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Assistive Control of a Hip EXoskeleton Assistance Robot (HEXA-I) for Rehabilitation of Stroke Patients

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***Abstract*— Most stroke patients suffer from hemiplegia and lose control on half of their body. This article proposes an assistive control strategy to induce a symmetric pattern for hemiplegic patients, using a hip exoskeleton assistance robot (HEXA-I). Combination of an impedance control, as a high-level controller, and a sliding mode control (SMC) with disturbance observer (DOB), as a low-level control, forms the proposed assistive strategy. The proposed algorithm records the trajectory of healthy leg in zero impedance mode and implements it on the affected side. A simple phase detection algorithm is used to implement the gait trajectory on the affected leg, during the swing phase. The assistive strategy is experimentally implemented on three healthy subjects by HEXA-I. The subjects were asked to simulate a hemiplegia walking. The results show that the assistive strategy would help patients to achieve a symmetric walking pattern and modify the gait of the affected side, based on their own trajectory.**

Keywords—Rehabilitation Robot, Hemiplegic Patients, Symmetric Gait Pattern, Assistive Strategy, Impedance Controller.

I. INTRODUCTION

Nowadays, exoskeleton robots are developed in two different categories, either empowering healthy people, or rehabilitating patients. Robots in the first category are manufactured due to interest and need for combining the human body with robots in environments that require high endurance and power. These robots increase people's strength, velocity, and accuracy, letting them carry heavy loads. Normally, healthy people wear these robots. BLEEX and Exo-Hiker are two examples of this type of exoskeletons [1-3]. In the second category, assistive exoskeletons are designed based on an efficient structure combining mechanical design, control, and assistive strategies as a respond to the movement problems of patients with high motor disabilities (i.e., complete spinal cord injury (SCI)). These robots can increase their life quality and sense of belonging to community and help to diminish their secondary health complications. Baunsgaard et al. conducted an experimental study on a group of patients with SCI using Ekso Bionics exoskeletons [4-6]. Results indicated potential benefits and improvements in gait function and balance. Also, partial help in the joints is provided for patients by these devices [7,8]. In this paper, an assistive strategy control is presented and implemented on an exoskeleton robot for patient rehabilitation (the second category).

There are several kinds of problems that lead to difficulty or impossibility of lower limb movement. Patients with stroke and SCI are among the most important groups who experience a reduction or complete loss of mobility of their lower extremities caused by nervous system trauma. According to statistics, the annual worldwide number of SCI cases is between 250,000 and 500,000 [9]. Half of these people have a complete lesion [10]. Therefore, the importance of developing lower limb exoskeletons with proper design and control strategy that can adapt to patients' bodies and understand their movement purpose is evident.

The main goal of lower limb exoskeletons is to help patients guide the trajectory of their movements, do repetitive training, provide physical support for daily activities, and facilitate labor-intensiveness by decreasing the load acting on the operator [11]. Lower-limb exoskeletons are generally divided into rehabilitative, assistive, and empowering devices. Rehabilitative exoskeletons are used at therapeutic sessions to boost the treatment process. Repeatability in the movements and accurate monitoring of the sessions are some of the advantages of these robots. Disorders after stroke such as impaired motor coordination, muscle weakness and spasticity, and reduced

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ankle dorsiflexion (drop foot (DF)) and knee flexion during walking can be treated with these devices.

The control strategy in the exoskeleton robot is critical for patient rehabilitation. Some researchers use predefined trajectories; for instance, MPC algorithms and adaptive fuzzy control are used for motion control of a lower limb exoskeleton robot in [5, 6] and [1], respectively. In [2], an assistive strategy based on a strength index is presented for a hip exoskeleton robot. Also, in [3, 12], a new assistive control strategy, named output feedback assistive control (OFAC), is experimentally implemented on a one-degree-of-freedom exoskeleton robot. Impedance control is one of the widely used control approaches for the assistive and rehabilitation exoskeletons, used in various robots like Lopes [13] or Lokomat [14]. In the recent decades, there has been a wide range of suggested impedance control methods for controlling the exoskeleton robots such as active impedance control [15], fuzzy variable impedance control [16], virtual impedance control [17], and active control with observer [18].

