels. The left layer in the yellow background consists of a CPG control network whose output rhythm signal defines the target trajectory of the joint. The middle layer with a blue background is integrated with a sliding mode controller, and the position control law is designed according to the expected angle signal of the left layer and the actual angle signal of the right layer, and the output torque is converted into a pressure signal through a torque converter to drive the pneumatic muscle model. The pneumatic muscle model outputs the expansion length and tension of the pneumatic muscle. Compensation of pneumatic muscle pressure by the excited spindle of the intermediate layer. The right layer with the green background realizes the dynamic model of the leg joint driven by the pneumatic muscle, receives the tension signal from the middle layer, and outputs the actual joint angle signal.

Take the error as the expected joint angle minus the actual angle, θ_{hd} and θ_{kd} are the desired angles for the hip and knee joints.

$$\mathbf{e} = \begin{bmatrix} e_h \\ e_k \end{bmatrix} = \begin{bmatrix} \theta_{hd} - \theta_h \\ \theta_{kd} - \theta_k \end{bmatrix} \quad (\text{Equation 3})$$

Let the sliding mode function by:

$$\mathbf{s} = \begin{bmatrix} c_h e_h + \dot{e}_h \\ c_k e_k + \dot{e}_k \end{bmatrix} \quad (\text{Equation 4})$$

where, c_h and c_k are both positive constants, respectively.

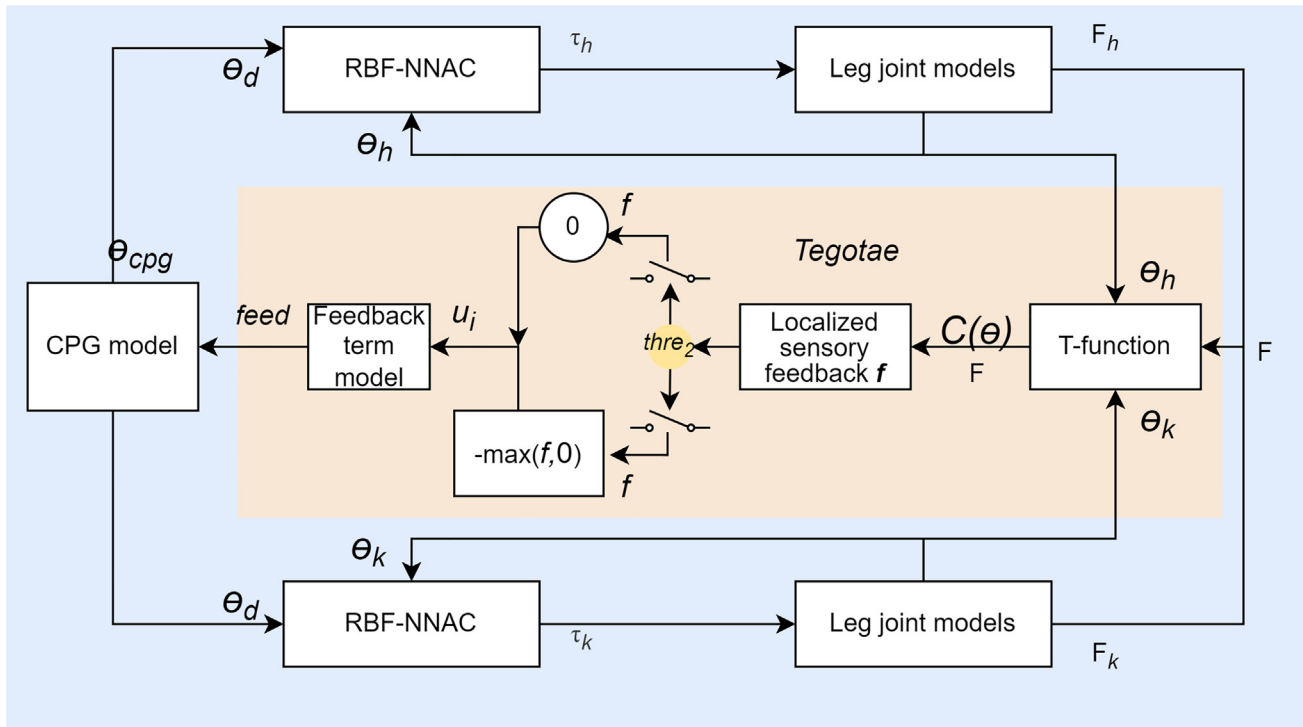


Figure 6. Model of deep tendon reflex controller

Based on the reaching law $\dot{s} = -\eta \text{sgn}(s)$, the SMC law is:

$$\begin{bmatrix} \tau_h \\ \tau_k \end{bmatrix} = D \begin{bmatrix} c_h \dot{e}_h + \ddot{\theta}_{hd} + C + f + \eta_h \text{sgn}(s_h) \\ c_k \dot{e}_k + \ddot{\theta}_{kd} + C + f + \eta_k \text{sgn}(s_k) \end{bmatrix} \quad (\text{Equation 5})$$

According to the Ia reflex proposed in Takahashi et al.¹⁹, the pneumatic muscle's contraction speed serves as the benchmark for reflex activation, which can simulate the biological Ia reflex when the pneumatic muscle joint is disturbed. However, under the rhythmic signal of CPG, the contraction speed of the pneumatic muscle may not significantly reflect some disturbances, resulting in the Ia reflex in Takahashi et al.¹⁹ cannot be activated. In view of this, this paper introduces a new parameter σ , which quantifies the responsiveness of the elongation length to temporal angular variations. The activation criterion of the spindle reflection, the σ_h of the bilateral pneumatic muscles adjacent to the hip joint can be expressed as:

$$\begin{cases} \sigma_{hl}(\theta_h) = \frac{d}{dt} \left(\frac{dx_{hl}}{d\theta_h} \right) \\ \sigma_{hr}(\theta_h) = \frac{d}{dt} \left(\frac{dx_{hr}}{d\theta_h} \right) \end{cases} \quad (\text{Equation 6})$$

where, x_{hl} and x_{hr} are the contraction lengths of the bilateral pneumatic muscles adjacent to the hip joint, which are expressed as follows:

$$\begin{aligned} x_{hl} &= L_0 - \sqrt{[(1 - \cos \theta_h)r + L \sin \theta_h]^2 + (r \sin \theta_h + L \cos \theta_h)^2} + L_{link} \\ x_{hr} &= L_0 - \sqrt{[(\cos \theta_h - 1)r + L \sin \theta_h]^2 + (r \sin \theta_h - L \cos \theta_h)^2} + L_{link} \end{aligned} \quad (\text{Equation 7})$$

Table 1. CPG walk gait model parameters

Parameters	Value	Parameters	Value
α	10000	β	0.75
μ	0.04	A_h	8.3(°)
a	100	A_k	5.3(°)
ω_{sw}	5π		

Table 2. PAM and leg model parameters

Parameters	Value	Parameters	Value
m_h	0.75(m)	L	0.24(m)
m_k	0.55(m)	l_k	0.24(m)
l_h	0.28(m)	L_0	0.14(m)
r	0.03(m)	g	9.8(m/s ²)
L_{link}	0.07(m)	v_1	-24.22
v_2	67.37	v_3	5.10
v_4	4.46	c_1	231.68

Here, L_0 and L_{link} represent the nominal length of the pneumatic muscle and the dimensions of the connecting rods on both sides, respectively. As shown in Figure 5, the alterations in the contraction speed of the bilateral pneumatic muscles near the hip joint and the change of σ from 2.5s to 2.7s by the trapezoidal disturbance with a peak of 0.1rad are shown. Under the CPG rhythm signal, the upper part of Figure 5 is the mutation of the expansion velocity of the pneumatic muscles disturbed by the disturbance, but it cannot exceed the peak value in the cycle, while the activation standard σ_h designed in this scheme under Figure 5 can exceed the peak value in the cycle. In other words, it can effectively tell us how the reactivity of the elongation length to angular shifts fluctuates over time under disturbances.

By imitating the biological spindle reflex, when the activation standard σ_h of a muscle in the hip joint exceeds the threshold $thre_1$, the spindle reflex pathway is activated, and the output stimulation signal is sent to the middle controller to adjust the input pressure P_h of the pneumatic muscle. The pneumatic muscle on one flank of the hip joint contracts while the opposite side expands, so that the P_h satisfies the following expression:

$$\begin{cases} P_{hl} = P_{dhl} \pm P_s \\ P_{hr} = P_{dhr} \mp P_s \end{cases} \quad (\text{Equation 8})$$

where, P_{dh} is the output pressure obtained by torque conversion, and P_s is the pressure compensated by the spindle reflection path.

$$P_{dh} = \begin{cases} (F - v_2x)/(c_1 - v_1x) \\ (F - v_4x)/(c_1 - v_3x) \end{cases} \quad (\text{Equation 9})$$

$$P_s = \begin{cases} k_s \cdot e \cdot \sigma_{hl} & \sigma_{hl} \geq thre_1 \\ 0 & \sigma_{hl} < thre_1 \end{cases} \quad (\text{Equation 10})$$

where, F is the joint tension, v_1, v_2, v_3, v_4, c_1 are the coefficients of the pneumatic muscle model, and k_s is a constant. Taking the left pneumatic muscle as an example, when σ_{hl} does not reach the set threshold, the pressure P_s reflected by the spindle is 0, otherwise, the corresponding compensation pressure is generated.

Design of deep tendon reflex controller

As shown in Figure 6, the hierarchical structure diagram of the deep tendon reflex controller clearly defines the functions of the inner and outer layers. The outer layer includes the CPG model, RBF neural network adaptive controller, and pneumatic muscle single-leg mechanism model. This layer is responsible for approximating the uncertainty of the pneumatic muscle leg mechanism, and a neural network adaptive control law based on joint torque is designed. In addition, it is also responsible for outputting the tension and joint angle of the pneumatic muscle. The CPG model receives feedback signals from the inner layer and generates regular gait signals at the anticipated angle of the joint. The inner layer includes the modeling of Tegotae algorithm and the CPG feedback model, which together constitute the deep tendon reflex pathway.

The error function is defined by Equation 3:

$$r_{PAM} = \dot{e} + He \quad (\text{Equation 11})$$

Table 3. Parameters of the spindle reflection control system

Parameters	Value	Parameters	Value
c_h	51.35	η_h	50
c_k	50	η_k	67.72
k_s	3000	$thre_1$	0.04

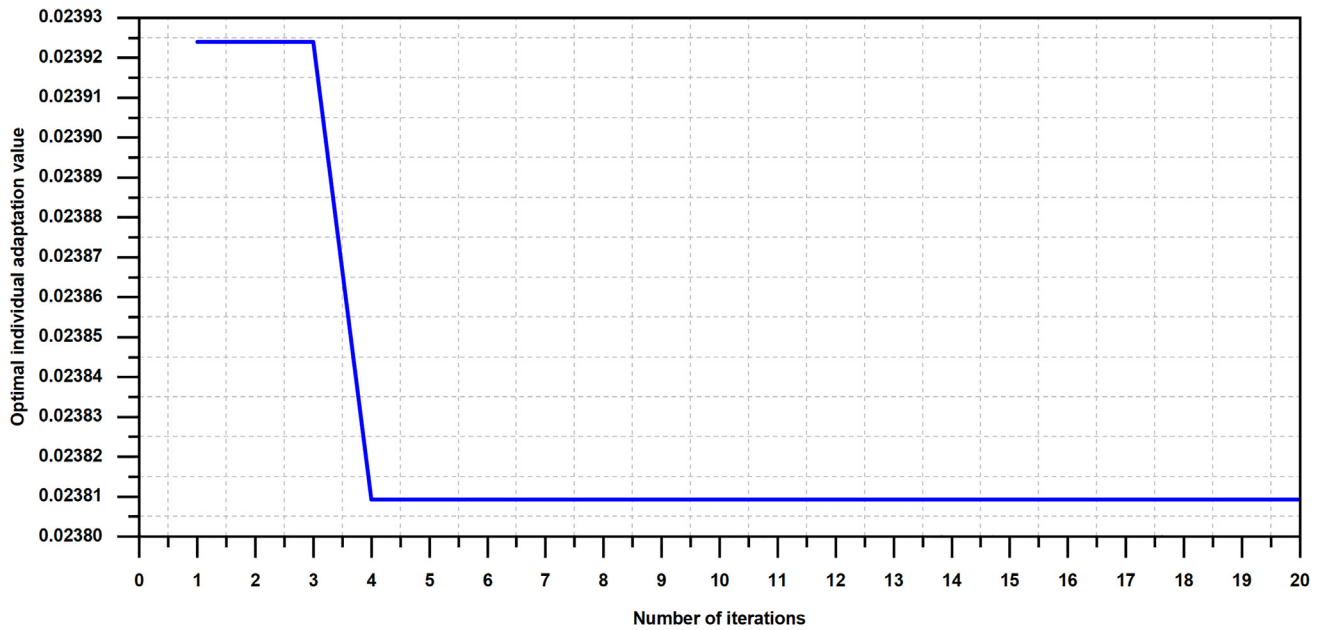


Figure 7. Iterative process of Beetle Antennae search algorithm

where, $H = H^T > 0$, can get:

$$\dot{\theta} = \dot{\theta}_d + H\epsilon - r_{PAM} \quad (\text{Equation 12})$$

