Design and Validation of a Lightweight Hip Exoskeleton Driven by Series Elastic Actuator With Two-Motor Variable Speed Transmission

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Abstract—To overcome the different requirements of torque-velocity characteristics for walking, running, stand-to-sit, sit-to-stand, and climbing stairs, we propose a novel concept for actuator design, namely, a series elastic actuator with two-motor variable speed transmission. The two-motor variable speed transmission can be adjusted in real-time to realize variable torque-velocity characteristics. A novel lightweight wearable hip exoskeleton driven by a series elastic actuator with two-motor variable speed transmission, named SoochowExo, has been developed in this paper for use in the elderly population. The weight of the whole hip exoskeleton is 2.85 kg (excluding batteries), including two actuators and the frame. The proposed hip exoskeleton can match the weight of the state-of-the-art hip exoskeleton while offering suitable torque and velocity for sitting-to-standing, walking, running on level ground, and climbing stairs. The benchtop tests and the preliminary human subject tests further confirm the design.

Index Terms—Hip exoskeleton, variable speed transmission, series elastic actuator, locomotion modes, multiple tasks.

I. INTRODUCTION

Aging is accompanied by physical performance and sense reduction due to muscle weakness and motor unit loss [1]. The major concerns for senior citizens are handicaps related to sitting-to-standing, climbing stairs, and walking. The hip exoskeleton [2], [3], [4], [5], [6], [7], [8], [9] has become a rising research topic in recent years due to the small inertia added to the leg and the device’s ability to assist elderly people in walking, sitting-to-standing, and climbing stairs. However, the current hip exoskeletons still have limitations, such as wearability, weight, and assistive performance.

Human hip joints are very important for many activities that are classified as activities of daily living (ADL), including walking, running, sitting-to-standing, climbing stairs, and the real-time adjustment of the step width to avoid falling [10], [11]. Furthermore, the hip joint has different characteristics for the different types of motion. In particular, the velocity and torque requirements for walking and sitting-to-standing are opposite. The joint needs the high torque and slow velocity of the hip flexion/extension (HFE) joints during sitting-to-standing, whereas it needs a high velocity with small torque for walking and running [12], [13]. To satisfy the requirement of high torque assistance for sitting-to-standing, most exoskeletons have been designed using high-reduce radio transmission or high-power motors [14], [15], [16]. This design will inevitably increase the inertia and weight. To improve the wearability, in addition to improving the actuator’s ability, the hip exoskeleton should be as light as possible, and the structure should be slimly designed. To reduce weight, most hip exoskeletons adopt low-power motors or low reduce radio gear to meet the high-velocity requirement for walking and running. However, this will compromise the loss of the ability of high-torque assistance. Su proposed a quasi-direct drive actuation using a custom high torque density motor and low ratio gear transmission for a hip exoskeleton that demonstrates mechanical versatility for being lightweight (3.4kg overall mass), highly-backdrivable (0.4 Nm back drive torque) with high nominal torque (17.5 Nm) and high control bandwidth (62.4 Hz) [17]. However, the nominal torque of 17.5Nm is far away from the human biological hip moment requirement of the sitting-to-standing.

An exciting concept, namely, a dual reduction actuator for the knee joint of the flexible exoskeleton GEMS L-Type, has been recently introduced [18]. The two reduction radios were fixed and switched through a clutch. And the exoskeleton has to stop when the reduction radios switch. Yang, et al. [19] and Rouse, et al. [20] designed hip and knee exoskeletons so that the gear ratio can be changed during movement. Vanderborght, et al. [21] designed a variable stiffness actuator that used another motor to change the actuator stiffness. Horst, et al. [22] designed a lead screw and belt-based gear variable actuator for Orthotics. Jang designed an active-type
twisted string actuator (TSA)-based on continuously variable transmission (CVT) for the robot application [23]. Lee designed a new actuator with continuously variable transmission using parallel dual-motors and a planetary gear for mobile robots [24]. Tran developed a powered knee prosthesis with actively variable transmission for multiple tasks [25], [26]. However, there has been comparatively little work on developing a hip exoskeleton with variable speed transmission to meet the different torque-velocity for the different gait tasks.