In this paper, a novel combination of spring-damper impedance controller as a high-level controller and sliding mode controller with disturbance observer as a low-level controller is conducted on the HEXA-I to help patients with half-body musculoskeletal disorders. This controller receives the reference trajectory from the healthy leg in the swing phase and applies it to the unhealthy one. The stand phase controller is set based on the actual tests on the treadmill so the controller on both hips would be zero impedance unless the unhealthy leg is in the swing phase. The controller has been tested on three healthy subjects, and the gait symmetry before and after the conduction of the controller was extracted.

In the next sections, the following details are provided. Section II introduces HEXA-I. Section III represents the assistive strategy. Section IV indicates the experimental results, and section V is the overall conclusion of the paper.

II. DESIGN AND MANUFACTURING OF HEXA-I

HEXA-I is a lower limb assistive exoskeleton designed and manufactured at the Center of Advanced Rehabilitation and Robotics Research at Ferdowsi University of Mashhad (FUM CARE). The main goal of this exoskeleton is to return the ability of gait to patients with movement disorders caused by stroke or other musculoskeletal problems. The design process of the HEXA-I is based on three main biomechanical parameters: the torque needed in the active joints, the range of movements in each joint, and compliance and conformity with the human body.

The HEXA-I has six degrees of freedom, three in each joint. The power in active joints is supplied from Maxon EC 90 Flat-160 watt with an operating voltage of 24 V and a nominal speed of 2720 rpm. These brushless motors have a two-channel encoder and hall sensor, and are controlled with EPOS4 positioning controllers. The Epos4 drivers are connected via EtherCAT protocol to each other and master controller. We use the Embedded PC from Beckhoff Co. as a master controller to have a real-time communication. TwinCAT 3.1 is the main software of the Embedded PC which was programmed by PLC programming. Additionally, the loadcell board is connected via CANOpen protocol to Embedded PC. A whole scheme of mentioned mechatronic relations is illustrated in Fig. 1.

In order to reach sufficient torque in joints, AG Harmonic Drive SHD-20-50-2SH gearboxes are used in the hip joints. These gearboxes can provide the highest order of speed reduction in a minimal volume. Having zero backlashes is another advantage of harmonic drive gearboxes that can be useful in control. They also have an efficiency of about 70 percent at the nominal speed of the motor. This combination of motor and gearbox provides about 16 Nm torque in hip joints. Due to the variable nonlinear efficiency of the harmonic drives, a load cell is used for sensing the output torque.

As depicted in Fig. 2(b), the output torque of Harmonic Drive gearbox is transmitted to the main link through an intermediary link and a loadcell. Both sides of the loadcell are hinged on the intermediary link and the main link. The main link can rotate freely around point C which is the center of the gearbox. The intermediary link, loadcell, and the main link have no motion relatively.

One of the essential factors in exoskeleton robots is their safety when used by patients. This helps both patients and physiotherapists to feel reassured and trust the robot in the physiotherapy sessions. As shown in **Error! Reference source not found.**2(a), hard stops, placed at each active joint, limit the range of motion within the desired safe zone. Plate springs are placed at the top of the hip joints, allowing a limited movement of about 5 degrees in the frontal plane.

Having the best possible adaptability is a critical aspect of a wearable robot. This can significantly affect the robot's performance and the patient's experience. As can be interpreted from Table I, owing to a sliding mechanism designed at the FUM robotics center, the robot can be used for people of different ages and genders.

