A Trajectory Tracking Control of a Robot Actuated With Pneumatic Artificial Muscles Based on Hysteresis Compensation

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ABSTRACT
This paper presents a new trajectory tracking control strategy for a novel lower-limb rehabilitant robot, AirGait, which is a parallel mechanism with three degrees of freedom and is actuated with four pneumatic artificial muscles (PAMs). Compared with the existing control methods, the feature of this approach is that it combines the feedforward/feedback (FF) controller based on the length-pressure hysteresis compensation of PAMs with a joint space control method on the trajectory tracking control of a parallel mechanism. For the controller design, the inverse and forward kinematic formulas of AirGait are developed firstly based on the structure analysis. Then, a lower-limb kinematic model of humans is developed and the human-like trajectory of time is obtained by using a Fourier series method. Finally, the control scheme is introduced and the trajectory tracking control of AirGait with two reference input signals is presented. The comparative experimental results indicate that the performance of this control approach is strong and this robot holds great promise for assisting lower-limb locomotion.

INDEX TERMS
Trajectory tracking control, hysteresis compensation, feedforward/feedback (FF) control, lower-limb rehabilitation robot, pneumatic artificial muscle (PAM), joint space control.

I. INTRODUCTION
The dyskinesia of lower-limbs is mainly caused by stroke, spinal cord injury, and brain injury [1]. Medical theory and clinical medicine prove that scientific rehabilitation training has a significant effect on the recovery and re-establishment of lower-limb movement function, besides timely effective surgical treatment and necessary medication [2]. However, the traditional rehabilitation training method mainly relies on the manual assistance of physiotherapists. In addition to being time consuming and having a high cost, it is difficult to meet the requirements of rehabilitation training with high frequency, intensity, pertinence, repetition, and continuity; the therapeutic effect mainly depends on the therapist’s technology and experience [3]. In order to solve the above problems, a new technology of safe, quantitative, effective, and repeatable training is needed. Lower-limb rehabilitation robots are part of this solution landscape and have become a research hotspot in the field of rehabilitation robotics [4].

The existing driving model of robots can be classified into rigid-driven (which is represented by motors and cylinders) and flexible-driven (mainly using the pneumatic artificial muscles, PAMs) [5]. As the affected limbs of patients are usually fragile, it is easy to cause secondary injury with the use of rigid-driven actuators. In addition, it is difficult to achieve force control for their unchangeable stiffness [6]. Therefore, the flexibility of the mechanism should be considered in the design of rehabilitation robots. The PAMs possess several unique advantages, such as compactness structure, low cost, high power-to-weight ratio, and significantly similar compliance to human muscles, which makes them very suitable for rehabilitation robots [7], [8]. However, the accurate trajectory tracking control of robots driven by PAMs is challenging, due to the nonlinear hysteretic behavior during its working process [9], [10].
The traditional method applies the model-based advanced control algorithms to realize the trajectory tracking control of rehabilitation robots driven by PAMs. Zhu et al. [11] presented a projection-based adaptive robust control method to realize the accurate trajectory tracking control of a parallel manipulator driven by three PAMs. Yang et al. [12] proposed a Hammerstein adaptive impedance controller based on a Hammerstein impedance model to realize the control of a bionic wrist joint that actuated with PAMs. Shi and Shen [13] introduced a hybrid controller combining a sliding mode controller and an adaptive fuzzy CMAC to eliminate the non-linearity, uncertainty, and coupling effects of three degrees of freedom (3-DOF) parallel platform. Xie and Jamwal [14] developed an iterative fuzzy controller to realize the control of a new wearable ankle rehabilitation robot driven by PAMs in a parallel form. However, the effect of these methods is usually not ideal, because of the fluctuation of the pressure, change of temperature, and nonlinear hysteresis phenomenon of PAMs make it difficult to develop accurate mathematical models for these control strategies [15].