In this paper, a lightweight, compact, compliant robotic hip exoskeleton is developed for the elderly population and the population with lower-limb impairments. To overcome the different requirements of torque-velocity characteristics for walking, running, stand-to-sit, sit-to-stand, and climbing stairs, we propose a novel concept for actuator design, namely, a series elastic actuator with two-motor variable speed transmission. The speed transmission ratio can be adjusted in real-time to realize variable torque-velocity characteristics. Furthermore, two-motor variable speed transmission can adapt to elderly people’s personalized motion characteristics due to age and physical condition.

The main contributions of this paper are as follows:
1) introduce the concept of the series elastic actuator with two-motor variable speed transmission to the hip exoskeleton design to meet the different requirements of torque-velocity characteristics for walking, running, stand-to-sit, sit-to-stand, and climbing stairs;
2) develop a novel lightweight, wearable hip exoskeleton driven by series elastic actuator with two-motor variable speed transmission, named SoochowExo, to promote the independent living of the elderly and the population with lower-limb impairments.

The paper is structured as follows. The hardware and controller design are described in Sections II and III. Section III and V present the bench-top testing and the preliminary human subject tests, which show the performance of the SoochowExo. The discussion and conclusion are described in Sections VI and VII, respectively.

II. HARDWARE DESIGN

A. Design Objectives

The main objective of the hip exoskeleton is to assist the elderly and the population with lower-limb impairments in sitting-to-standing, walking, running, and climbing stairs. The actuator requirements of torque and speed are different for different locomotion modes, such as walking, running, stand-to-sit, sit-to-stand, and climbing stairs [13], [27], [28]. The actuators of hip exoskeleton are required to working in distinctively different torque-speed load conditions. To achieve this, a series elastic actuator with two-motor variable speed transmission is designed to meet the different requirements for the assistive torque and velocity. The peak torque and velocity are designed to meet the velocity requirement, gain higher torque output, and reduce the weight. To ensure a wide range of speeds, the actuator’s requirement of the hip exoskeleton firstly is to have high velocity, and then can offer large assistive torque for the sitting-to-standing and slow walking. The design requirements of the hip exoskeleton are summarized in Table I. The hip exoskeleton was designed to offer assistive torque of 60 Nm with the velocity of 2.3 rad/s at the highest transmission ratio, while output torque of 12 Nm with the velocity of 5.6 rad/s at the lowest transmission ratio.

### Table I. Summarizes the Hip Exoskeleton Design Goals

| Requirement                  | Target       | Actual       |
|------------------------------|--------------|--------------|
| Total active DOFs            | Hip flex./ext. | Hip flex./ext. |
| Speed transmission ratio     | 6:1 – 32:1   | 6.1 – 32:1   |
| Peak torque range (Nm)       | 12 ~ 60      | 12 ~ 62      |
| Peak velocity range (rad/s)  | 5.6 ~ 2.3    | 5.9 ~ 2.8    |
| Weight (excl. power supply)  | As light as possible | 2.85 kg     |

FIG. 1. System overview of the proposed hip exoskeleton: SoochowExo.
TABLE II
THE MATERIAL AND WEIGHT FOR DIFFERENT PARTS OF THE HIP EXOSKELETON

| Item         | Quantity | Material         | Weight |
|--------------|----------|------------------|--------|
| Actuator with link | 2        | aluminum alloy   | 0.875  |
| Brace        | 2        | Plastic, textile | 0.15   |
| Suspenders   | 1        | textile          | 0.1    |
| Frame        | 2        | plastic          | 0.2    |
| Belt         | 1        | fabric           | 0.2    |
| Circuit      | 1        | -                | 0.1    |
| Total        |          |                  | 2.85kg |

wearer. The overall hip exoskeleton system weight without a battery is 2.85 kg. The material and weight for different parts of the hip exoskeleton are shown in Table II.