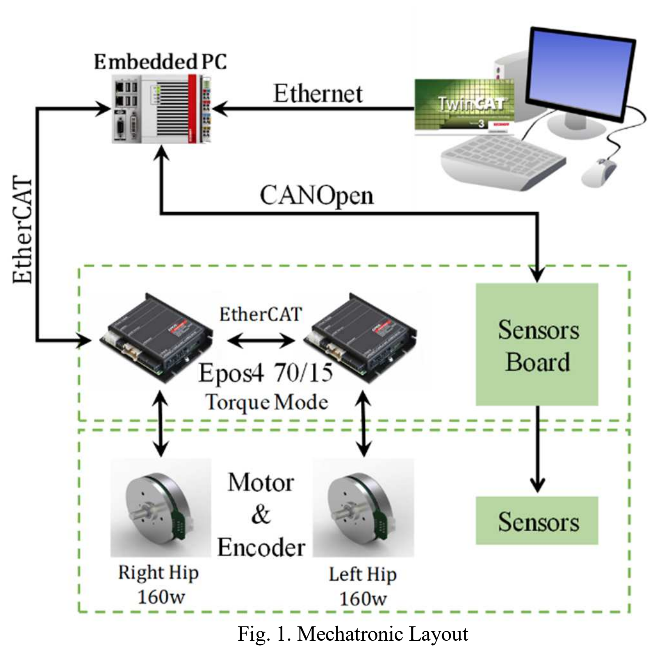

Fig. 1. Mechatronic Layout

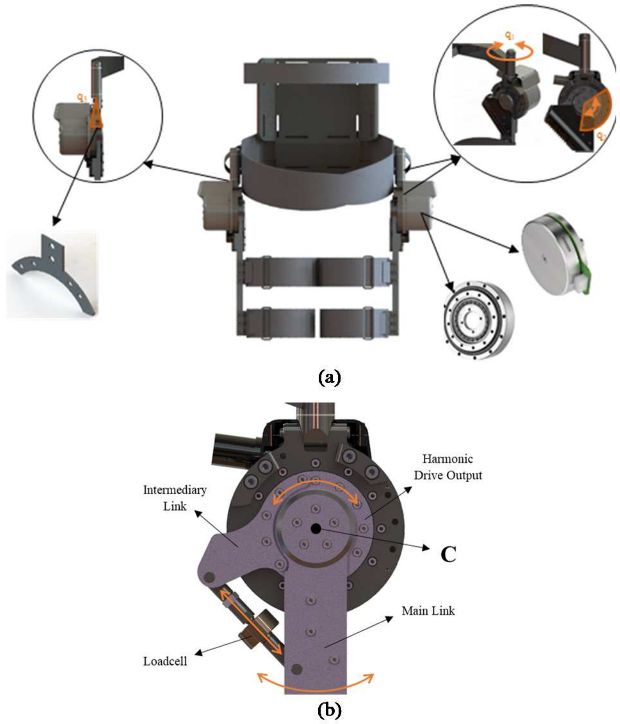

Fig. 2. (a) HEXA-I and details (b) mounted load-cell between links.

Table I. Range of motion and adjustment for HEXA-I

	Range of adjustment	The angular range of motion		
	Torso (mm)	q_1(rad)	q_2(rad)	q_3(rad)
Min	345	Free	-5	-5
Max	395	Free	100	-5

III. ASSISTIVE STRATEGY

For hemiplegic patients, using the trajectory of the healthy leg of each user as a reference for their unhealthy leg is convenient. Symmetric gait is one of the main parameters for rehabilitation and is a standard parameter to be measured and considered. In this section, this algorithm is introduced to be implemented on the HEXA-I.

The trajectory of the healthy leg is measured and recorded by the motor encoders and main processor, respectively. Then, the recorded trajectory should be implemented on the unhealthy leg at the beginning of the swing phase. For detecting the swing phase, the velocity and position of healthy and unhealthy hip joints are considered as follows,

$$\begin{gathered} IF\ \theta_{Hip\_health} > \theta_{Hip\_Unhealth}\ \&\ |\dot{\boldsymbol{\Theta}}| < \epsilon\, I_{2\times 1}\ THEN \\ Swing\ =\ True; \\ ELSE \\ Swing\ =\ False; \\ END \end{gathered} \tag{1}$$

where ϵ is a positive constant, θ_{Hip_health} and $\theta_{Hip\_Unhealth}$ are the angle of healthy and unhealthy hip joints of robot links, respectively, and $\dot{\boldsymbol{\Theta}}$ is the vector of hip joints velocity. Therefore, after detecting the swing phase, the recorded trajectory is implemented on the unhealthy leg.