From Equations 1 and 12, we can obtain:

$$\begin{aligned} D\dot{r}_{PAM} &= D(H\dot{\epsilon} + \ddot{\theta}_d - \ddot{\theta}) = D(H\dot{\epsilon} + \ddot{\theta}_d) - D\ddot{\theta} \\ &= D(H\dot{\epsilon} + \ddot{\theta}_d) - \tau + C + F + \tau_d = \varpi + \tau_d - \tau \end{aligned} \quad (\text{Equation 13})$$

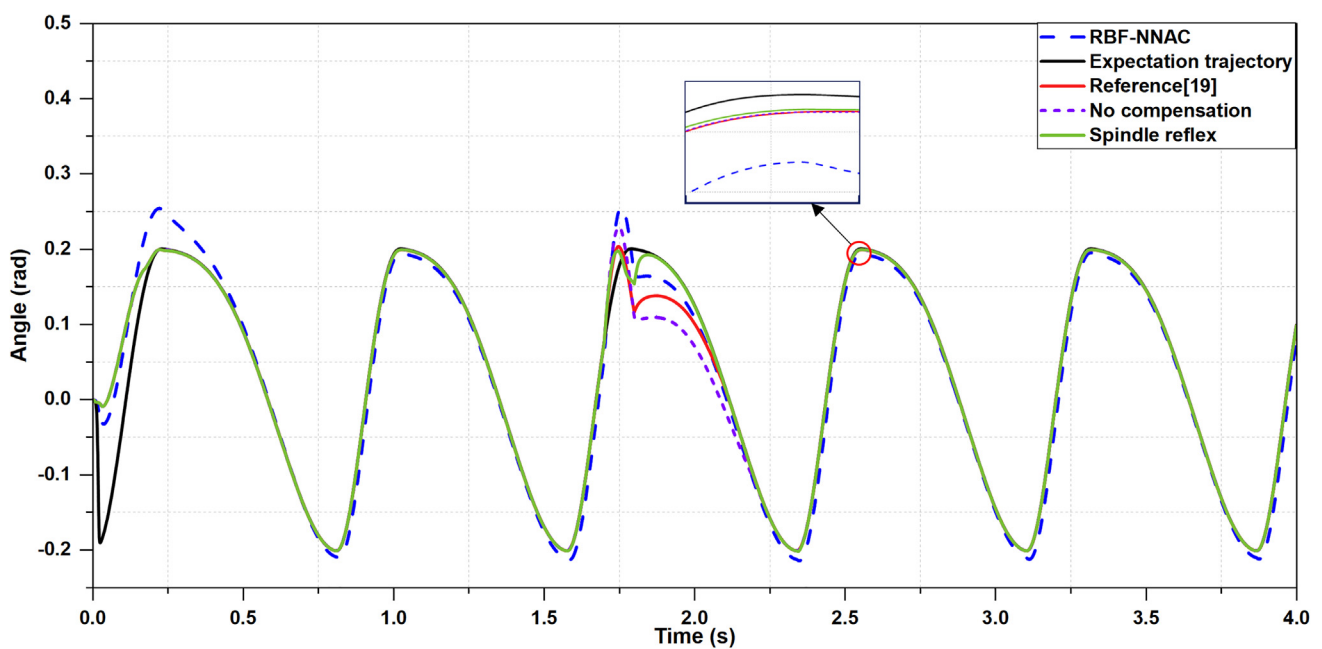


Figure 8. Comparison of hip angles under sinusoidal impact perturbations

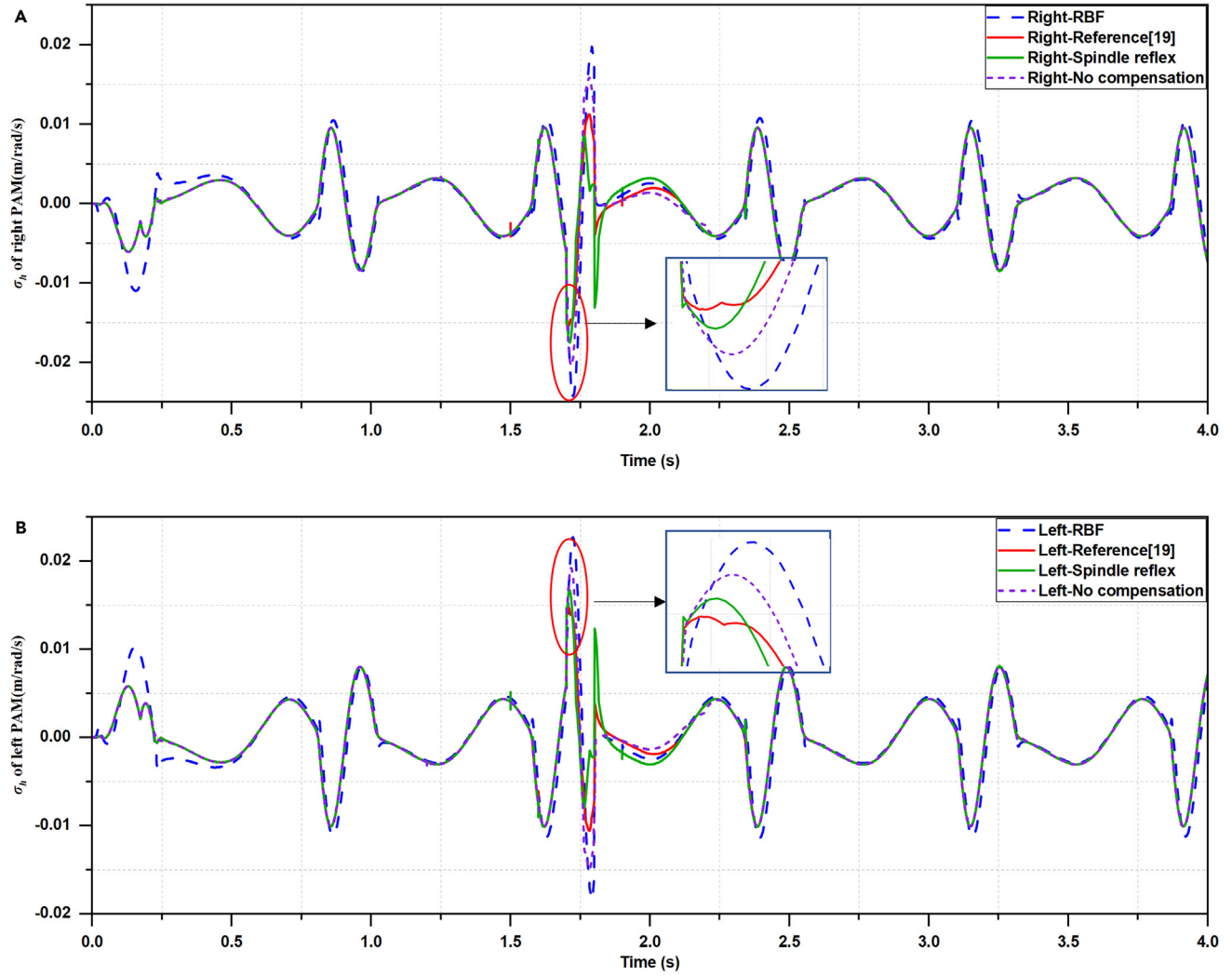


Figure 9. Comparison of σ_h under sinusoidal impact perturbations

(A) Change of σ_h of right PAM under four methods.

(B) Change of σ_h of left PAM under four methods.

where, τ_d is the disturbance term and $\varpi = D(\ddot{\theta}_d + H\dot{e}) + C + F$ is the uncertainty term.

Taking $X = [e \quad \dot{e} \quad \theta_d \quad \dot{\theta}_d \quad \ddot{\theta}_d]^T$ as the input network, the RBF neural network is used to approximate ϖ . The ideal RBF network is:

$$\begin{cases} \phi_j = \exp(-\|x - c_j\|^2 / b_j^2) \\ y = W\phi(x) \end{cases} \quad (\text{Equation 14})$$

where, x is the network input, j is the j th node of the hidden layer, c_j is the center parameter of the Gaussian basis function, b_j is the width parameter, and W is the network weight.

The RBF neural network control law is:

$$\tau = \widehat{W}^T \phi(x) + K_v r_{PAM} - v \quad (\text{Equation 15})$$

where, $\widehat{W}$ is the estimated value of the weight, K_v is a positive definite diagonal matrix, and $v = -\epsilon_n \text{sgn}(r_{PAM})$ is a robust term to reduce the approximation error. The adaptive law of neural network weights is:

$$\dot{\widehat{W}} = \Gamma \phi r_{PAM}^T \quad (\text{Equation 16})$$

where Γ is a positive definite diagonal matrix.

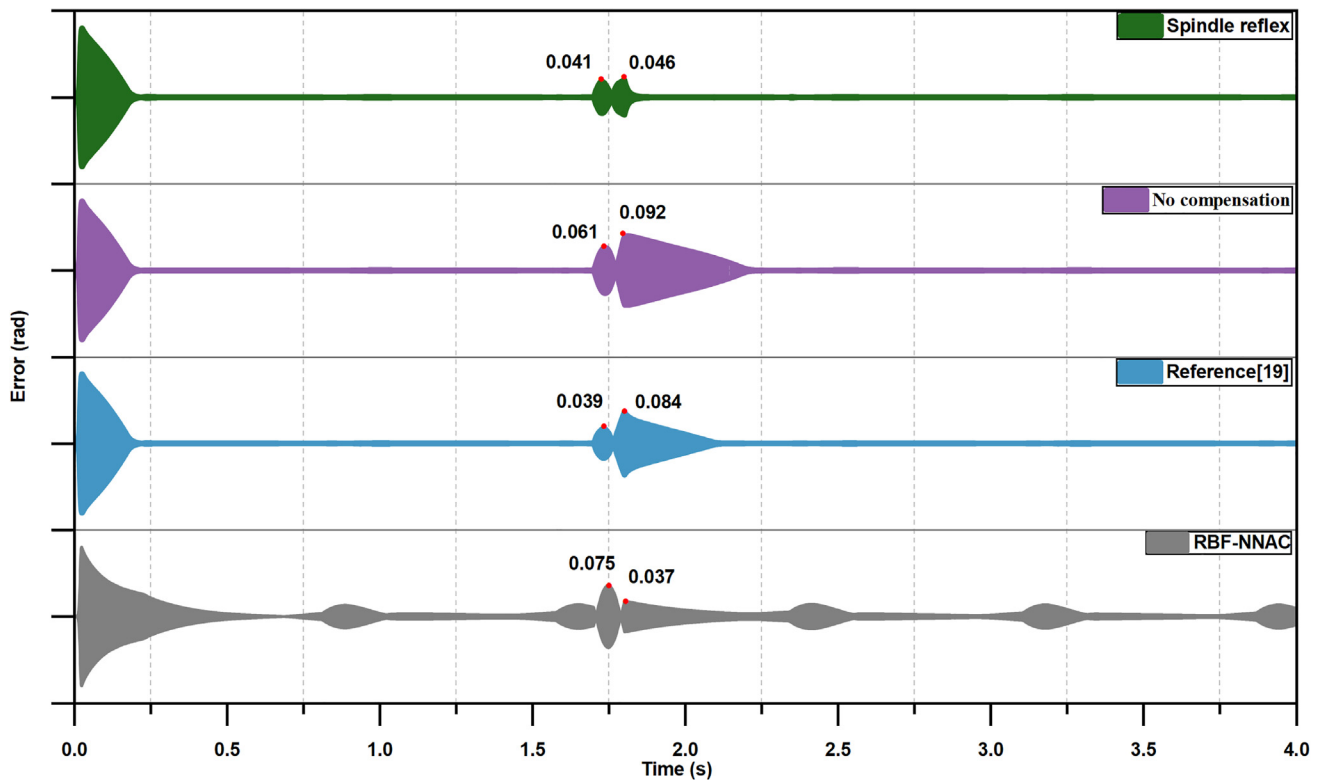


Figure 10. Comparison of error under sinusoidal impact perturbations

Tegotae is a method that measures the congruence between the perceived reaction and the controller's anticipation and is often used to design CPG-based controllers. Firstly, the T function is obtained by quantifying Tegotae, and the expression (17) based on variable separation is obtained, which is expressed in the form of joint angle θ and pneumatic muscle tension F :

$$T(\theta, F) = C(\theta)S(F) = -\cos(\theta) \cdot F \quad (\text{Equation 17})$$