Recently, the control strategies of PAMs based on hysteresis compensation are gradually emerging for its simple concept and ease of implementation [16]. However, most of the literature focuses on the hysteresis modeling [17], [18] and the trajectory tracking control based on the hysteresis compensation of a single PAM [19], [20]. Few results have been reported on the application of hysteresis compensation in the control of mechanisms actuated by PAMs, especially for the parallel case. In fact, the parallel mechanisms are better suited for ankle exercises in a three-dimensional space due to the need for a safe workspace and a large actuation torque [21], [22]. Yeh et al. [23] proposed the control of a lower-limb orthosis actuated with PAMs, where a modified Maxwell-slip model is adopted to characterize their nonlinear hysteresis behaviors. There appears to be only two reports [24], [25] presenting the application of hysteresis compensation control of PAMs using a parallel mechanism. In these two papers, the Preisach model is used to model the hysteresis nonlinearity of PAM and the control of a parallel manipulator driven by three PAMs is investigated. However, the application of the Preisach model limits the control accuracy, because it cannot characterize the asymmetric hysteresis loops of PAMs [26]. Meanwhile, the details on the experimental apparatus are not presented and the designed trajectory is too simple in both papers, where the designed trajectory is only a simple sinusoidal signal with 1-DOF of the mechanism. Therefore, this research is dedicated to solving the application of length-pressure hysteresis compensation of PAMs in the trajectory tracking control of a parallel rehabilitation robot. In this paper, the combination of a feedforward/feedback (FF) control scheme based on length-pressure hysteresis compensation of PAMs [27]–[29] and joint space control is adopted to realize the trajectory tracking control of AirGait, which is a parallel lower-limb rehabilitation robot actuated with PAMs.

The rest of this paper is organized as follows. Section 2 describes the structure and working principle of AirGait, the inverse and forward kinematics are developed in detail. Then, the lower-limb kinematic model of humans is developed and the human-like trajectory of time is obtained by using a Fourier series method in Section 3. Finally, the trajectory tracking control experiment of AirGait is implemented with two reference input signals in Section 4 to validate the performance of the proposed control strategy, before conclusions are drawn in Section 5.

II. MODELING OF AIRGAIT

The analytical formulations of the inverse and forward kinematics for AirGait are presented in this section. The former is adopted to determine the lengths of four PAMs according to the trajectory of the moving platform, while the latter is used to calculate the trajectory of the moving platform from lengths of the four PAMs.

A. SYSTEM DESCRIPTION

The main mechanism diagram of the proposed parallel rehabilitation robot is illustrated in Fig. 1. It contains the base, moving platform, PRR limbs, PSS limbs, and PR limbs (also called restricted limbs). The topological structure is a 3-DOF 2-PSS-(2-PRR-PR) R parallel mechanism. Here, R, P, and S denote revolute, prismatic, and spherical joints, respectively; while P denotes an actuated prismatic joint. Limbs 1 and 3 belong to the PRR limb while limbs 2 and 4 belong to the PSS limb. With the notable structure, the parallel mechanism possesses 3-DOF, including one translation along the vertical direction (called raising/dropping movement), one rotation about the axis u (called dorsiflexion/plantarflexion movement), and one rotation about the axis v (called inversion/eversion movement).

The kinematic diagram of AirGait is illustrated in Fig. 2, where B_{i}(i = 1, 2, 3, 4) is the intersection point of the prismatic joint and the base; A_{1}, A_{3}, P_{1}, P_{3} are the centers of the revolute joints of the PRR limbs; A_{2}, A_{4}, P_{2}, P_{4} are the centers of the spherical joints of the PSS limbs; O and O’ are the centers of the base and moving platform respectively. The coordinate xyz (called K for simplicity) is established in point O with the axis x along the vector OB_{1}, the axis z is vertical to the plane consisting of point B_{i}(i = 1, 2, 3, 4), and the axis y obeys the right-hand rule. θ is the rotation angle of the moving platform around the axis v (called the dorsiflexion/plantarflexion angle) and ψ is the rotation angle of the moving platform around the axis u (called the inversion/eversion angle).

The schematic diagram of the moving platform is illustrated in Fig. 3. The local coordinate K’ for simplicity) is established at the point O’ to describe the position and orientation of the moving platform. Here, the axis u points from O’ to A_{1}, the axis w is vertical to the plane consisting of the point A_{i}(i = 1, 2, 3, 4), and the axis v obeys the right-hand rule. Then, the orientation matrix of K’ relative
where, \( \mathbf{u}, \mathbf{v} \) and \( \mathbf{w} \) represent the unit vectors of the \( u \)-, \( v \)- and \( w \)-axis, respectively.