Based on the dynamic structure of the robot and using force sensors between the robot link and the gearbox's output, the governing equations are presented as follows. As shown in the schematic view of the robot in **Error! Reference source not found.**2, θ_m represents the angle of motor and the angle of robot link which is controlled in sagittal plane is indicated by θ_l. τ_m, τ_l and τ_{int} are the motor torque, the torque applied to the link and the torque exerted to the human, respectively. The load-cell measures the torque applied to the link, which is responsible for transmitting the torque to the link. F indicates this measured force.

$$\tau_l = -F \times r_f \tag{2}$$

$$N = {}^{\theta_m}/_{\theta_l} \tag{3}$$

In the equations above, the reduction ratio of the harmonic drive is shown with N, and r_f is the normal distance from the center of rotation of the link to the point that the force sensor applies force to the link.

The dynamic equation of the actuator can be written in harmonic side as follows,

$$N\tau_m = J_A\ddot{\theta}_l + B_A\dot{\theta}_l + \mu sign(\dot{\theta}_l) + \tau_l \tag{4}$$

where J_A, B_A, and μ, are the moment of inertia of the actuator, viscous coefficient of friction of the actuator, and the Columbus coefficient of friction, respectively.

On the other hand, the following dynamic equation can be written for the robot link,

$$\tau_l = J_l\ddot{\theta}_l + mgl_{C.G}\sin(\theta_l) + \tau_{int} \tag{5}$$

where τ_{int}, is the amount of torque applied by the robot to help the human, $mgl_{C.G}$ is the robot weight multiplied by the distance between the center of rotation and the center of mass of the link. By substituting equation (5) into equation (4) and also equalizing the angle of rotation of the link with the angle of the output of the harmonic drive, it can be written,

$$N\tau_m = J\ddot{\theta}_l + B\dot{\theta}_l + \mu sign(\dot{\theta}_l) + mgl_{C.G}\sin(\theta_l) + \tau_{int} \tag{6}$$

where J and B are defined as $J = J_A + J_l\ and\ B = B_A$.

For the healthy leg, the controller should provide the condition so that the patient can walk without any disturbance or interference. For this purpose, the interaction force between the robot and the healthy leg, τ_{int}, should ideally be zero which is called zero impedance [13]. Therefore, in this case, the interaction torque is defined as: $\tau_{int} \to \tau_{int,desired} = 0$, and from equation (6), it can be written,

$$N\tau_{m,desired} = J\ddot{\theta}_l + B\dot{\theta}_l + \mu sign(\dot{\theta}_l) + mgl_{C.G}\sin(\theta_l) \tag{7}$$

For the affected leg, after a time delay, the assistive torque is calculated using the stored trajectory and the spring and damper impedance model.

$$\tau_{int,desired} = K_{Imp}\Delta\theta_{Imp} + B_{Imp}\Delta\dot{\theta}_{Imp} \quad (8)$$

Substitution of equation (8) into equation (5) results in:

$$N\tau_{m,desired} = J\ddot{\theta}_l + B\dot{\theta}_l + \mu sign(\dot{\theta}_l) + mgl_{C.G}\sin(\theta_l) + K_{Imp}\Delta\theta_{Imp} + B_{Imp}\Delta\dot{\theta}_{Imp} \quad (9)$$

where $\Delta\theta_{Imp} = \theta_{desired} - \theta_l$.