In the case of increased joint resistance of the pneumatic muscle, the control system needs to make adaptive adjustments to the resistance changes. More air pressure will be input into the pneumatic muscle. Excessive increase in air pressure will cause the joint angle to exceed the

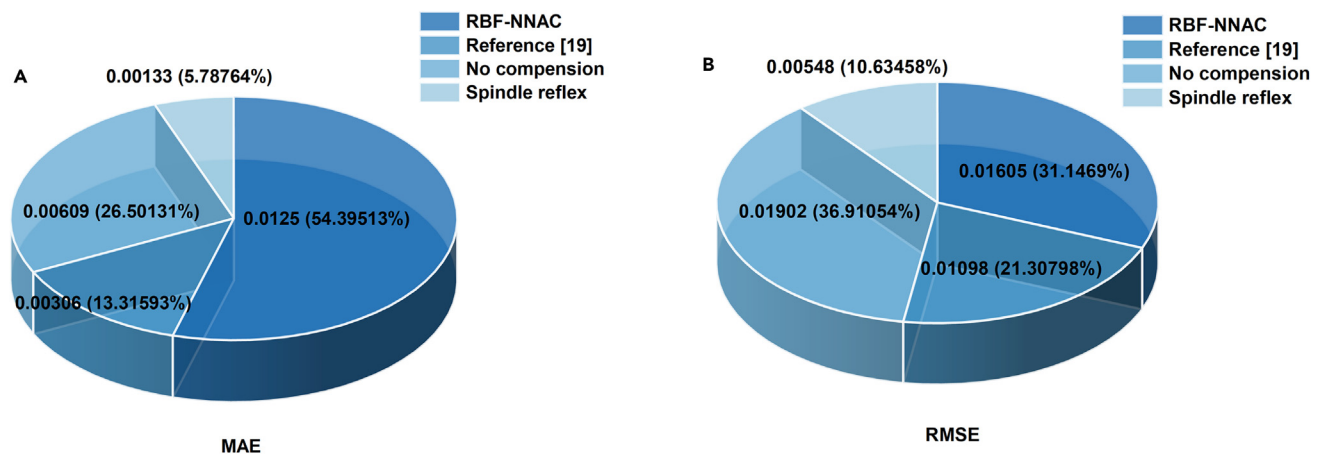


Figure 11. Comparison of MAE and RMSE under sinusoidal impact perturbations

(A) Comparison of MAE under sinusoidal impact perturbations.
(B) Comparison of RMSE under sinusoidal impact perturbations.

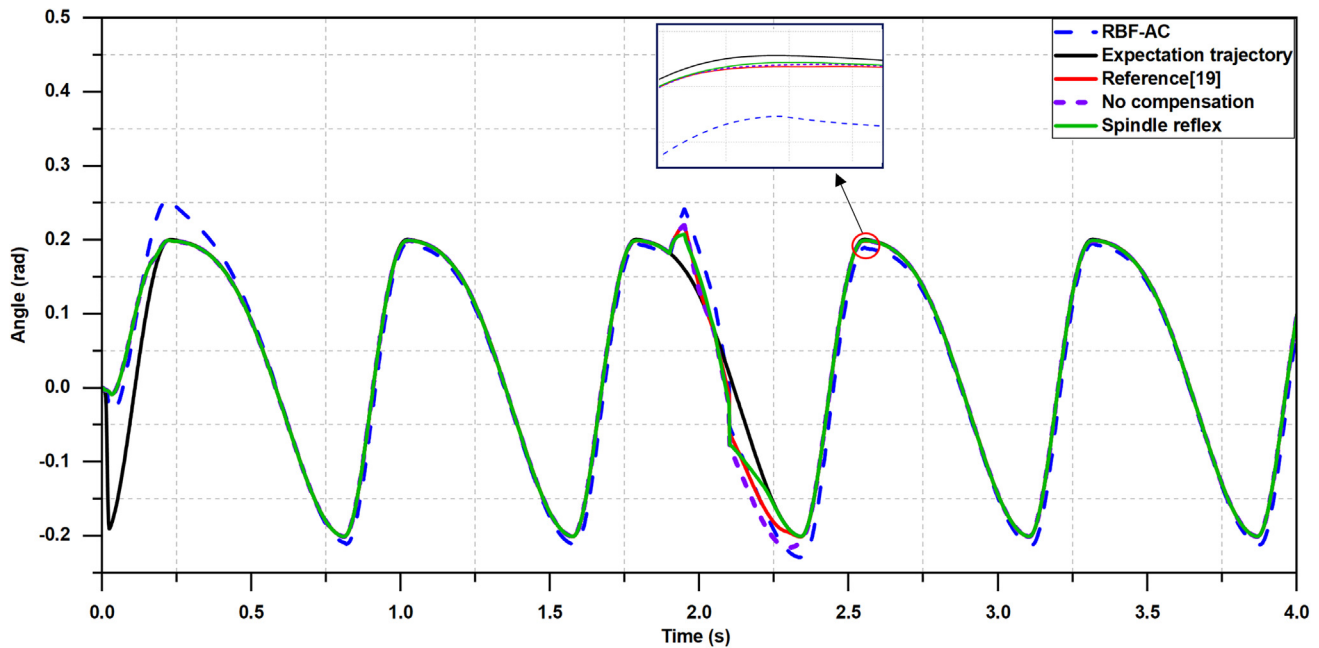


Figure 12. Comparison of hip angles under trapezoidal impact perturbations

expected range. The design of Equation 17 makes Tegotae decrease when the tension of the pneumatic muscle is detected to be too large. The small amount of T function indicates that the tension of the pneumatic muscle is too large and the joint angle exceeds the stable range. Therefore, local sensory feedback f_T is designed to stabilize Tegotae, that is, the amount of T function is increased by adjusting θ . f_T is expressed as follows:

$$f_T = k_t \frac{\partial T(\theta, F)}{\partial \theta} = k_t \cdot \sin \theta \cdot F \quad (\text{Equation 18})$$

where, k_t is the coefficient constant.

In the control system of this scheme, how to call the adjustment function of f_T depends on the angle received by the joint, and the CPG model with feedback term satisfies this requirement.

The feedback feed received by the CPG is designed as:

$$u_i = \begin{cases} -\max(0, f) & T(\theta, F) \leq \text{thre}_2 \\ 0 & T(\theta, F) > \text{thre}_2 \end{cases} \quad i = 1, 2 \quad (\text{Equation 19})$$

where, u_1 and u_2 are the individual feedback components for the hip and knee joints. Once f_T is a negative feedback term, it will disappear, and the direction is opposite to f_T , that is, CPG needs to act on the force opposite to the excessive tension.

RESULTS AND DISCUSSION

In this research, the efficacy of the spindle reflex control system and the deep tendon reflex control system were verified for two different muscle states. Firstly, two kinds of sudden shocks with different amplitudes were applied to the pneumatic muscle on the hip joint to evaluate the anti-disturbance ability of the spindle reflection on the pneumatic muscle. Secondly, to verify the effectiveness of deep tendon reflex in compensating the excessive tension of pneumatic muscle and inhibiting external interference, continuous blocking force and external interference were applied to the knee joint of the pneumatic muscle leg mechanism, respectively. In both cases, the rhythm signal output by CPG is a walk gait signal with an amplitude of 0.2 rad. The detailed parameters are presented in Table 1.

Anti-interference verification of spindle reflection control system

In the process of hip joint movement, two different impact disturbances are added. One is a sinusoidal signal with an amplitude of 0.1 rad and a frequency of 31.42 rad/s in the range of 1.7 s–1.8 s. The other is the trapezoidal signal with a peak value of 0.1 rad, rising slope of 2 and falling slope of -2 in the range of 1.9 s–2.1 s. These two types of perturbations often have the effect of simulating collisions of elasticity²⁷ and incomplete rigidity,²⁸ which is more in line with the characteristics of pneumatic muscles as flexible actuators.^{29,30} The parameters of the pneumatic muscle and leg model are shown in Table 2, and the parameters for the spindle reflex control system are detailed in Table 3. Among them, the

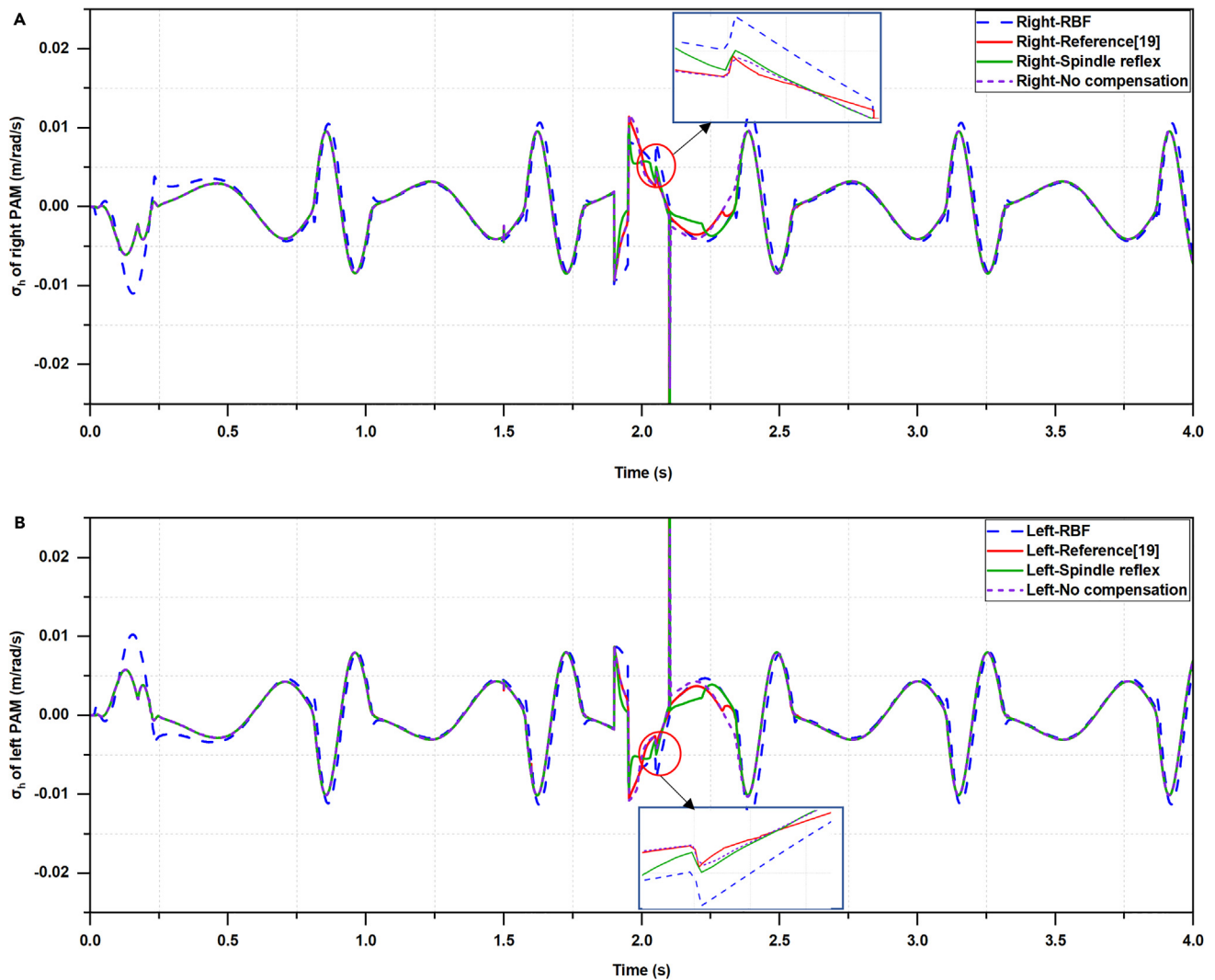


Figure 13. Comparison of σ_h under trapezoidal impact perturbations

(A) Change of σ_h of right PAM under four methods.