\( e \) is the distance between point \( P \) and \( O' \). \( \gamma_i \) is the angle of \( \overline{OB_i} \) relative to axis \( x \) (or \( \overline{PA_i} \) relative to axis \( u \)), and

\[
\gamma_i = (i - 1) \frac{\pi}{2}, \quad i = 1, 2, 3, 4
\]  

**B. INVERSE KINEMATICS**

The close-loop vector equation of \( O' \) which is associated with the \( i \)th kinematic chain is as follows

\[
\mathbf{r}_z = \mathbf{b}_i + q_i \mathbf{z} + l_i \mathbf{w}_i - a_i, \quad i = 1, 2, 3, 4
\]  

where, \( \mathbf{r}, \mathbf{a}_i, \mathbf{b}_i, q_i, l_i \) denote the vector \( \overline{OO'} \), the vector \( \overline{OA_i} \), the vector \( \overline{OB_i} \), the \( i \)th active joint variable, and the length of \( \overline{PA_i} \), respectively. \( \mathbf{z} \) denotes the unit vector of the axis \( z \), and \( \mathbf{w}_i \) denotes the unit vector along \( \overline{PA_i} \).

\[b_i = b_i \left( \cos \gamma_i \sin \gamma_i \ 0 \right)^T,\]
\[a_i = a_i \left( \cos \gamma_i \sin \gamma_i \ 0 \right)^T,\]
\[b_1 = b_3, \quad b_2 = b_4, \quad a_1 = a_3, \quad a_2 = a_4, \quad l_1 = l_3, \quad l_2 = l_4\]

Assuming \( \mathbf{c}_i = \mathbf{a}_i - \mathbf{b}_i \), Eq. (3) can be expressed as

\[
\mathbf{r}_z + \mathbf{c}_i - q_i \mathbf{z} = l_i \mathbf{w}_i, \quad i = 1, 2, 3, 4
\]  

The inverse position solution can be achieved as follows

\[
q_i = (\mathbf{c}_i^T \mathbf{z} + r_z) - \sqrt{l_i^2 - (\mathbf{c}_i^T x)^2 - (\mathbf{c}_i^T y)^2}, \quad i = 1, 2, 3, 4
\]  

Meanwhile, we can obtain the unit vector of each chain according Eq. (3) as follows

\[
\mathbf{w}_i = (\mathbf{r} - \mathbf{b}_i - q_i \mathbf{z} + \mathbf{a}_i) / l_i, \quad i = 1, 2, 3, 4
\]
C. FORWARD KINEMATICS

It can be found that the PRR and PR limbs in AirGait constitute a planar mechanism (refer to Fig. 4), so the following constraint equation can be constructed.

\[
\begin{align*}
(b_1 - a_1 \cos \theta)^2 + (r_z - q_1 - a_1 \sin \theta)^2 &= l_1^2 \\
(b_1 - a_1 \cos \theta)^2 + (r_z - q_3 + a_1 \sin \theta)^2 &= l_1^2
\end{align*}
\]

(7)

FIGURE 4. Structure diagram of AirGait in dorsiflexion/plantarflexion plane.

The constraint can be further simplified as follows

\[
\theta = \arcsin \left( \frac{q_3 - q_1}{2a_1} \right)
\]

(8)

\[
r_z = q_1 + a_1 \sin \theta + \sqrt{l_1^2 - (b_1 - a_1 \cos \theta)^2}
\]

(9)

Furthermore, the angle \( \psi \) can be obtained based on Eq. (3) as follows

\[
\psi = \arcsin \left( \frac{q_2 - q_4}{2a_2 \cos \theta} \right)
\]

(10)

D. WORKING PRINCIPLE

The robot is actuated with four PAMs, PAM1 (PAM2) and PAM3 (PAM4) are connected to the moving platform to form an antagonistic layout structure. The moving platform performs raising/dropping movement when the four PAMs move synchronously (elongating or contracting at the same time). The antagonistic movement of PAM 1 and PAM 3 drive the dorsiflexion/plantarflexion movement of platform and the antagonistic movement of PAM 2 and PAM 4 drive the inversion/eversion movement of platform.

Fig. 5 illustrates the relationship between the rehabilitation movement of the gait simulation mechanism and the gait trajectory of the human foot. In the rehabilitation training process of this gait simulation mechanism, the human foot is attached to the moving platform, so it can be considered that the human foot center coincides with the center of the moving platform.

The values of mechanism parameters are listed in Table 1.

III. HUMAN-LIKE TRAJECTORY DESIGN

The mathematical model of the lower-limb contains two parts: the kinematic model and the human-like trajectory model. The kinematic model describes the relationship between the lower-limb exoskeleton and its joint angles; while the latter presents the relationship between the trajectory of the foot and time.