After calculating the optimal interaction torque and motor torque from equations (6) to (9) with impedance control as a high-level controller, which is responsible for estimating the required torque to assist the patient, a sliding mode controller with disturbance observer [19] (designed and validated by the author in another research) is used for the low-level control to implement the desired torque on the patient's legs, a summary of our low-level controller is demonstrated as follows and a comprehensive overview of the assistive strategy is presented in **Error! Reference source not found.**ig. 3. In our controller we considered five parameters for forming applied torque by the motor in which U_f, U_h, U_G, U_C and U_d are friction, human motion and gravity compensation, controller signal and disturbance compensation, respectively.

$$N\tau_m = U_f + U_h + U_G + U_C + U_d \quad (10)$$

$$U_f = \mu sign(\dot{\theta}_l) \quad (11)$$

$$U_h = J\ddot{\theta}_h + B\dot{\theta}_h \quad (12)$$

$$U_G = mgl_{C.G}\sin(\theta_l) \quad (13)$$

The angular position of human hip is indicated by θ_h and its derivatives are measured by IMU which have been placed in (12). By defining a sliding mode surface based on error of torque tracking as follows, the control signal is obtained as (15), where K_h is a spring model of human-robot interaction and ρ is error of estimated disturbances.

$$S = 4e + \dot{e} \quad (14)$$

$$U_C = {}^{J}\!/_{K_h}\left(4\dot{\tau}_{int,desired} - 4\dot{\tau}_{int} + \ddot{\tau}_{int,desired} + {}^{B}\!/_{J}\,\dot{\tau}_{int} + {}^{K_h}\!/_{J}\,\tau_{int}\right) + \rho\mathrm{Sat}(S) \quad (15)$$

To prevent chattering, the function Sat(S) is exploited as follows in which γ is a constant for smooth switching.

$$\mathrm{Sat}(S) = \begin{cases} \frac{S}{\gamma} & |S| \le \gamma \\ \mathrm{sign}(S) & |S| > \gamma \end{cases} \quad (16)$$

As seen in (17), disturbance compensation is achieved with using nominal model as defined by (18).

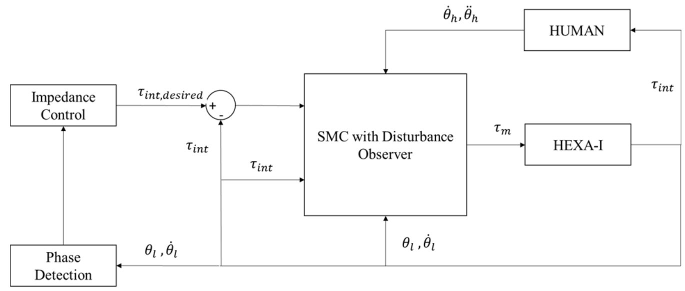

Fig. 3. The comprehensive overview of the assistive strategy.

$$U_d = \frac{1}{2}(\tau_{int}M_n^{-1} - U_C) \quad (17)$$

$$M_n = \frac{{}^{K_h}\!/_{J}}{s^2 + {}^{B}\!/_{J}s + {}^{K_h}\!/_{J}} \quad (18)$$

IV. EXPERIMENTAL RESULT

In this section, the proposed algorithm is experimentally implemented on the HEXA-I robot. Three healthy subjects with different weights and heights are considered to validate the performance of the proposed algorithm. The subjects were asked to simulate a hemiplegic walking. The stance and swing phases are detected online by (1), and zero impedance mode is applied for all phases of the healthy hip joint and stance phase of the unhealthy hip joint. Then, the trajectory of healthy hip joint in the swing phase is recorded to be considered as reference for the unhealthy hip joint. Finally, the HEXA-I helps subjects to obtain a symmetric gait pattern by implementing the gait of the healthy leg on the affected leg. For this test, subjects 1 and 3 chose treadmill walking with slow speed (0.6 m/s) and subject 2 chose to walk on the ground with very slow speed (about 0.3 m/s).