The hip exoskeleton includes the following core elements:

1) Two-motor variable speed transmission: To meet the assistance of various tasks, such as level-walking and sitting-to-standing, the transmission ratio of the HFE actuators of the hip exoskeleton could continue to change adaptively. The series elastic actuator with two-motor variable speed transmission uses a novel transmission system that adapts the actuator torque and speed to the demand of different ambulation tasks. For example, the speed transmission ratio adjusts to high for tasks that require high torque and low speed, such as sitting-to-standing tasks, and adjusts to low for tasks that require high speed with low output torque, such as walking and running.

2) Series elastic actuator (SEA): The actuator is designed based on the SEA concept presented in our previous works [7]. The SEA configuration can realize accurate interaction force control and complaint interaction with the wearer, as well as the torque sensor, which measures the displacement under the load.

C. The Principle of the Two-Motor Variable Speed Transmission

The principle of the two-motor variable speed transmission for the hip exoskeleton is based on the planetary gear mechanism. A planetary gear includes four parts: sun gear, ring gear, planet gears, and carrier. There have two motion control inputs, one is the sun gear and the other is the ring gear rotation, to adjust the rotation speed of the carrier and the planet gears, as shown in Fig. 2.

When the ring gear is fixed ($\dot{\theta}_2 = 0$), the velocity relation between the input 1 and output is:

$$\dot{\theta}_{out} = \left(\frac{Z_s}{Z_s + Z_r}\right) \dot{\theta}_1$$  

(1)

When the sun gear is connected with input 1 and the ring gear is connected with input 2, the output velocity $\dot{\theta}_{out}$ can be expressed as

$$\dot{\theta}_{out} = \left(\frac{Z_s}{Z_s + Z_r}\right) \dot{\theta}_1 + \left(\frac{Z_r}{Z_s + Z_r}\right) \dot{\theta}_2$$  

(2)

where $Z_s$, $Z_p$, and $Z_r$ is the number of sun gear teeth, the planetaries teeth, and the ring gear teeth, respectively.

Fig. 3 shows the concept of the planetary gear-based two-motor variable speed transmission in our design. Two planetary gear subsystems are series-connected together in the two-motor variable speed transmission. The basic principle is that two inputs contribute to one output. The first planetary gear’s reduction ratio is constant, while the second planetary gear’s reduction ratio is determined by two inputs $\dot{\theta}_1$ and $\dot{\theta}_2$. The main input $\dot{\theta}_1$ comes from the output of the first planetary gear and is connected to the sun gear of the second planetary stage. The second input $\dot{\theta}_2$ is connected to the ring gear. A worm and gear driven by the small-power motor were applied at the input $\dot{\theta}_2$ to change the reduction ratio of actuators and can also provide a self-locking function.

When the small-power motor is powered off ($\dot{\theta}_{m2} = 0$), the two-motor variable speed transmission worked in the highest-transmission ratio mode. The speed transmission ratio $R_H$ is:

$$\dot{\theta}_{out} = \frac{Z_3}{Z_3 + Z_4} \dot{\theta}_1$$  

(3)

$$\dot{\theta}_1 = \frac{z_1}{z_1 + z_2} \dot{\theta}_{m1}$$  

(4)

$$R_H = \frac{z_1 \cdot z_3}{(z_1 + z_2)(z_3 + z_4)}$$  

(5)

When the $\dot{\theta}_2$ rotated in the opposite direction to the main drive motor, then Two motor variable speed transmission worked in the low-transmission ratio mode. The speed
transmission ratio $R_L$ is computed as follows:

$$\dot{\theta}_{out} = \frac{z_3}{z_3 + z_4} \dot{\theta}_1 - \frac{z_4}{z_3 + z_4} \dot{\theta}_2$$ (6)

$$\dot{\theta}_1 = \frac{z_1}{z_1 + z_2} \dot{\theta}_{m1}$$ (7)

$$\dot{\theta}_2 = \frac{z_6}{z_6} \dot{\theta}_{m2}$$ (8)

$$\dot{\theta}_{m2} = k \dot{\theta}_{m1}$$ (9)

$$R_L = \frac{z_1 \cdot z_3 \cdot z_6 - z_4 \cdot z_5 \cdot k \cdot (z_1 + z_2)}{(z_1 + z_2)(z_3 + z_4)z_6}$$ (10)

where $z_1$, $z_2$ are the number of sun gear teeth and ring gear teeth of the planetary gear 1, respectively, $z_3$, $z_4$ are the number of sun gear teeth and ring gear teeth of the planetary gear 2, respectively, $z_5$, $z_6$ is the number of worms and worm gear teeth, respectively, $k$ is proportion factor of the velocity between the main motor and secondary motor.