A. KINEMATIC OF LOWER-LIMB

The lower-limb is simplified as a 3-linkage model [30], which is depicted as Fig. 6. Points \( A, B, \) and \( C \) are the centers of the hip, knee, and ankle joints, respectively. The triangle consisting of points \( C, D, \) and \( E \) represents the human foot, and point \( F \) is the foot center. The lengths of the thigh and shin are represented by \( l_{ab} \) and \( l_{bc} \). The \( xy \) plane of \( O-xyz \) is parallel with the sagittal plane, where the \( y \)-axis is vertical upward, the \( z \)-axis is vertical outward, and the \( x \)-axis satisfies the right-hand rule. Hence, the kinematics of the lower-limb are only related to the coordinates \( x \) and \( y \) and can be described as follows

\[
\begin{align*}
    r_a &= 0 \\
    r_b &= r_a + l_{ab}\theta_h \\
    r_c &= r_b + l_{bc}\theta_k \\
    r_d &= r_c + l_{cd}\theta_f \\
    r_e &= r_c + l_{ce}\theta_m \\
    r_f &= (r_d + r_e)/2
\end{align*}
\]

(11)
where, \( r_d \sim r_f \) represent the coordinates of the points \( A \sim F \), and the geometric relationship between the joint angles and the lower-limbs are as follows

\[
\theta_h = \begin{bmatrix}
\sin(\theta_{hip}) \\
-\cos(\theta_{hip})
\end{bmatrix}, \quad \theta_k = \begin{bmatrix}
\sin(\theta_{hip} - \theta_{knee}) \\
-\cos(\theta_{hip} - \theta_{knee})
\end{bmatrix},
\]

\[
\theta_n = \arccos\left(\frac{l_d^2 + l_f^2 - l_c^2}{2l_d l_f}\right), \quad \theta_f = \theta_n - \theta_{ankle},
\]

\[
\theta_f = \begin{bmatrix}
\cos(\theta_f - \theta_{hip} + \theta_{knee}) \\
-\sin(\theta_f - \theta_{hip} + \theta_{knee})
\end{bmatrix}
\]

\[
\theta_m = \arccos\left(\frac{l_n^2 + l_e^2 - l_{de}^2}{2l_n l_e}\right),
\]

\[
\theta_m = \begin{bmatrix}
\cos(\theta_m + \theta_f - \theta_{hip} + \theta_{knee}) \\
-\sin(\theta_m + \theta_f - \theta_{hip} + \theta_{knee})
\end{bmatrix}
\]

The coordinates of the points \( A \sim F \) can be obtained by substituting the hip, knee, and ankle joint angle data into Eq. (11).

### B. TRAJECTORY DESIGN

In order to obtain the human-like trajectory, the hip, knee, and ankle joint data presented in the literature [31] is substituted into Eq. (11). Fig. 7 is the stick diagram of the lower-limbs during walking and Fig. 8 shows the corresponding trajectory of the foot center (raising/dropping movement) and the dorsiflexion/plantarflexion angle.

To obtain the description of raising/dropping and dorsiflexion/plantarflexion movements on time \( t \), the Fourier series is applied as the fit functions. These functions can be expressed as follows

\[
\begin{align*}
x_f &= a_{x0} + \sum_{i=1}^{n_x} a_{xi} \cos(\omega t) + \sum_{i=1}^{n_x} b_{xi} \sin(\omega t) \\
y_f &= a_{y0} + \sum_{i=1}^{n_y} a_{yi} \cos(\omega t) + \sum_{i=1}^{n_y} b_{yi} \sin(\omega t) \\
\theta &= a_{c0} + \sum_{i=1}^{n_c} a_{ci} \cos(\omega t) + \sum_{i=1}^{n_c} b_{ci} \sin(\omega t)
\end{align*}
\]

where, \( x_f \) and \( y_f \) are the abscissas and ordinates of the foot-center, respectively; \( \theta \) is dorsiflexion/plantarflexion angle. The fitting numbers of \( x_f \), \( y_f \) and \( \theta \) are represented by \( n_x \), \( n_y \), and \( n_c \), they are given as six, eight, and eight. The fitting results are described in Fig. 8, and the fitting parameters are shown in Table 2. The corresponding root mean square errors of the fitting results are given in Table 3. The fitting results indicate that the obtained coefficients can describe the trajectory of foot precisely.

### IV. CONTROL STRATEGY

The formulation of the control strategy guarantees the motion functionality of the mechanism. Therefore, it is necessary to design a reasonable control strategy according to the structural characteristics of the mechanism to ensure high levels of control performance and accuracy.