(B) Change of σ_h of left PAM under four methods.

sliding mode surface coefficient and the reaching law coefficient of the sliding mode controller are selected after the iterative optimization of the beetle whisker algorithm. The fitness function value changes with the number of iterations as shown in Figure 7, and the optimal value is reached in the fourth iteration.

Firstly, the corresponding performance of three different control methods and desired angles under sinusoidal impact disturbance is shown in Figure 8. The black line is the desired trajectory without interference, the blue line is the trajectory of the RBF-NNAC method, the red line is the trajectory of the method in Takahashi et al.¹⁹, the purple dash line is the angle trajectory without compensation, and the green line is the trajectory after the spindle reflection compensation. The change of σ_h is shown in Figure 9. In Figure 8, the angles of all methods remain stable before the impact occurs. When the sinusoidal impact occurs, as shown in Figure 9, σ_h exceeds the threshold. At this time, all three methods suppress the interference to varying degrees. RBF-NNAC is most affected by the impact disturbance, but the angle convergence speed is improved. The reflection behavior of Takahashi et al.¹⁹ can significantly reduce the angle mutation under the impact and pull the angle under the reflection behavior to resist the disturbance. In contrast, the proposed spindle reflection method has the best anti-interference effect and has a faster convergence speed than Takahashi et al.¹⁹ and as shown in the partially enlarged part of Figure 8, the tracking effect of RBF-NNAC without disturbance is the worst. The proposed method is slightly better than other methods.

Figure 10 is a kite diagram of trajectory tracking error with three methods and no compensation. Compared with the case without compensation, the method proposed in Takahashi et al.¹⁹ shows a certain decrease in error. RBF-NNAC can accelerate the error convergence to the

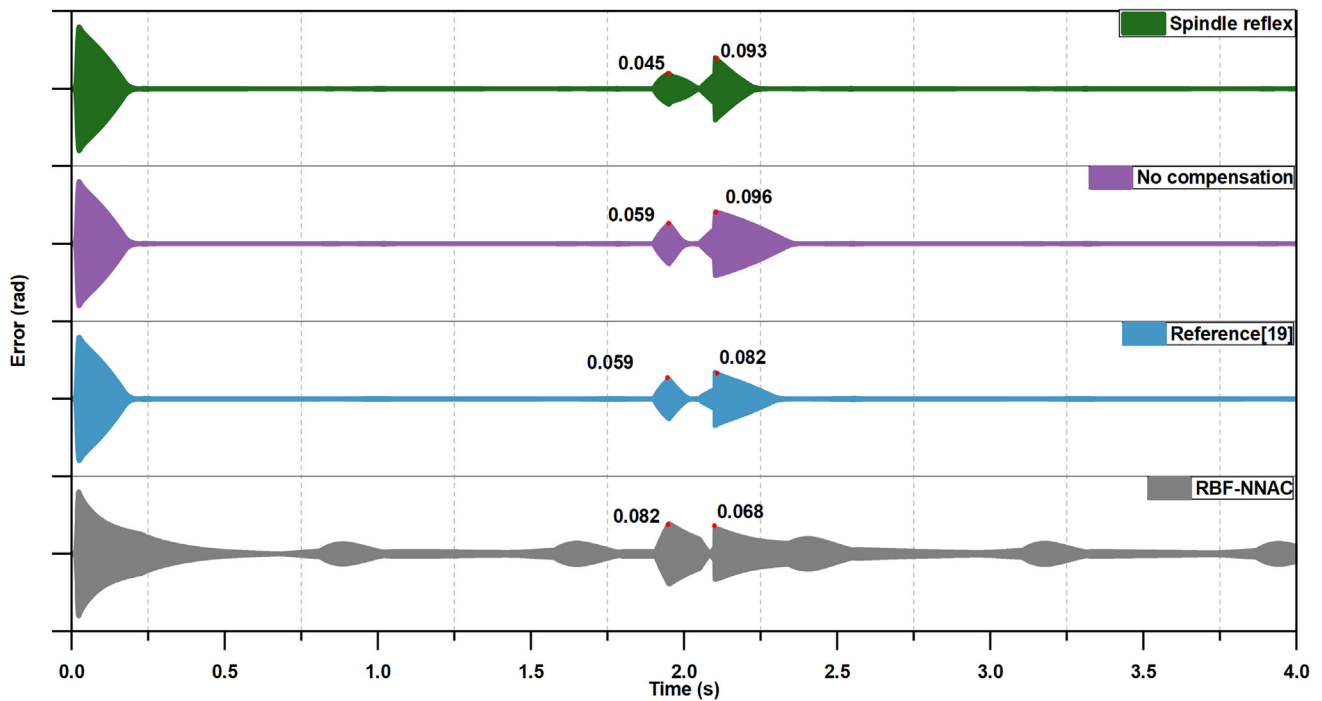


Figure 14. Comparison of error under trapezoidal impact perturbations

minimum speed, but the error is large when the disturbance occurs. The spindle reflection method can not only reduce the error peak, but also achieve faster error convergence, and the maximum error peak is 0.046 rad. The corresponding MAE and RMSE are shown in Figure 11. The MAE of the spindle reflection is reduced by 78.16%, and the RMSE is diminished by 71.18%, outperforming alternative techniques.

Secondly, the corresponding performance of three different control methods and expected angles under trapezoidal impact disturbance is shown in Figure 12, and the changes are shown in Figure 13. With the occurrence of the disturbance, the tracking effect of the RBF-NNAC method is poor. The angular convergence speed of the method in Takahashi et al.¹⁹ is higher than that without compensation. In contrast, the tracking effect of the proposed spindle reflection method is the best, and it responds quickly when disturbed, and the joint angle converges faster than Takahashi et al.¹⁹, and as shown in the partially enlarged part of Figure 12, the tracking effect of the proposed method is better than that of other methods without disturbance. The trajectory tracking error kite diagram and the corresponding MAE, and RMSE are shown in Figures 14 and 15, respectively. The error peak of the Takahashi et al.¹⁹ can be reduced compared to that before compensation. Although the maximum error peak of the spindle reflection is slightly higher than that of the Takahashi et al.¹⁹, the convergence speed is the fastest, while

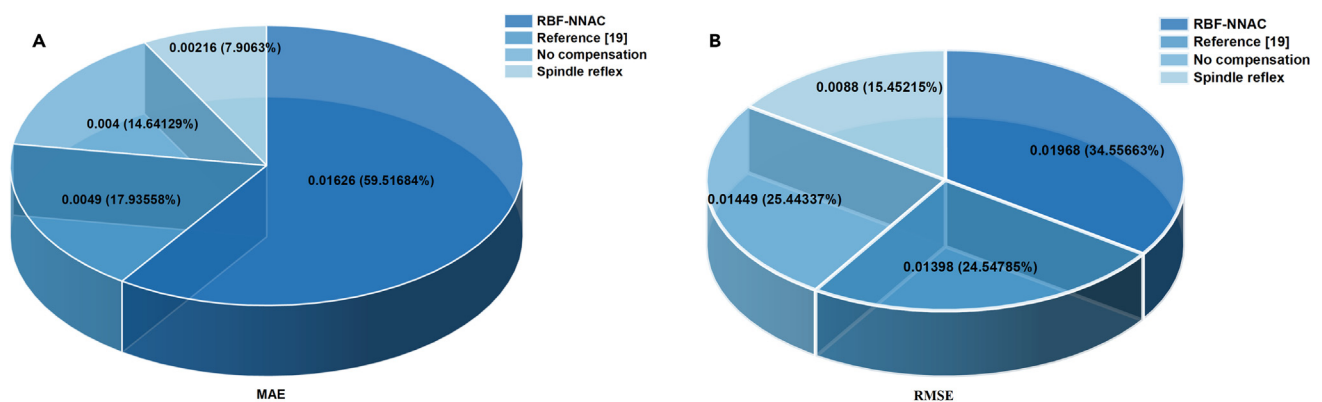


Figure 15. Comparison of MAE and RMSE under trapezoidal impact perturbations

(A) Comparison of MAE under trapezoidal impact perturbations.

(B) Comparison of RMSE under trapezoidal impact perturbations.

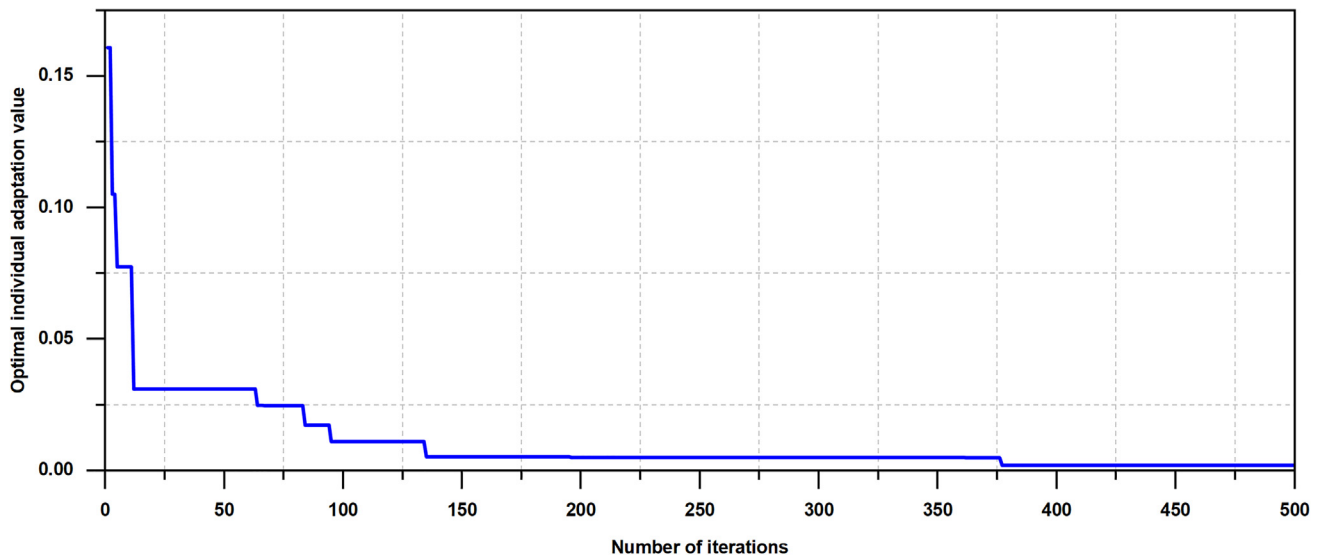


Figure 16. Iterative process of particle swarm optimization algorithm

the RBF-NNAC is greatly affected by the disturbance and the convergence is the slowest. The MAE of the spindle reflection is reduced by 46.73% and the RMSE is reduced by 39.29%, which is better than other methods.

Anti-interference verification of deep tendon reflex control system

In the process of knee joint movement, a force opposite to the direction of joint movement is added to simulate the blocking force. The blocking force disturbance model is defined as:

$$d = -k_{block} \cdot \dot{\theta} \cdot \delta \quad (\text{Equation 20})$$

where, k_{block} is the blocking coefficient, indicating the blocking strength, and δ is the step function, which is used to activate the blocking force disturbance at a specific time.