Error! Reference source not found. shows the trajectory of healthy hip joint during the swing and stance phases. The actual trajectory of the affected hip joint is also depicted if Fig. 4. The results show that the proposed method effectively assists the subjects in following the symmetric pattern with acceptable tolerance. This indicates the robustness of the algorithm independent of conditions.

In order to achieve more transparent illustration, the tracking error between reference trajectory and actual angular position of unhealthy hip joint is depicted in Fig. 5. In Table II mean square error (MSE) and root MSE (RMSE) of the trajectory of the affected hip are calculated and presented for the three subjects. The MSE and RMSE are less than 0.002 and 0.04 rad, respectively. Small tracking errors indicate the successful performance of the designed impedance controller and SMC-DOB method, in imposing the desired trajectory to the affected hip.

According to the position tracking error and its first order derivative, impedance control is used for calculating the appropriate interaction torque (8) to apply on the unhealthy side of human. Fig. 6 demonstrates the reference and actual torque of our assistive strategy which indicates the sliding mode control with disturbance observer tries well to track the desired torque. Also, in Fig. 7, the torque error is depicted that show the range of errors in the worst case are approximately 2 N.m. Table II reports the MSE and RMSE of the torque tracking to show the performance of torque tracking controller. The MSE and RMSE are less than 0.001 Nm and 0.96 Nm, respectively.

The results verify that the proposed method can effectively record the trajectory of the healthy side, control the interaction torque, and implement the recorded gait on the affected side. Therefore, a symmetric gait pattern is imposed to the patient. This can increase the effectiveness of the physiotherapy sessions and speed up the recovery of the patients.

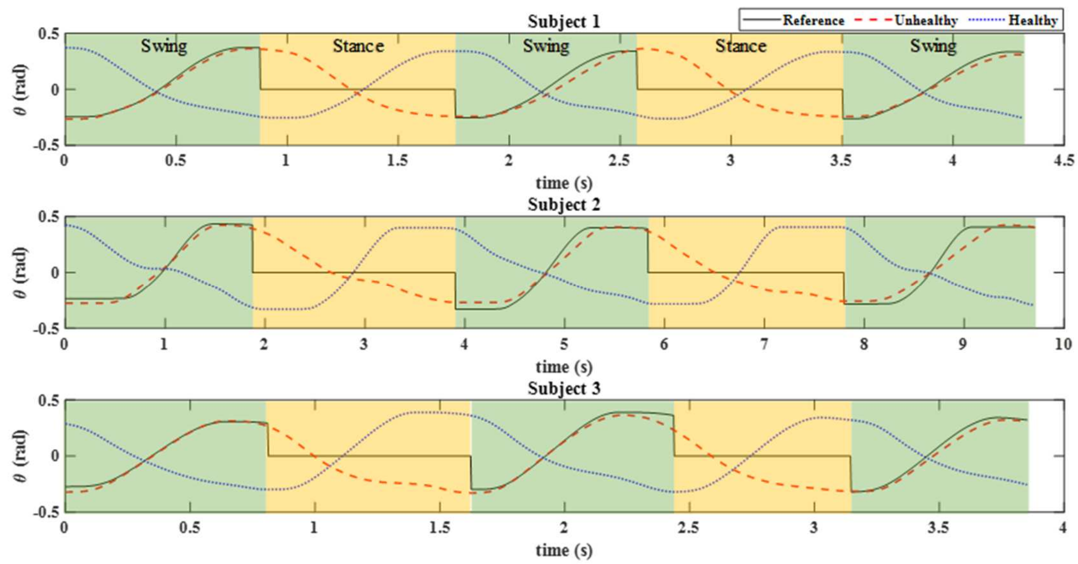

Fig. 4. Reference (black line) and actual position (red dash-line) of unhealthy hip joint and actual position (blue dot-line) of healthy hip joint. Determine the swing and stance phase by transparent box colored in green and yellow, respectively.