#### A. CONTROL STRATEGY

The trajectory tracking control of AirGait is based on the control scheme of the joint space control strategy [32]. The core of this approach is that the control of each driving joint of the mechanism is independent, i.e., each controller is independent and they do not communicate. The performance of this control strategy is determined by each branch chain: the control performance of each branch directly affects the control accuracy of the whole control system. The control performance of each branch has been introduced in detail in...
prior research [29], and the FF control scheme of one PAM is illustrated in Fig. 9. The desired length \( q_d \) of the PAM can be mapped into a desired control input signal \( P_d \) applied to the proportional pressure regulating valve (PPRV) after the calculation of the hysteresis compensation. Meanwhile, a feedback loop is added to overcome the highly nonlinear dynamics of the PAM. The conventional PID controller is placed in the feedback loop, which can be expressed as

\[
\Delta P = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt}
\]

where, \( e(t) \) is the tracking error; \( \Delta P \) is the output of the PID controller; \( K_p, K_i, \) and \( K_d \) are the proportional, integral, and derivative gains, respectively.

The control scheme of AirGait is shown in Fig. 10. The control system consists of four modules: input, inverse kinematics, single-chain actuator, and forward kinematics.
The input module is used to generate the desired trajectory of the moving platform; the two trajectory is applied in this paper, as they are human-like and coupling trajectories. The inverse and forward kinematic modules are formulated in Section 2.

For the trajectory tracking control of AirGait, the desired trajectory $x_d$ is the input of the control system. After being calculated by the inverse kinematics of AirGait, the desired length of each PAM is obtained as the desired control signal of each branch. In order to verify the control effect of the control method, the actual lengths of each PAM collected by displacement sensors in Fig. 10 are used as the inputs of the forward kinematics. The actual trajectory $x_r$ is calculated after the forward kinematic computation. The comparison between $x_d$ and $x_r$ can be used to appraise the performance of this control scheme.

The parameters of the PID controller for the four PAMs are obtained by utilizing the trial and error method presented in ref [29], [33], and they are set as $K_p = 0.08$, $K_i = 0.01$, and $K_d = 0$.

**B. HYSTERESIS MODELING**

The trajectory tracking control of AirGait is based on hysteresis feedforward compensation, the MSGPI model and its inversion are adopted in hysteresis modeling and compensation in this paper. The architecture of MSGPI model is illustrated in Fig. 11.

It is a cascade of a finite number of SGPOs and DZOs, $x(t)$ is the input of the MSGPI model, $y_P$ is the output of SGPI model, and $y_M$ is the output of MSGPI model. The MSGPI model can be derived:

$$y_M(k) = \Gamma[x](k) = w_s^T S_d \left[ F'_r(x(k), y_0) \right]$$

$$w_s = (w_{s0}, w_{s1}, \cdots, w_{sm})^T, \quad d = (d_0, d_1, \cdots, d_m)^T$$

$$S_d[y](k) = (S_{d0}[y](k), S_{d1}[y](k), \cdots, S_{dm}[y](k))^T$$

$$y_P(k) = F'_{sg}(x(k), y_0) = q' \gamma(x(k)) + \sum_{i=1}^{n} p(r_i) F'_{r_i}[x](k)$$

where $w_s$, $S_d[y](k)$ and $d$ are the vectors of weights, DZOs and thresholds, respectively; $m$ is the number of DZOs. The element in $d$ is defined as

$$d_j = \frac{j}{m} \max(y_P)$$

The output of SGPI model is as follows:

$$y_P(k) = F'_{sg}(x(k), y_0) = q' \gamma(x(k)) + \sum_{i=1}^{n} p(r_i) F'_{r_i}[x](k)$$
where \( n \) is the number of SGPOs; \( q \) is a positive constant; \( y_0 = [y_{10}, \cdots, y_{n0}]^T \) is the initial state. The threshold value \( r_i \) and the weight of the \( i \)th SGPO \( p_i \) can be given as
\[
\begin{align*}
    r_i &= \alpha_i \quad (17) \\
p_i &= p(r_i) = \rho e^{-\tau r_i} \quad (18)
\end{align*}
\]
where \( \alpha, \rho \) and \( \tau \) are positive constants identified from experimental data of the PAM.

The envelop function of SGPO is given by
\[
\gamma(x(t)) = c_0 \tanh[c_1 x(k) + c_2] + c_3 \quad (19)
\]
where \( c_0, c_1, c_2, c_3 \) are constants to be identified.