D. Fully-Integrated SEA- With-Two-Motor-Variable-Speed-Transmission

Fig. 4 shows the CAD of the SEA-with-two-motor-variable-speed-transmission. The system consists of the main motor, secondary motor, two planetary gear modules, two motor variable speed transmission, and strings. The main motor is directed connected with the sun gear of the first planetary gear module using a coupler. The carrier of the first planetary gear module was mounted next to the two-motor variable speed transmission. The two-motor variable speed transmission includes a sun gear, ring gear, three planet gears, a carrier, a worm-and-gear, and a secondary motor. The output of the first planetary gear module is connected with the sun gear of the two-motor variable speed transmission. The ring gear of the two-motor variable speed transmission connected with the second motor through a worm-and-gear.

Fig. 5 shows the fabricated fully-integrated SEA-with-two-motor-variable-speed-transmission with dimensions of
Ø90 mm × 51mm. The overall actuator weight is 680 g (actuator with link weight is 875 g), including the main motor and second motor, two planetary gear-based two-motor variable speed transmission systems, and two high-resolution encoders. Furthermore, the motor driver and STM32 microcontroller-based embedded control system are integrated into the actuator as a module.

To meet the small dimension, lightweight, high power density ratio requirements of hip exoskeleton design, a custom high torque density motor (Our motor was manufactured by Unitree Robotics) was adopted into our design to work as the main motor of the SEA-with-two-motor-variable-speed-transmission. The customized high torque density motor (280 g), which can output nominal torque of 2 Nm with a transmission. The off-board and battery are placed at the back of the exoskeleton. One DSP chip (TMS320F2812)-based embedded system operates controllers that read all sensor data to compute high-level control algorithms. The high-level controller communicates with a motor controller that is integrated into the actuator through a CAN bus. There are two IMUs on both thighs to estimate the acceleration of hip flexion/extension and addition/abduction. There is one more IMU placed at the back to measure the angles, velocity, and acceleration of the upper body.

B. Low-Level Torque Control of the SEA-With-Two-Motor-Variable-Speed-Transmission

For the low-level controller, the controller performs closed-looped torque tracking control of the SEA-with-two-motor-variable-speed-transmission. The torque sensor data measured by the deformation of the torsion spring are fed back to the low-level controller. The torque control is transformed into the torsion spring’s deflection control:

\[ \tau_d (\theta) = k\theta_s \]  

where \( \theta_s \) is the torsion spring’s deflection, and \( k \) is the stiffness of the torsion spring.

The torsion spring’s deflection control is based on the proportional-integral differential (PID) controller. Reference torque signal is the input and is converted into a command spring deflection angle for the feedback term. The output of the PID torque controller is the desired velocity \( \dot{\theta}_{out} \). Then we can get the control command of the main motor and secondary motor through:

\[ \dot{\theta}_{out} = \frac{z_3 + z_4}{z_3 + z_4} \cdot \frac{z_1}{z_1 + z_2} \dot{\theta}_{m1} - \frac{z_3 + z_4}{z_3 + z_4} \cdot \frac{z_5}{z_6} \dot{\theta}_{m2} \]  