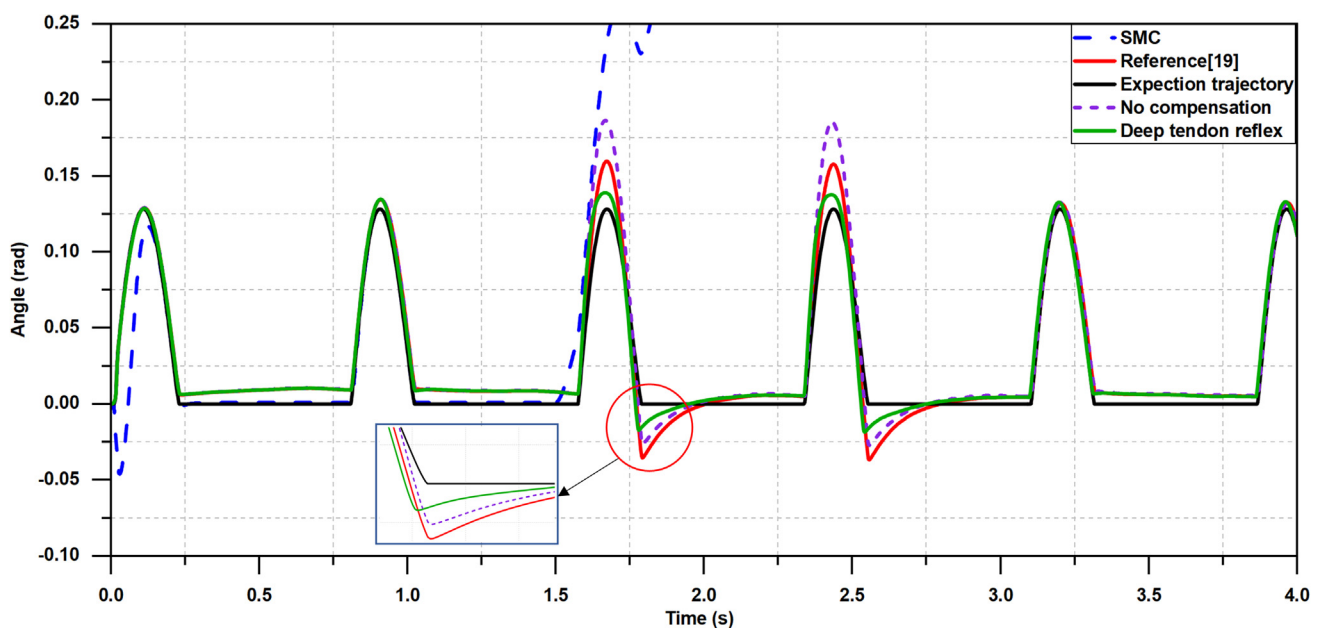


Figure 17. Comparison of knee angles under $d = -8\dot{\theta}\delta$

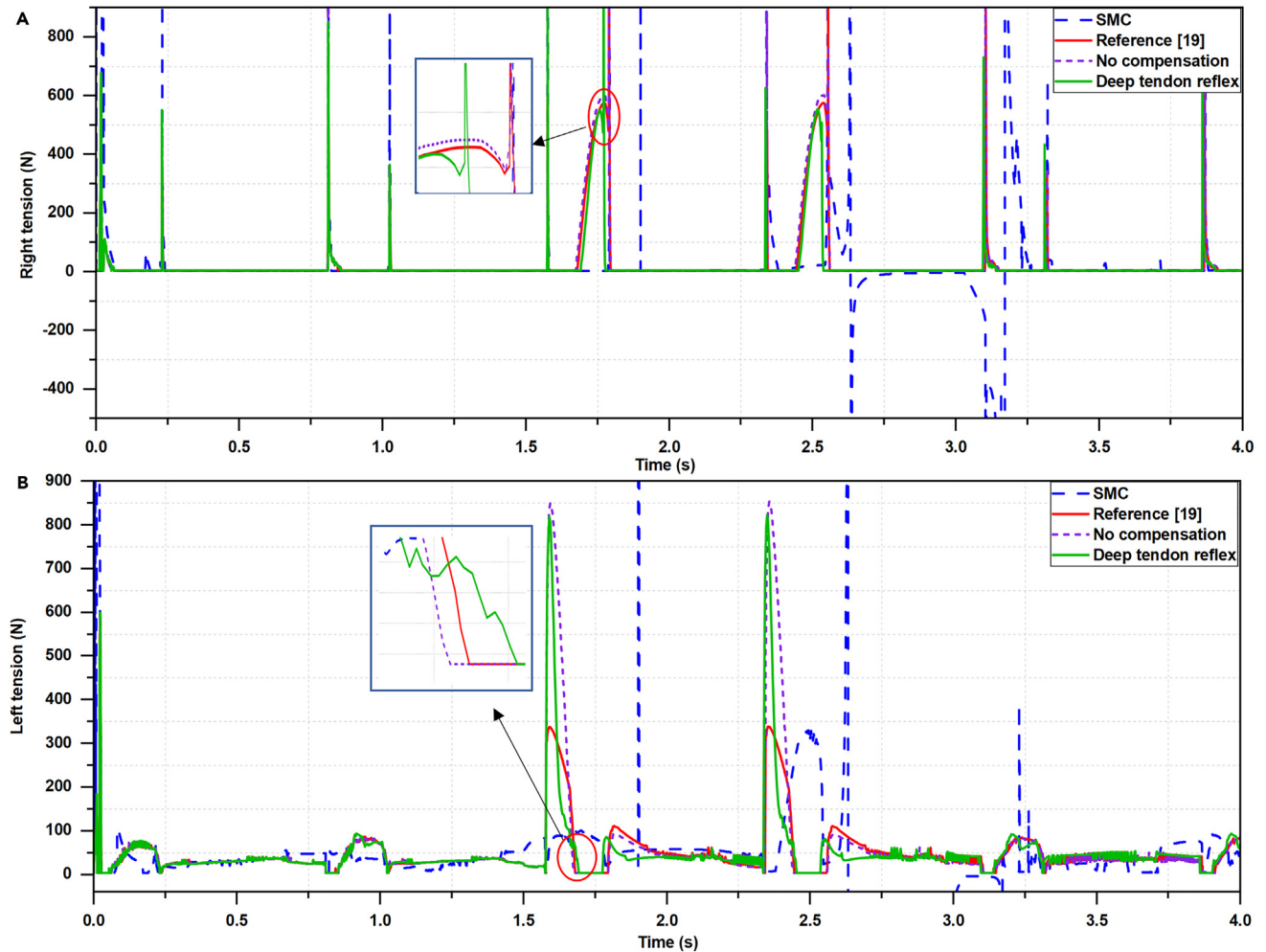


Figure 18. Comparison of F under $d = -8\dot{\theta}\delta$

(A) F contrast of the right pneumatic muscle under $d = -8\dot{\theta}\delta$.

(B) F contrast of the left pneumatic muscle under $d = -8\dot{\theta}\delta$.

The value k_t of the deep tendon reflex control system is 0.001 and $thre_2$ is -100 . The Gaussian basis function center parameters, width parameters, and network initial weights of the RBF-NNAC controller are optimized by the particle swarm optimization algorithm. After selection, the fitness changes with the number of iterations as shown in Figure 16.

$$Takec = \begin{bmatrix} 1.61 & 2.62 & 0.16 & -0.31 & -0.48 & 0.41 & -1.38 \\ 0.03 & -1.81 & -0.39 & -0.49 & -1.05 & 0.32 & -0.61 \\ -2.11 & 0.18 & -0.94 & 1.61 & 0.55 & 0.75 & -1.71 \\ -2.28 & -0.51 & 0.83 & -1.46 & -0.47 & 0.25 & 0.18 \\ 0.05 & 0.91 & -0.54 & -1.48 & -1.97 & -0.72 & -0.42 \end{bmatrix},$$

$$b = [1.49; 0.11; -1.60; 0.1; -1.09; 1.24; -0.09], W = [2.03 \ 0.66 \ -0.82 \ 0.002 \ -1.29 \ 0.47 \ 0.25]^T.$$

The blocking force disturbance is $d = -8\dot{\theta}\delta$ and $d = -12 \sin(\pi t/10)\dot{\theta}\delta$, and the step time is 1.5 s–3 s. The deep tendon reflex effect of the knee joint is verified, respectively. When $d = -8\dot{\theta}\delta$, Figure 17 shows the knee joint angle trajectory under different control strategies. Figure 18 is the change of two pneumatic muscle tension on the knee. In Figure 17, the blue dash is the SMC method, the red line is the method in Takahashi et al.¹⁹, the desired path is indicated with a black line, the case without compensation is indicated with the purple dash, and the green line is the proposed deep tendon reflex method. When the blocking force disturbance occurs, the SMC method has high tracking accuracy before the disturbance, but the anti-disturbance performance is insufficient when the disturbance occurs. The method in Takahashi et al.¹⁹ and the proposed deep tendon reflex can effectively reduce the disturbance effect, and as shown in Figure 18, the pneumatic muscle tension of SMC produces severe buffeting to make the tension too large. The method in Takahashi et al.¹⁹ has a certain degree

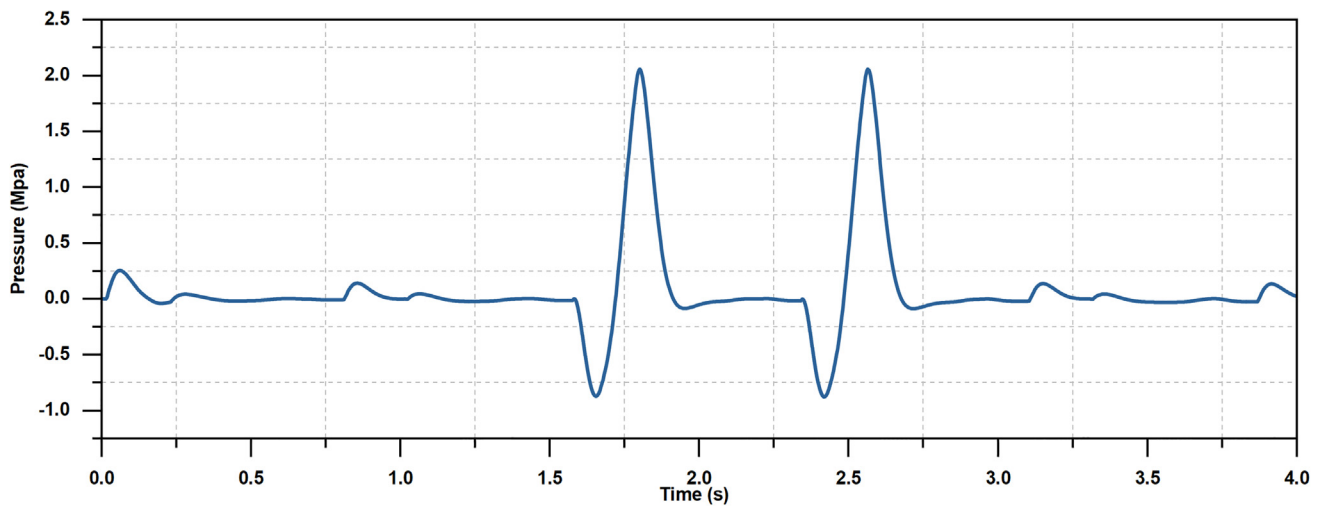


Figure 19. PAM air pressure on the right side of the knee under $d = -8\dot{\theta}\delta$

of suppression before the pneumatic muscle tension is too large, and the proposed deep tendon reflex is fast convergence after the disturbance occurs. This is because when the T function detects that the tension is too large, there is a delay in the input of the local perceptual feedback regulation function to the CPG model. However, the compensation effect of tension in the reduction process is better than that of Takahashi et al.¹⁹, as shown in the local amplification part. Although the method in Takahashi et al.¹⁹ can reduce the influence of time delay by compensating outside the CPG, it will lead to the existence of negative pressure in the pneumatic muscle, as shown in Figure 19, which can exacerbate the lag effect of the PAM and result in material deterioration of the muscle. As shown in Figure 20, the angle tracking errors of the three methods and without compensation are compared. Table 4 presents the corresponding MAE and RMSE quantitative analysis. The MAE of deep tendon reflex is reduced by 23.64%, and RMSE has been lowered by 37.94%, outperforming the other two cases.