The identified parameters of the MSGPI model using ten SGPOs (\( n = 10 \)) and ten DZOs (\( m = 10 \)) for the four PAMs are illustrated in Tables 4 and 5.

**TABLE 4.** Identified parameters of SGPO.

| Parameters | PAM1 | PAM2 | PAM3 | PAM4 |
|------------|------|------|------|------|
| \( c_0 \) | 2.3946 | 2.7342 | 2.3909 | 2.6115 |
| \( c_1 \) | 0.2761 | 0.2593 | 0.2731 | 0.2738 |
| \( c_2 \) | -0.2956 | -0.1357 | -0.2572 | -0.2648 |
| \( c_3 \) | 0.6234 | 0.4475 | 0.5369 | 0.5930 |
| \( q \) | 0.1868 | 0.1593 | 0.2193 | 0.1363 |
| \( \rho \) | 0.5869 | 0.5243 | 0.7969 | 0.6702 |
| \( \tau \) | 6.8812 | 6.9314 | 6.9461 | 6.5756 |
| \( \alpha \) | 0.08 | 0.08 | 0.08 | 0.08 |

**TABLE 5.** Identified parameters of DZO.

| Parameters | PAM1 | PAM2 | PAM3 | PAM4 |
|------------|------|------|------|------|
| \( w_1 \) | 0.0680 | 0.0473 | 0.0563 | 0.0589 |
| \( w_2 \) | 0.0001 | 0.0209 | -0.0035 | -0.0046 |
| \( w_3 \) | 0.0231 | 0.0135 | 0.0174 | 0.0179 |
| \( w_4 \) | 0.0410 | 0.0436 | 0.0317 | 0.0357 |
| \( w_5 \) | -0.0105 | 0.0206 | -0.0067 | -0.0064 |
| \( w_6 \) | 0.0036 | -0.0033 | 0.0029 | 0.0044 |
| \( w_7 \) | -0.0371 | -0.0268 | -0.0078 | -0.0090 |
| \( w_8 \) | 0.0017 | -0.0121 | 0.0004 | -0.0004 |
| \( w_9 \) | -0.0170 | -0.0162 | -0.0140 | -0.0148 |
| \( w_{10} \) | 0.0090 | 0.0090 | 0.0090 | 0.0090 |

**V. EXPERIMENTS AND RESULTS**

In this section, the humanlike and coupling trajectory are designed and adopted as training trajectory to verify the effect of this control scheme. Meanwhile, two comparative experiments are implemented to verify the robustness of the control scheme: (1) The comparative study between SGPI and MSGPI model; (2) The change of control accuracy with the increasing of loads.

**A. EXPERIMENTAL APPARATUS**

In order to verify the movement feasibility of AirGait and the effectiveness of the proposed control strategy, the related trajectory tracking experiments are implemented in this section. The experimental apparatus is shown in Fig. 12, which consists of the AirGait prototype, four proportional pressure regulating valves, a switching power, an air switch, and a computer. A NI data acquisition board 6230 is embedded in the computer, and the control algorithm is developed using the graphical programming platform of LabVIEW.

**FIGURE 12.** Experimental apparatus of AirGait.

**B. HUMAN-LIKE TRAJECTORY**

As mentioned in Section 3.2, the human-like trajectory is used as the input tracking signal of AirGait. However, due to the constraints of the travel of the PAM, it is necessary to reduce the tracking signal in an equal proportion. The expression of the processed tracking signal is as follows
\[
\begin{align*}
    r_z &= H_0 + A_f y_f - \frac{(\max(y_t) + \min(y_t))}{2} \quad (20) \\
    \theta &= A_r \tan\left(\frac{y_d - y_e}{x_d - x_e}\right) - \theta_r \quad (21)
\end{align*}
\]
where, \( A_f \) and \( A_r \) are the reduction coefficients of raising/dropping and dorsiflexion/plantarflexion trajectory of the moving platform; \( \theta_r \) is the translation term of the trajectory of the moving platform, \( H_0 \) is the height of the moving platform in the initial state (the absolute pressures of the four PAMs are zero); \( y_t \) is the ordinates of foot-center, which can be obtained from Eq.(11); \( y_f \) is described in Eq.(12). Eq. (20) and Eq. (21) are used to convert the foot-centered coordinates to the global coordinate system \( O-xyz \) as shown in Fig. 2, thus completing the mapping between the human gait trajectory and the desired control trajectory. The parameters in Eq. (20) and Eq. (21) are listed in Table 6.