C. High-Level Assistive Control

The hip exoskeleton works in various modes, such as level walking (LW), stair ascent (SA), stair descent (SD), sitting-to-standing, and standing-to-sitting. The relationship between the assistive timing and the gait cycle is different for the various locomotion modes inspired by the human hip joint biological torque [30], [31]. The control goal is to offer effective assistive torque to adapt to the different locomotion modes. Starting from the heel strike (\( \theta_{heel-strike} \)), the controller generates the desired assistive torque. The assistive torque profile is a mixture of four halves of minimum jerk curves joined together at their tops, as shown in Fig. 6.
where \( \theta \) is the hip joint angle. The gait cycle begins and ends at the heel-strike event. \( \theta_{\text{onset}} \) is maximum flexion angle, which is an average value based on previous strides measured through IMUs [32]. The proposed assistive torque profile mimics the human biological hip moment profile. Over a gait cycle, the assistive torque profile can generate an assistive torque for both hip flexion and extension. Three parameters, \( \theta_{p,f} \), \( \tau_{p,f} \) and \( \tau_{p,e} \), are adjusted in real-time to adapt to the different locomotion modes (LW, SD, SA, running) and the different speeds. \( \theta_{p,f} \) is defined as follows:

\[
\theta_{p,f} = A \cdot \theta_{\text{onset}}
\]

where \( A \) is a constant, which is to determine the hip flexion assistive torque onset timing (increasing from toe-off and end at the maximum flexion angle) in the gait cycle. And \( A \) will be set as different values for the LW, running, SD, and SA. The onset timing is determined by the gait events. \( \tau_{p,f} \) and \( \tau_{p,e} \) are scaled for the different locomotion modes. Additionally, \( \tau_{p,f} \) and \( \tau_{p,e} \) are also scaled for different walking speeds and benefits from the actuator being able to actively vary the reduction ratio. The three key parameters \( (A, \tau_{p,f} \) and \( \tau_{p,e}) \) can dictate the assistance profile that is offset timing, assistance duration, and assistance magnitude.

IV. BENCHTOP EXPERIMENTS

A. Backdrivability and Zero-Torque Control

Performance of the SEA-With-Two-Motor-Variable-Speed-Transmission

We conducted benchtop testing and quantified the performance in terms of the torque and velocity capabilities and backdrivability. The fully integrated SEA-with-two-motor-variable-speed-transmission was fixed during the benchtop experiments. The output shaft of the actuator was manually pushed. The torque and angle data are measured through a spring-based torque sensor and encoders.

In the first test, the actuator was working in the highest-reduction ratio mode, both motor M1 and M2 are power off. Fig. 7 (a) shows the relationship between the back-drive torque and the angle. The proposed hip exoskeleton’s passive compliance is due to the elasticity introduced by the customized torsion spring. In the second test, SEA-with-two-motor-variable-speed-transmission worked at close-looped zero torque control to testing the active compliance. The back-drive torque of the fully integrated SEA-with-two-motor-variable-speed-transmission within 0.1 Nm for the different motion frequencies, as shown in Fig. 7 (b).

B. Closed-Loop Torque Control Bandwidth With Different Reduction Ratio

To test the torque and velocity characteristics of the fully integrated series elastic actuator with two-motor variable speed transmission, the actuator was velocity-controlled motion with different loadings. The peak torque can reach 12 Nm when the actuator operates in the lowest-transmission ratio mode (6:1), and the normal velocity is more than 5.9 rad/s. The actuator is operated with a peak torque of 62 Nm and a normal velocity
C. Continual Torque Control of the SEA-With-Two-Motor-Variable-Speed-Transmission

In this experiment, the proposed SEA-with-two-motor-variable-speed-transmission torque and velocity characteristics are examined in the condition that the speed transmission ratio continually adjusting, while outside of SEA-with-two-motor-variable-speed-transmission is interacted with an external motion. A high-power motor (300W) with a reduction gear of 200:1 was used as external motion. A commercial torque sensor is connected between the SEA-with-two-motor-variable-speed-transmission and external motion to measure the load torque.

**Test 1**: The SEA-with-two-motor-variable-speed-transmission is controlled to track a torque increased from 0 Nm to 60 Nm within the 60 s, while the external motor is braked.

**Test 2**: The SEA-with-two-motor-variable-speed-transmission is controlled to track a torque increased from 0 Nm to 60 Nm within the 60 s, while the external motor with a fixed speed of 3 rad/s.