When $d = -12 \sin(\pi t/10)\dot{\theta}\delta$, the three control methods and uncompensated knee joint angle trajectories are shown in Figure 21. Similarly to $d = -8\dot{\theta}\delta$, SMC shows poor tracking performance in the face of continuous and strong resistance disturbance. This performance degradation can be attributed to the fact that the disturbance exceeds the robustness threshold of the SMC, resulting in the system not being stably maintained on the sliding surface, and at this time, the method of Takahashi et al.¹⁹ and the proposed deep tendon reflex can

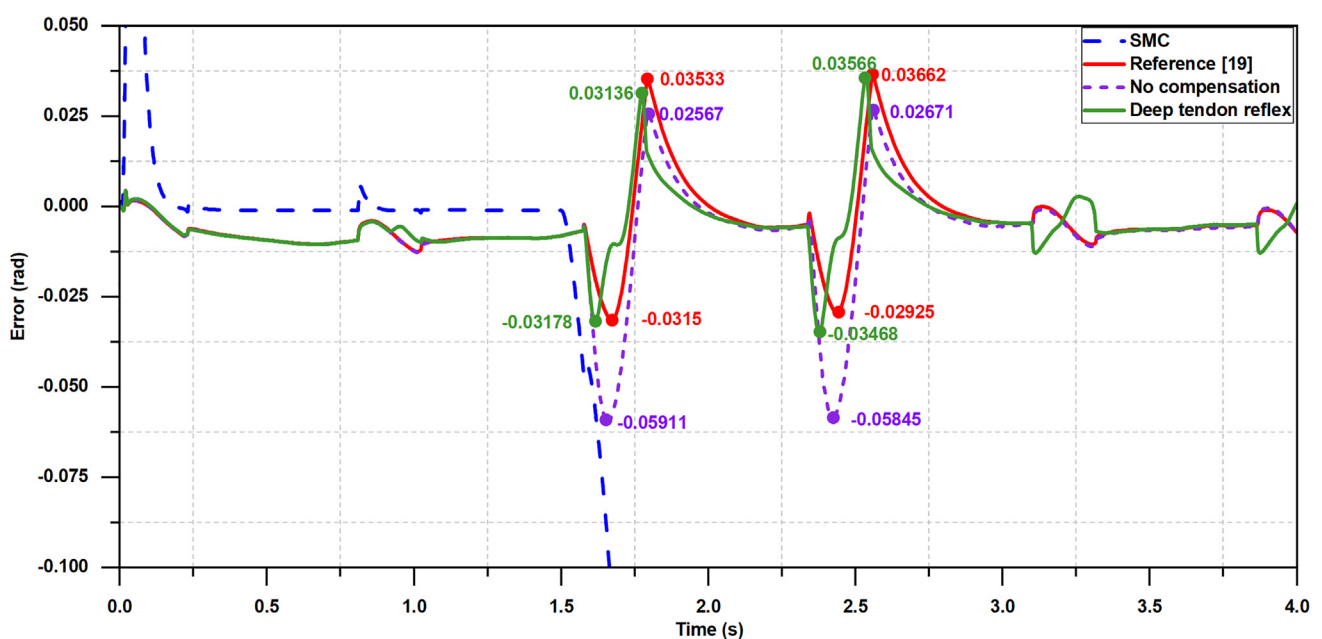


Figure 20. Comparison of errors under $d = -8\dot{\theta}\delta$

Table 4. Comparison of MAE and RMSE under $d = -8\dot{\theta}\delta$

Methods	MAE	Methods	RMSE
SMC	0.71743	SMC	1.03794
Takahashi et al. ¹⁹	0.00944	Takahashi et al. ¹⁹	0.01247
No compensation	0.00998	No compensation	0.0155
Deep tendon reflex	0.00762	Deep tendon reflex	0.00962

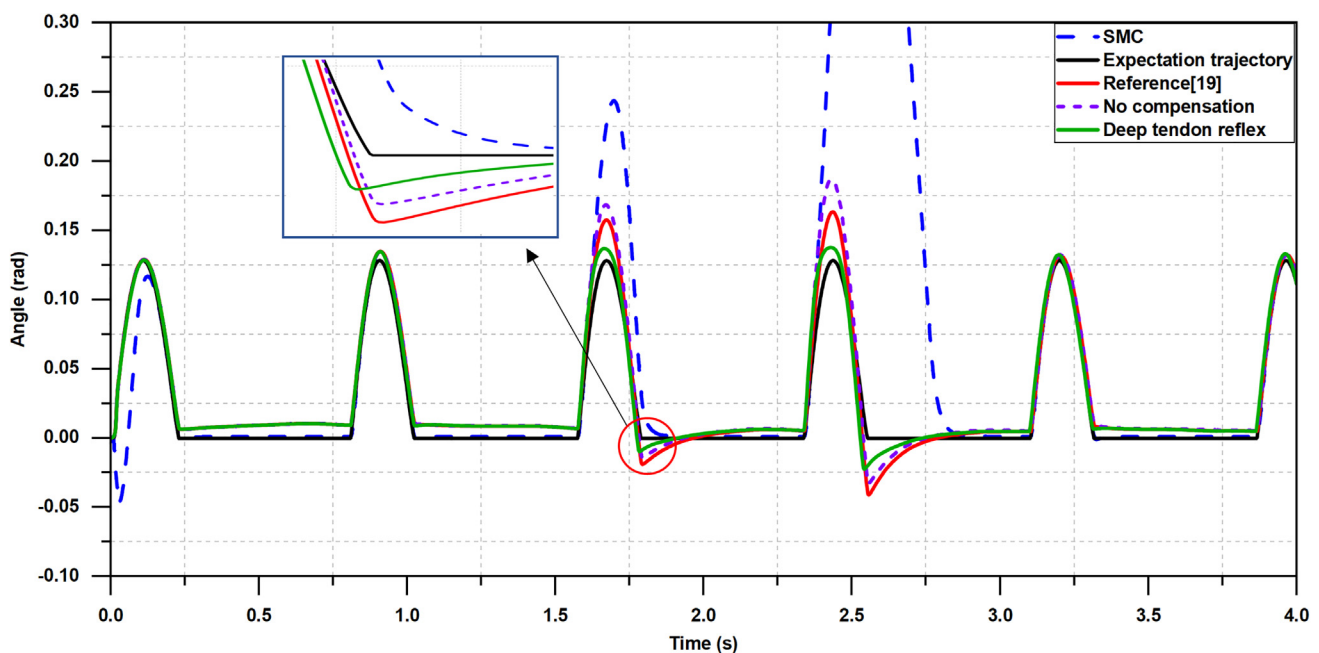
continuously compensate for the disturbance. As shown in Figure 22, the variation in the tension of the bilateral pneumatic muscles around the knee is similar to that of $d = -8\dot{\theta}\delta$. Although the method of Takahashi et al.¹⁹ compensates outside the CPG to reduce the effect of delay, it will cause negative pressure in the pneumatic muscles, as shown in Figure 23.

As shown in Figure 24, the angle tracking errors of the three methods are compared with those without compensation. The error of the method in Takahashi et al.¹⁹ is reduced compared with that without compensation. The SMC is greatly affected by the disturbance, and the deep tendon reflex can reduce the error peak and converge the error to the minimum faster. Table 5 lists the relevant MAE and RMSE values. The MAE of deep tendon reflex is reduced by 20.96% and RMSE has been decreased by 34.12%, surpassing the performance of the alternative two methodologies.

A pulse signal of amplitude 5 and duration 1.5 s–3 s is applied during the knee joint movement as a disturbance of external impact. The three control methods and the angle trajectory of the knee joint without compensation are shown in Figure 25. In the case of persistent and large external interference, the SMC cannot achieve stable Angle tracking, which is similar to the two cases in Figures 17 and 21. Takahashi et al.¹⁹ and deep tendon reflex can be compensated continuously during the disturbance time, but the compensation effect of the method in Takahashi et al.¹⁹ is not obvious. Figure 26 shows the changes in pneumatic muscle tension on both sides of the knee joint. Literature Takahashi et al.¹⁹ reduces the tension but cannot avoid negative air pressure, as shown in Figure 27. The comparison of tracking errors of the three methods is shown in Figure 28. The error of the proposed method is better than that of the method in Takahashi et al.¹⁹ on the whole. Table 6 shows the corresponding MAE and RMSE data comparison. The MAE of deep tendon reflex is reduced by 28.51% and RMSE has been decreased by 20.31%, surpassing the performance of the alternative two methodologies.

Conclusion

In this study, two kinds of reflection control are designed for the robot leg joints driven by pneumatic muscles. Based on the advantages of pneumatic muscles in bionic control research and the biological reflection mechanism, the spindle reflection and deep tendon reflex control system based on CPG are designed. Through the comparison of four groups of experiments and three methods, the impact compensation of


Figure 21. Comparison of knee angles under $d = -12 \sin(\pi t / 10) \dot{\theta} \delta$

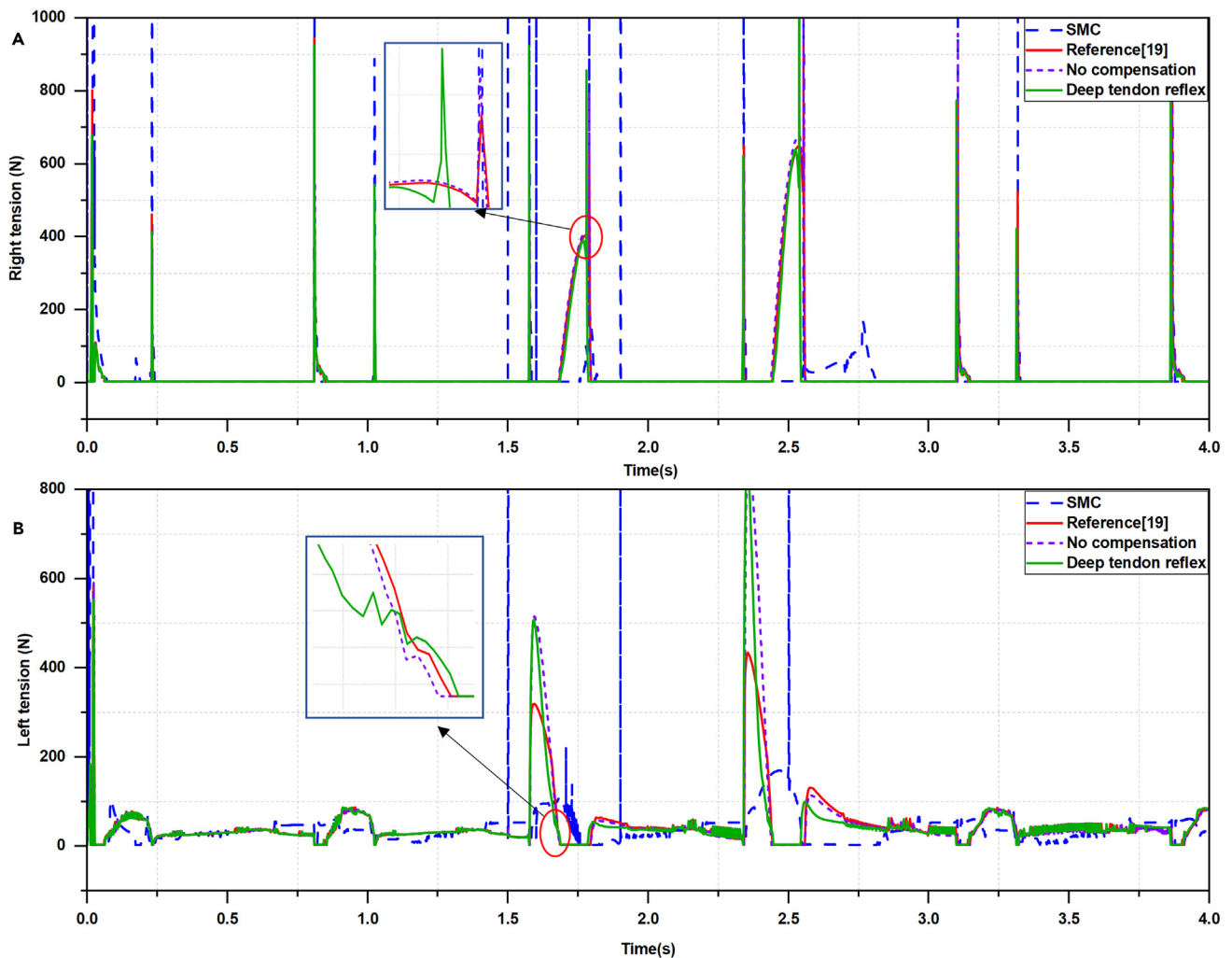


Figure 22. Comparison of F under $d = -12 \sin(\pi t / 10) \dot{\theta} \delta$
(A) F contrast of the right pneumatic muscle under $d = -12 \sin(\pi t / 10) \dot{\theta} \delta$.
(B) F contrast of the left pneumatic muscle under $d = -12 \sin(\pi t / 10) \dot{\theta} \delta$.

spindle reflection on pneumatic muscle driven joints under sudden disturbance is verified, and the limitations of pneumatic muscle stretching speed under CPG rhythm signal and different disturbances are considered. The inhibition of deep tendon reflex on pneumatic muscle tension under the disturbance of blocking force for a period of time is verified. Considering the advantages of Tegotae control in the design of the CPG feedback term, the pneumatic muscle tension is detected by the T function, and the CPG feedback term of inhibiting motion is output. The results show that the spindle reflex and deep tendon reflex can improve the adaptability of the pneumatic muscle leg mechanism in exercise.