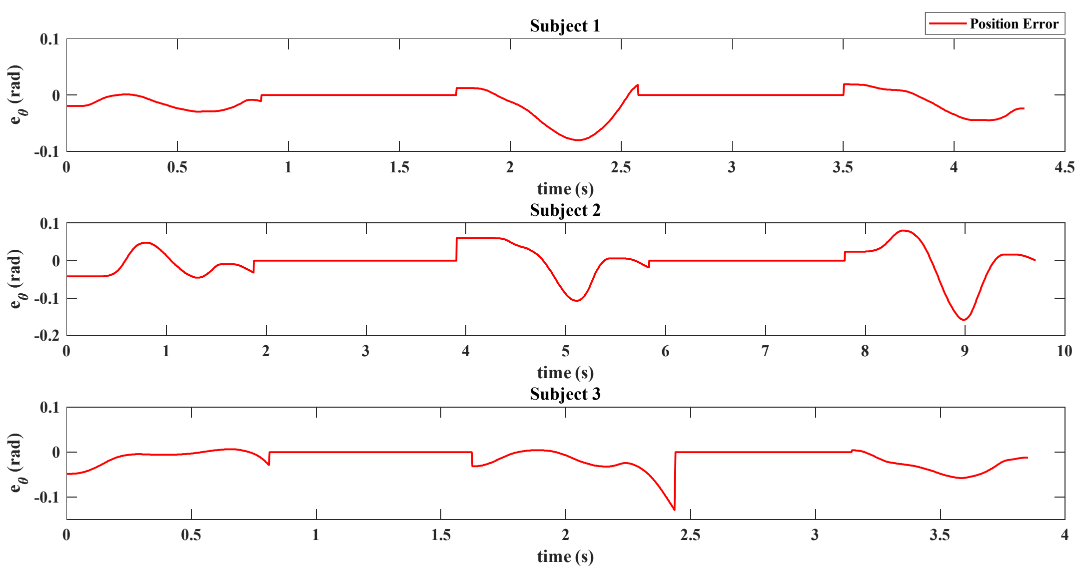

Fig. 5. Tracking error of unhealthy hip joint

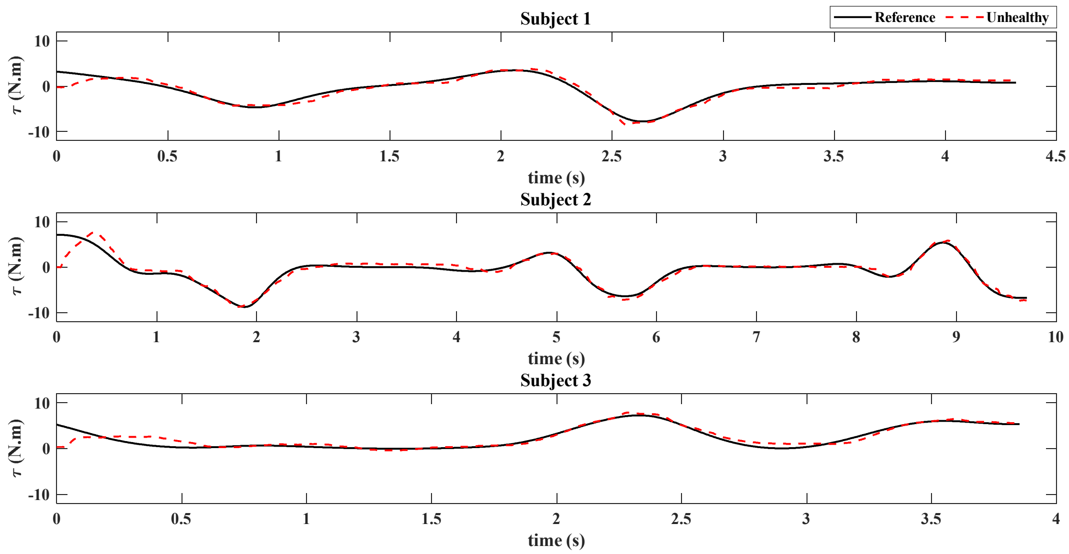

Fig. 6. Torque reference and actual interaction torque of impedance control for three subjects

Table II. Mean Square Errors (MSE) and Root MSEs (RMSE) of the trajectory tracking and torque tracking for subjects 1, 2, and 3.