**Test 3**: The SEA-with-two-motor-variable-speed-transmission is controlled to track a fixed torque of 10 Nm, while the external motion is increased from 0 rad/s to 10 rad/s within the 60 s.

The SEA-with-two-motor-variable-speed-transmission output torque, the velocity and current of the main and secondary motor, and external motion velocity were recorded. Fig. 11 shows the test results, from top to the bottom (Fig. 9 (a) - Fig. 9 (c) ) is the results of *Test 1*, *Test 2*, and *Test 3*. For *Test 1*, as shown in Fig. 9 (a), we can see that only the main motor M1 motion. The SEA-with-two-motor-variable-speed-transmission worked at the highest-transmission ratio mode. The motor current increased with torque increasing. For *Test 2*, as shown in Fig. 9 (b), the secondary motor M2 began motion at T1 and stopped at T2 to adjust the reduction ratio to meet both the torque and velocity requirements. For *Test 3*, as shown in Fig. 9 (c), the secondary motor M2 began motion at T1 to adjust the reduction ratio.

V. PRELIMINARY HUMAN SUBJECT TESTS

Five healthy subjects (age 28.5±6 y.o., weight 78.5±9.9 kg, height 1.76±0.26 m) participated in the preliminary human...
Fig. 9. Continual torque control. Note: The M2 velocity in the plots is the harmonic gear drive output side’s velocity. (a) Test 1, (b) Test 2, (c) Test 3.

subject tests. All subjects signed an informed consent form. The experiments were approved by the Ethical Committee of Soochow University. The hip exoskeleton was powered by a lithium-ion battery (400 g), which can support the device in operation for 1.5 hours. The actuator, electric circuit, and battery were fixed in the bag, which was fixed at the wearer’s back.

The hip joint angle and assistive torque of the hip exoskeleton were recorded to analyze the performance of the assistance. The hip joint angles and assistive torque were measured by an encoded spring-based torque sensor integrated into a fully integrated series elastic actuator with actively variable reduction ratio transmission. The hip angles during the free motion were performed without wearing the hip exoskeleton (no exo) and were measured through an inertial motion capture system (Perception Neuron 2.0, Noitom Technology Ltd.). The heel-strike event, which was detected through two loading cells placed at each shoe, was used to normalize the gait periods.

A. Sit-to-Stand Test

The subjects wore the hip exoskeleton and performed sit-to-stand trials with different peak torque assistances. The subjects were asked to keep the same speed to sitting-to-standing at each trial. For the sitting-to-standing, the assistive torque profile is:

$$\tau_d(\theta) = 3\tau_{peak} \left( \frac{\theta_{stand} - \theta}{\theta_{stand} - \theta_{sit}} \right)^2 - 2\tau_{peak} \left( \frac{\theta_{stand} - \theta}{\theta_{stand} - \theta_{sit}} \right)^3$$

(19)

where $$\tau_{peak}$$ is the peak assistive torque, $$\theta_{stand}$$ is the hip flexion angle when the human stands, and $$\theta_{sit}$$ is the hip flexion angle when the human sits. We set $$\theta_{stand}$$ to 5 degrees; the hip exoskeleton will work in zero torque mode when the hip flexes and is smaller than 5 degrees, which allows the subject to freely move. The peak assistive torque was set as 50 Nm, 30 Nm, 10 Nm, and 0 Nm (power off) for the four test groups.

Fig. 10 shows the HFE joint angle, assistive torque under the peak assistive torque was set as 50 Nm, 30 Nm, 10 Nm, and 0 Nm (power off). There were no significant changes in the hip joint angle on the peak assistive torque was set as 50 Nm, 30 Nm, 10 Nm, and 0 Nm (power off). We can see from Fig. 8 that the assistive torques start from the beginning sitting on the chair and are gradually reduced to zero with standing. The assistive torques show that the hip exoskeleton can output assistive torque up to 50 Nm.