Limitations of the study

The biological reflection mechanism is extremely complex, and a variety of neurotransmitters and signaling pathways are designed. Although the proposed spindle reflection and deep tendon reflex control methods have good functional bionic performance, they fail to fully simulate the complexity of real biological systems, and there are technical challenges for sensor integration applied to pneumatic muscles. Therefore, for the proposed reflection method, future research will further explore the cross-application of perceptual bionics and intelligent bionics in pneumatic muscle-driven robots.

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Binrui Wang (wangbrpaper@163.com).

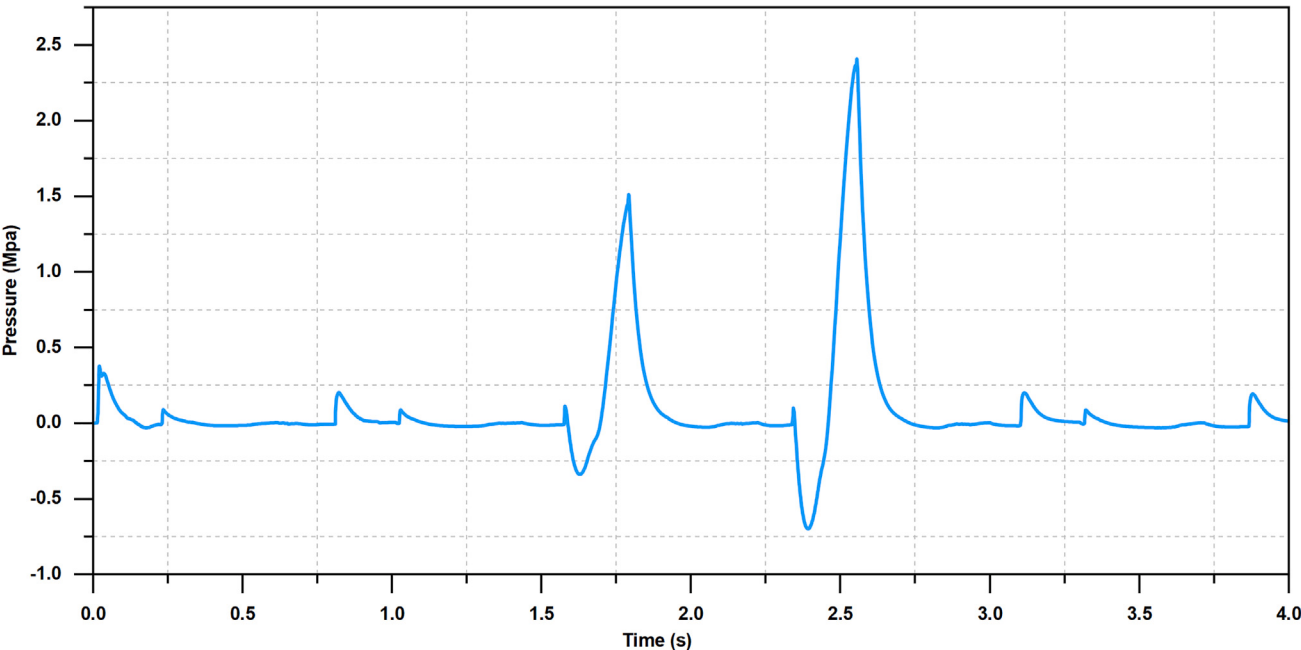


Figure 23. PAM air pressure on the right side of the knee under $d = -12 \sin(\pi t / 10) \dot{\theta} \delta$

Materials availability

This study is based on existing materials and does not produce new materials.

Data and code availability

- The [lead contact](#) will provide access to the data presented in this study upon request.
- The [lead contact](#) will share the code used in this paper upon request.
- Supplementary information necessary to reinterpret the findings of this paper can be obtained from the [lead contact](#) upon request.

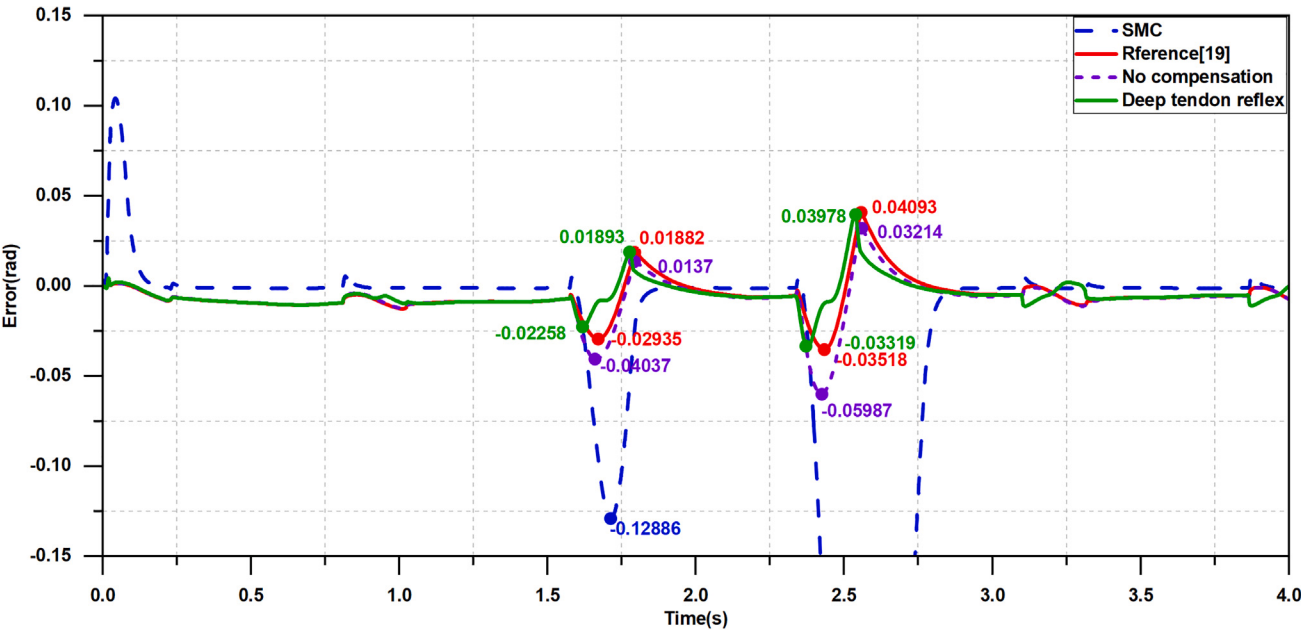


Figure 24. Comparison of errors under $d = -12 \sin(\pi t / 10) \dot{\theta} \delta$

Table 5. Comparison of MAE and RMSE under $d = -12 \sin(\pi t/10) \dot{\theta} \dot{\delta}$

Methods	MAE	Methods	RMSE
SMC	0.03417	SMC	0.10431
Takahashi et al. ¹⁹	0.00894	Takahashi et al. ¹⁹	0.01197
No compensation	0.00935	No compensation	0.01392
Deep tendon reflex	0.00739	Deep tendon reflex	0.00917

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AUTHOR CONTRIBUTIONS

L.W. conceived the research. Z.C. designed and carried out the experiment, and prepared the drawings and papers. X.W. and B.W. provide support for experimentation, testing, and analysis.

DECLARATION OF INTERESTS

The authors declare no competing interests.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

- [KEY RESOURCES TABLE](#)
- [METHOD DETAILS](#)
 - Further description of blocking force perturbations
 - Description of robot motion disturbance
- [QUANTIFICATION AND STATISTICAL ANALYSIS](#)

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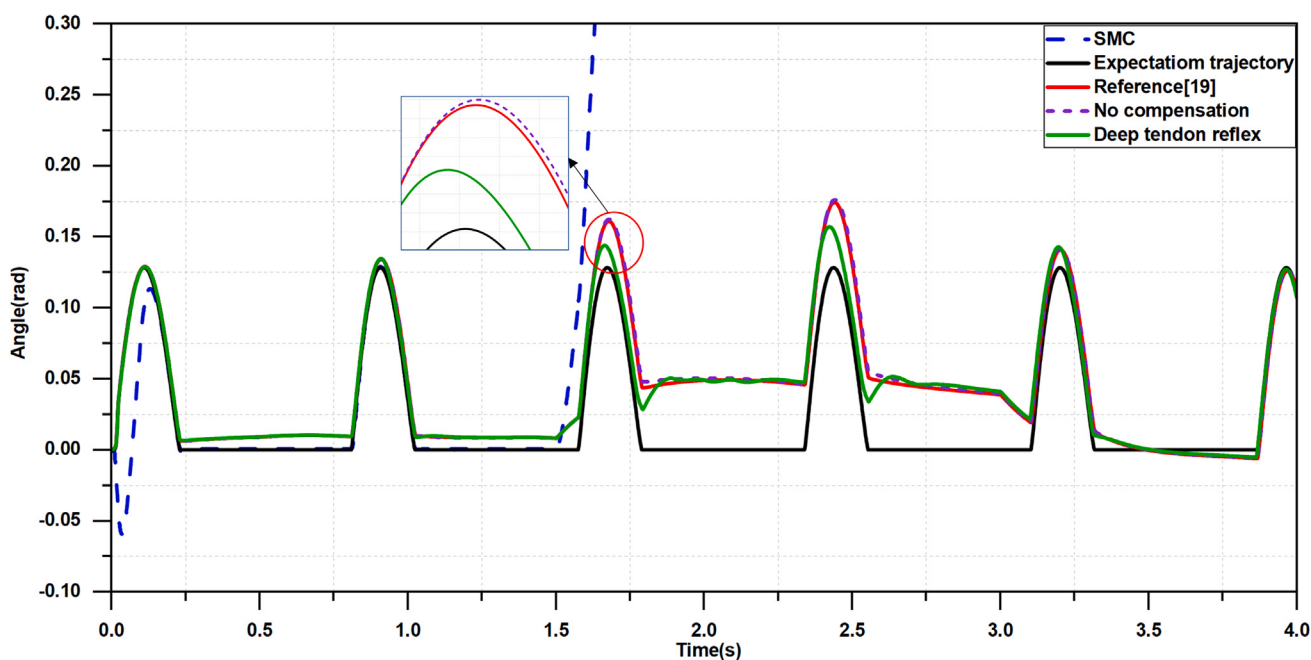