Subject	Trajectory Tracking		Torque Tracking	
	MSE (10^{-3})	$RMSE$	MSE (10^{-3})	$RMSE$
1	0.5945	0.0244	0.4864	0.6974
2	1.7	0.0411	0.9127	0.9554
3	0.6206	0.0249	0.7005	0.8370

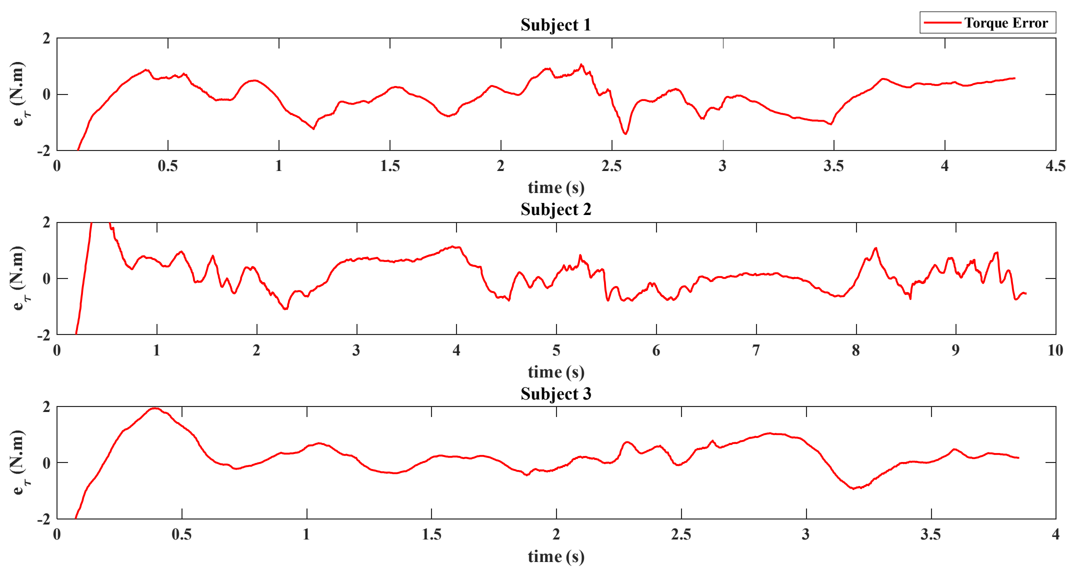

Fig. 7. Torque error of impedance control for three subjects

V. Conclusion

In this paper, an assistive control strategy is proposed and implemented on a hip exoskeleton to return the symmetric gait pattern to hemiplegic patients. The method uses a zero-impedance controller for the healthy side to allow free motions for the healthy leg. This provides the possibility of recording the trajectory of the healthy gait as the reference trajectory for the affected leg. The algorithm uses an impedance controller to calculate the torque, required for the affected leg to follow the gait of the healthy leg. Finally, a sliding mode controller with disturbance observer is used to adjust the interaction torque, according to the required torque calculated by the impedance controller. The proposed method is evaluated in some experiments by three healthy subjects. The subjects were asked to wear the robot and simulate hemiplegic walking. The results of implementing the proposed method show that gait of the healthy leg is successfully recorded in the zero-impedance mode, the SMC-DOB method has accurately controlled the interaction torque to track the torque defined by the impedance controller, and the affected leg is successfully controlled to track the trajectory of the healthy leg. Therefore, the proposed method can be used for rehabilitation of hemiplegic patients by inducing a symmetric gait pattern. Our future works will focus on adding assist-as-needed feature to the proposed method and evaluating it on hemiplegic patients.

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