B. Different Locomotion Modes Assistance Tests

The subjects walked on a treadmill for 10 min at a fixed speed of 1.2 m/s, ran on a treadmill for 10 min at a fixed speed of 2.2 m/s, and ascended and descending a stair (four floors, 230 stairs) under three conditions: wearing the hip exoskeleton with assistance (assist on), wearing the hip exoskeleton without assistance (assist off), and without wearing the hip exoskeleton (no exo) [35]. Participants were asked to keep the selected cadences constant during the ascending stair and descending stairs. We set A as different values for LW, SA, SD, and running based on the human biological hip moment [12], [13].

Fig. 11 shows the average kinematic and assistive force delivered by the hip exoskeleton under three conditions: assist on, assist off, and no exo. Fig. 11 shows that the assistive torque begins at the heel-strike event, smoothly increases
TABLE IV
ASSISTANCE PARAMETERS FOR THE DIFFERENT LOCOMOTION MODES

| Mode   | $\tau_{p,f}$ (Nm/kg) | $\tau_{p,e}$ (Nm/kg) | $A$ (%) | Speed (m/s) |
|--------|----------------------|----------------------|--------|-------------|
| LW     | 0.2                  | -0.2                 | 65     | 1.2         |
| SA     | 0.3                  | -0.5                 | 20     | -           |
| SD     | 0.4                  | -0.4                 | 30     | -           |
| Running| 0.1                  | -0.1                 | 20     | 2.2         |

$\tau_{p,f}$ and $\tau_{p,e}$ are the flexion and extension peak torque, respectively. $A$ is a constant, which is to determine the hip flexion assistive torque onset timing (increasing from toe-off and end at the maximum flexion angle) in the gait cycle.

TABLE V
PERFORMANCE OF ASSISTANCE FOR THE DIFFERENT LOCOMOTION MODES

| Mode   | Angle (deg) | Peak Torque (Nm/kg) | Peak Velocity (rad/s) | Torque Tracking Error (RMSE) |
|--------|-------------|---------------------|-----------------------|------------------------------|
| LW     | (-14, 23)   | 0.22                | 2.43                  | 0.189                        |
| Running| (-12, 18)   | 0.12                | 5.48                  | 0.234                        |
| SA     | (4, 39)     | 0.53                | 2.98                  | 0.201                        |
| SD     | (-14, 37)   | 0.42                | 3.21                  | 0.209                        |

to the negative peak and ends at heel-off, then increases to the positive peak and ends at maximum hip flexion for all locomotion modes. Table V summarized the performance of hip exoskeleton assistance for the different locomotion modes. The peak torque reached 0.22 Nm/kg, 0.12 Nm/kg, 0.53 Nm/kg, 0.42 Nm/kg, 0.21 Nm/kg, 0.12 Nm/kg, 0.32 Nm/kg, and 0.42 Nm/kg at extension and flexion for walking, running, SA, and SD, respectively. The assistive torque up to peak flexion torque reached 20%, 20%, 30%, and 40% for the walking, running, SA, and SD, respectively, while up to extension torque at 20%, 20%, 30%, 40%. In summary, the hip exoskeleton only introduced minimum changes to gait kinematics. The assistive force tracked the designed profiles for different locomotion modes. Furthermore, the assistive torque could also adapt to different subjects’ independent walking speeds.

VI. DISCUSSION

The design of hip exoskeletons for elderly individuals is challenging in terms of the weight of the exoskeleton, the compromise between force and velocity, the comfortable wearer–exoskeleton interface, and assistance performance. The hip joints work together on many activities, such as sitting-to-standing, walking, running, and climbing stairs. There are diverse characteristics of the different activities. The torque and velocity requirements for walking/running and sitting-to-standing are opposite. The motivation of this paper is to address this opposite and to avoid using a high-power motor to reduce the weight of the hip exoskeleton.