Figure 25. Comparison of knee angles under pulse signal

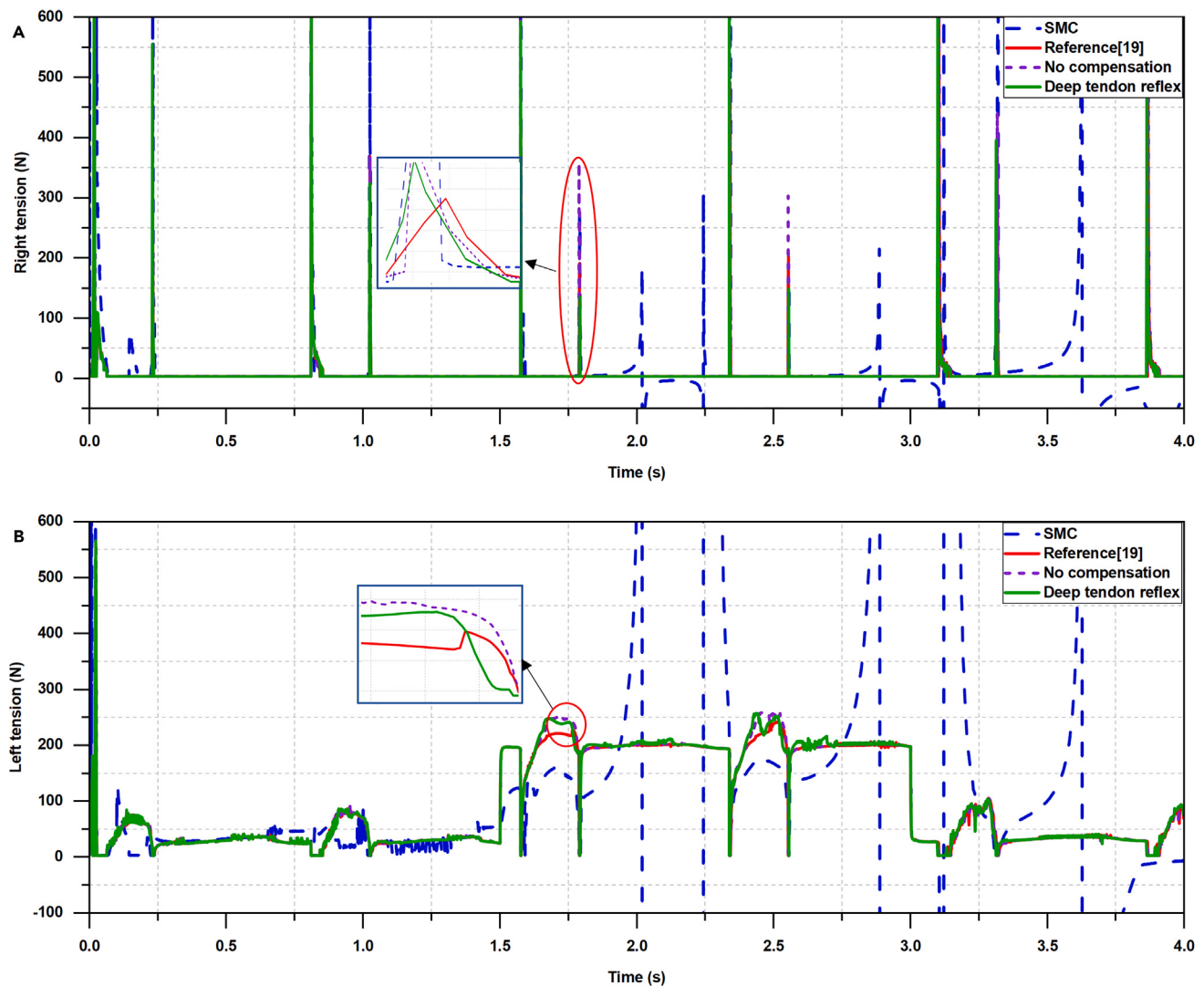


Figure 26. Comparison of F under pulse signal

(A) F contrast of the right pneumatic muscle under pulse signal.

(B) F contrast of the left pneumatic muscle under pulse signal.

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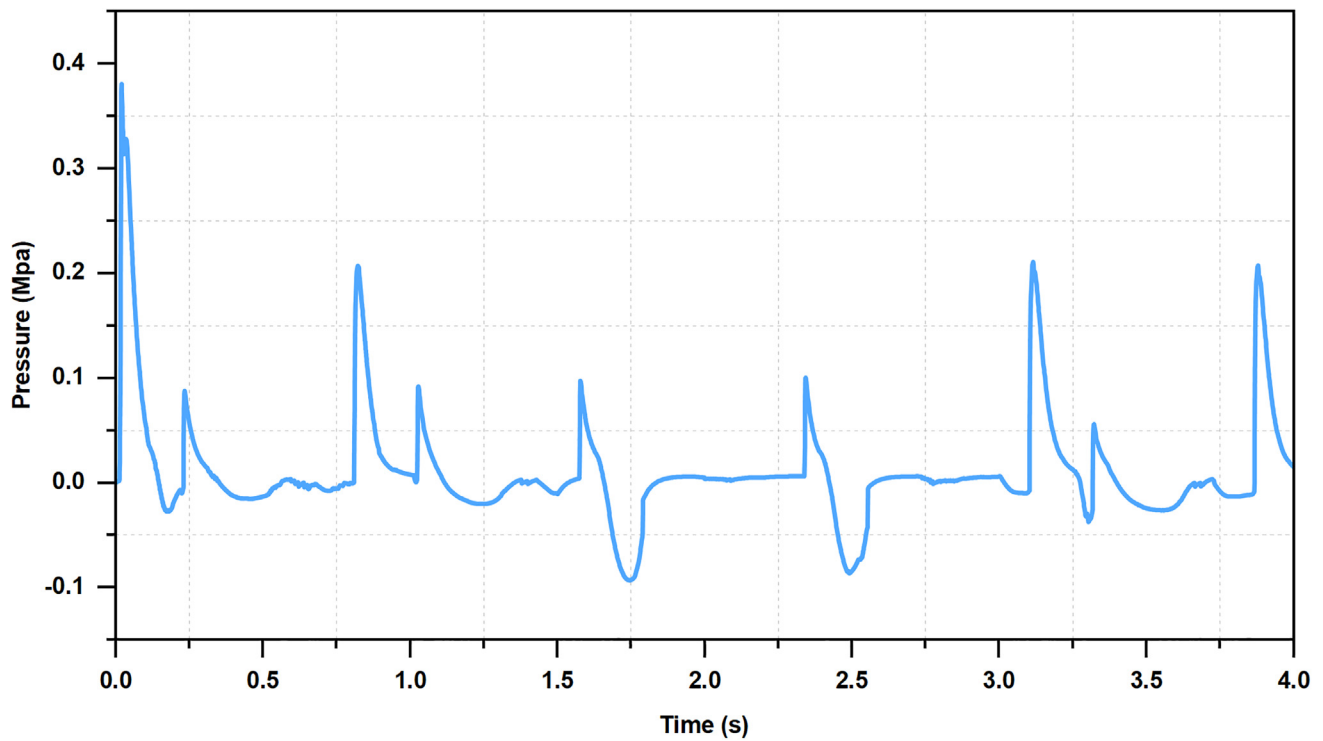


Figure 27. PAM air pressure on the right side of the knee under pulse signal

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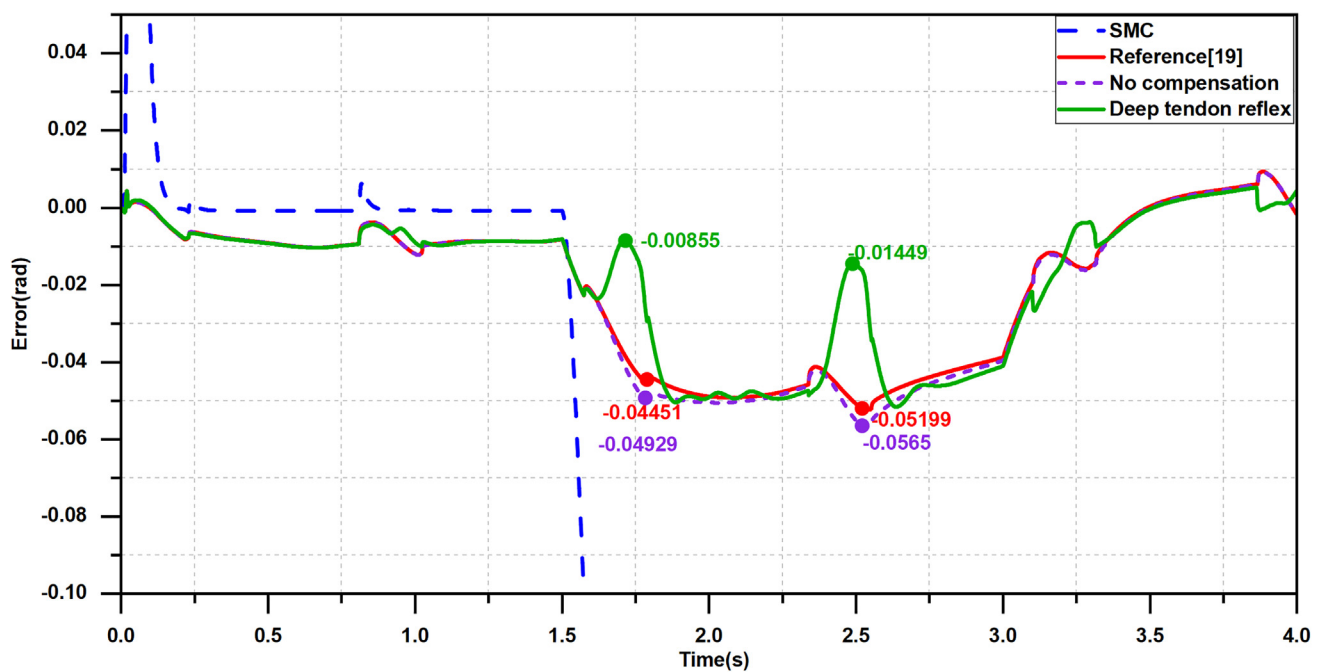


Figure 28. Comparison of errors under pulse signal

Table 6. Comparison of MAE and RMSE under pulse signal

Methods	MAE	Methods	RMSE
SMC	2.04856	SMC	4.35381
Takahashi et al. ¹⁹	0.02745	Takahashi et al. ¹⁹	0.03308
No compensation	0.02876	No compensation	0.03495
Deep tendon reflex	0.02056	Deep tendon reflex	0.02785

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Software and algorithms		
MATLAB	MathWorks	https://www.mathworks.com/
Solidworks	Dassault Systemes S.A	https://www.solidworks.com/
Origin	OriginLab	https://www.originlab.com/
Other		
Pneumatic Artificial Muscle (DMSP-10-144N-RM-CM)	FESTO	https://www.festo.com.cn/
Electro-Pneumatic Regulator (ITV1050)	SMC	https://www.smc.com.cn/

METHOD DETAILS

Further description of blocking force perturbations

The blocking force perturbation $d = -k_{block} \cdot \dot{\theta} \cdot \delta$ we used was to verify that the deep tendon reflex control system causes excessive tension in the pneumatic muscle when the joint driven by the pneumatic muscle is affected by the perturbation. In practice, the increase of joint resistance driven by the pneumatic muscle will lead to the increase in the tension of the pneumatic muscle. Therefore, the blocking force we use is represented as $d = -k_{block} \cdot \dot{\theta} \cdot \delta$ force in the opposite direction of the joint motion, the magnitude of which is determined by k_{block} , and $\dot{\theta}$ is the tangential velocity of the joint, representing the direction. This blocking force is similar to the actual situation in that it captures the general characteristics of the actual system, such as the presence of foreign objects in the joint or the increased friction of the joint damage, that is, the increased joint resistance.

Description of robot motion disturbance

The perturbations we apply to the leg joints of a pneumatic muscle-driven robot include not only the case where the leg touches an obstacle, but also the case where there is a foreign body in the joint or the friction increases due to joint damage. Adding obstacle avoidance function to the walking process of the robot can effectively avoid obstacles on the path, but when the interference does not exist in the external environment, the obstacle avoidance function fails. Therefore, it is necessary to study different disturbance types. However, in the research on soft robots similar to those driven by pneumatic muscles, relatively high attention has been paid to joint resistance. At present, more scholars are conducting relevant research, such as literature,²⁹ literature.³⁰

QUANTIFICATION AND STATISTICAL ANALYSIS

All statistical analyses and results are described in the VERIFICATION ANALYSIS section. The data are generated by Origin2022 based on original data. Data are displayed in [Figures 5, 8, 9, 10, 12, 13, 14, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, and 28](#) and [Tables 4, 5, and 6](#). We further analyzed the errors using MAE and RMSE, as shown in [Figures 11 and 15](#) and [Tables 4, 5, and 6](#).