Fig. 13 shows the raising/dropping movement trajectory tracking results of the moving platform, and Fig. 14 is the trajectory tracking results of the four actuating PAMs. The errors of the four PAMs are listed in Table 7. The results
of Fig. 13 indicate that the actual trajectory of the moving platform calculated by the forward kinematic coincides with the expected trajectory, and the tracking errors are very small. Fig. 14 gives the performance of the trajectory tracking control of the four PAMs. It can be seen that the control performance at the original lengths is somewhat worse than
those of other parts of the desired trajectory, resulting in
bigger tracking errors appearing in the same places. There
are several possible reasons for this phenomenon: (1) There
exist internal forces of AirGait after assembly, and the PAMs
need to overcome these internal forces in the process of
returning to the original length. (2) The antagonistic layout
of PAMs cannot work when the moving platform only car-
ries out the raising/dropping movement, as the four PAMs lack an
external force returning them to their original length.

Fig. 15 illustrates the trajectory tracking results of the
dorsiflexion/plantarflexion movement, and Fig. 16 is the
corresponding trajectory tracking results of the two PAMs.

Table 8 presents the errors of the two PAMs. It can be seen
from Fig. 16 that the trajectory tracking effects of the two
PAMs are very good. Compared with Fig. 14, the trajectory
tracking errors of the PAMs in Fig. 16 are reduced signif-
icantly, especially in the location of the original lengths.
This is because PAM1 and PAM3 constitute an antagonistic
layout when the moving platform carries out the dorsiflex-
ion/plantarflexion movement. In this movement, when one
PAM is deflating and elongating, the second one is contract-
ing, pulling the first to restore its original length. In this
manner, it is easier for the elongated PAM to approach its
original length.

Fig. 13 shows that the overall trajectory tracking error is
relatively stable, and the maximum tracking error is approx-
imately 0.35 mm. Fig. 15 shows that the maximum tracking
error of the plantar dorsiflexion/plantarflexion angle is only
about 0.3 °. The results show that the kinematic model and
the control method have good control accuracy.
In order to further prove the motion performance of AirGait and the adaptability of this control strategy, a coupling trajectory is designed as the tracking signal. The coupling tracking signal is designed as

\[
\begin{align*}
    r_z(t) &= A_z \sin(2\pi ft + \phi_z) + L_z \\
    \theta(t) &= A_\theta \sin(2\pi ft + \phi_\theta) + L_\theta \\
    \psi(t) &= A_\psi \sin(2\pi ft + \phi_\psi) + L_\psi
\end{align*}
\]

where, \( r_z(t) \), \( \theta(t) \), and \( \psi(t) \) are the trajectories of raising/dropping, dorsiflexion/plantarflexion, and inversion/eversion movements of human lower limbs, respectively; \( A_z, A_\theta, \) and \( A_\psi \) are the amplitudes of the three movements; \( \phi_z, \phi_\theta, \) and \( \phi_\psi \) are the phase angles of the three movements; \( L_z, L_\theta, \) and \( L_\psi \) are the initial values of the three movements. Table 9 gives the parameters of Eq. (22).

The tracking responses and errors of the coupling trajectory are shown in Fig. 17 and Fig. 18. Table 10 presents the errors of the four PAMs, which indicates the four PAMs can track the desired trajectory well, meaning that the gait simulation mechanism also has good tracking effects for coupling movement. Compared with the single raising/dropping movement described in Fig. 13 and Fig. 14, the tracking errors are also reduced obviously for the antagonistic layout of the PAMs.

### TABLE 7. Errors of raising/dropping movement.

| Errors  | PAM1 | PAM2 | PAM3 | PAM4 |
|---------|------|------|------|------|
| MAE (mm) | 1.0313 | 0.7821 | 1.1359 | 1.1034 |
| RMSE (mm) | 1.1605 | 0.8941 | 1.2939 | 1.2754 |
| MAX (mm)  | 2.0440 | 1.7840 | 2.6610 | 2.5000 |

### TABLE 8. Errors of dorsiflexing/plantarflexion movement.

| Errors  | MAE (mm) | RMSE (mm) | MAX (mm) |
|---------|----------|-----------|----------|
| PAM1    | 0.6382   | 0.8156    | 1.5630   |
| PAM3    | 0.6371   | 0.8304    | 1.6700   |

### C. COUPLING TRAJECTORY

In order to further prove the motion performance of AirGait and the adaptability of this control strategy, a coupling trajectory is designed as the tracking signal. The coupling tracking signal is designed as

\[
\begin{align*}
    r_z(t) &= A_z \sin(2\pi ft + \phi_z) + L_z \\
    \theta(t) &= A_\theta \sin(2\pi ft + \phi_\theta) + L_\theta \\
    \psi(t) &= A_\psi \sin(2\pi ft + \phi_\psi) + L_\psi
\end{align*}
\]

where, \( r_z(t) \), \( \theta(t) \), and \( \psi(t) \) are the trajectories of raising/dropping, dorsiflexion/plantarflexion, and inversion/eversion movements of human lower limbs, respectively; \( A_z, A_\theta, \) and \( A_\psi \) are the amplitudes of the three movements; \( \phi_z, \phi_\theta, \) and \( \phi_\psi \) are the phase angles of the three movements; \( L_z, L_\theta, \) and \( L_\psi \) are the initial values of the three movements. Table 9 gives the parameters of Eq. (22).

The tracking responses and errors of the coupling trajectory are shown in Fig. 17 and Fig. 18. Table 10 presents the errors of the four PAMs. Fig. 17 depicts the trajectory tracking effect of the moving platform under the conditions of the raising/dropping, dorsiflexion/plantarflexion, and inversion/eversion movements. Fig. 18 describes the trajectory tracking effects of the four PAMs, which indicates the four PAMs can track the desired trajectory well, meaning that the gait simulation mechanism also has good tracking effects for coupling movement. Compared with the single raising/dropping movement described in Fig. 13 and Fig. 14, the tracking errors are also reduced obviously for the antagonistic layout of the PAMs.

### TABLE 9. Parameters of coupling movement.

| Trajectory | \( r_z(t) \) | \( \theta(t) \) | \( \psi(t) \) |
|------------|---------------|---------------|---------------|
| Amplitude \( A \) | 5 mm | 10° | 10° |
| Frequency \( f \)       | 0.2 Hz | 0.2 Hz | 0.2 Hz |
| Phase angle \( \phi \) | 0 rad | 0 rad | 0 rad |
| Initial value \( L \) | 502 mm | 0° | 0° |

### TABLE 10. Errors of coupling movement.

| Errors  | PAM1 | PAM2 | PAM3 | PAM4 |
|---------|------|------|------|------|
| MAE (mm) | 0.3301 | 0.9518 | 1.5786 | 0.2339 |
| RMSE (mm) | 0.5738 | 1.6041 | 1.7230 | 0.2758 |
| MAX (mm)  | 0.8330 | 1.9050 | 2.9160 | 0.7960 |

### D. COMPARATIVE STUDY

In order to further verify the robustness of the control scheme, the comparative study between SGPI and MSGPI model and the change of control accuracy with the increasing of loads are implemented. The results of comparative study are shown...
PAMs, because the complex structure and nonlinear hysteretic behavior increase the difficulty of control greatly. The control of PAM based on hysteresis compensation is becoming a research hotspot for its simple control scheme. However, the application of this control scheme in a parallel mechanism is not common. To realize the accurate trajectory tracking control of a novel parallel lower-limb rehabilitation robot actuated with PAMs, called AirGait, a new control architecture is proposed in this paper. The MSGPI model is adopted to characterize the nonlinear length-pressure hysteresis of PAMs, and its inverse hysteresis compensation combined with feedback control and joint space control is utilized to achieve a highly accurate trajectory tracking performance for AirGait. The effectiveness of the proposed control strategy is verified by: (1) performing trajectory tracking control experiments with the human-like and coupling trajectories; (2) implementing the control accuracy comparative study between SGPI and MSGPI model; (3) researching the change of control accuracy with the increasing of loads. The tracking errors are bounded within a maximum of a few millimeters and degrees, which is a good achievement for PAMs in the
dynamic tracking application. However, it should be pointed out that both the structure design and the control strategy still need further improvement. The control performance is not ideal under the raising/dropping movement, because this movement cannot benefit from the antagonistic layout of the PAMs. An alternative method is to replace the sliding column of Fig. 1 as mechanical spring, urging the PAMs return to their original lengths rapidly. Meanwhile, there is a strong coupling relationship between the deformation and pressure of the PAMs, which makes them vulnerable to the interference of many factors (e.g., the interaction between branches). The motion errors of each branch are only corrected by the branch itself and are not regulated by other branches. However, the accuracy of the moving platform is relevant to all of the branches, and its moving accuracy can degenerate due to the lack of synchronous coordination among the branches. In our future work, the focus is going to be on further improvements to the control strategy and accuracy for this robot.

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