Benefitting the planetary gear’s multiport characteristics, a series elastic actuator with two-motor variable speed transmission is designed for our hip exoskeleton, which can support different speed transmissions. In the lowest-transmission ratio mode, the transmission ratio for the HFE joints is 6:1. Based on our benchtop tests, the peak velocity is more than 5.9 rad/s with an output torque of 16 Nm, which allows the wearer to run at 2.5 m/s, as shown in Fig. 11. In contrast, in the highest-transmission ratio mode, the transmission ratio for the HFE joints becomes 32:1. The resulting peak torque can reach 60 Nm, which can assist sitting-to-standing with 25% of the biological hip flexion torque, as shown in Fig. 10. Based on the two-motor variable speed transmission and custom high torque density motor, the fully integrated SEA weighing 870 g can generate assistive torque up to 60 Nm.
in the highest-transmission ratio mode and can allow the
hip exoskeleton to run at a high speed of 2.5 m/s in the
lowest-reduction mode. These performances are achieved by
adopting a high torque density motor and two-motor variable
speed transmission rather than using a high transmission ratio
or high-power motor due to their inherent heavy and bulky
characteristics.

The proposed SEA-with-two-motor-variable-speed-
transmission can continuously adjust the speed transmission
ratio similar to [26], and not only discretely adjust between
tasks like [25], [26], and [18]. Different from the two same
motor parallel arranged input to the planetary gear in [24],
there has a high-power motor work as the main input to output
the drive torque, and a low-power motor with the worm-and-
gear as secondary input work to adjust the speed transmission
ratio. Different from [24], the reduction ratio of the
proposed SEA-with-two-motor-variable-speed-transmission is
reduced with the increasing velocity of the secondary motor.
Furthermore, there have two planetary gears series connections
as the variable speed transmission. These configure reduced
the axial dimension and the weight of the actuator. Besides,
our two-motor variable speed transmission connected with a
torsion spring assemble as a series elastic actuator to realize
accurate interaction force control and complaint interaction
with the wearer, as well as the torque sensor.

The proposed wearable hip exoskeleton with the two-motor
variable speed transmission series elastic actuator is to promote
the independent living of the elderly and the population with
lower-limb impairments. The SEA-with-two-motor-variable-
speed-transmission can meet the individual needs of the elderly
because different elderly people and people with lower-limb
impairments have different assistance level requirements. Fur-
thermore, our exoskeleton also has the potential to reduce joint
loadings of non-disabled populations for regular activities.
The motivation of this paper is to propose an actuator design
concept for the hip exoskeleton. The speed transmission ratio
adjusts range can choose based on the user’s requirement.

Whatever how our effort, the hip exoskeleton still introduces
nonnegligible mass. Currently, the hip exoskeleton focuses
on reducing the weight to assist energy-efficient walking,
which has a frame to support the weight. A biomechanics
study [34] showed that the energy expenditure increased the
smallest when additional loading was applied to the waist com-
pared with the thigh, shank, or foot. The energy expenditure
will not significantly increase when the 4 kg mass loading
is at the waist. The proposed hip exoskeleton is 2.85 kg
(excluding batteries). And this weight is light than the most
of hip exoskeletons [4], [6], [7], [8], [9], [15], [16]. Our
hip exoskeleton with the rigid frame can connect with the
weight support frame, such as Kim designed bio-inspired knee
joint [35] or Lenzi designed self-aligning mechanism [36],
to balance the weight of the exoskeleton, it will be beneficial
for the elderly to wear the hip exoskeleton long time.

Several limitations related to the device’s design and con-
trols still limit the possibility of adoption without extra work.
There is a tradeoff between the actuator’s backdrivability and
the two-motor variable speed transmission. The backdrivabil-
ity of the SEA-with-two-motor-variable-speed-transmission
depends on the stiffness of the customized torsion spring when
both motor M1 and M2 power off. The back-drive torque is big
than [17], [37]. A simplistic control scheme was used in this
paper to evaluate the performance of the hip exoskeleton dur-
ing steady-state walking, running, SA, SD, RA, and RD. The
peak timing and peak force were fixed. Previous studies [38]
have shown that online peak force and timing optimization
can improve gait performance and reduce energy expenditure.
The load cells at the shoes were used in the controller to
detect the gait event and introduce cables at the shoes and
legs. In the future, detecting gait events based on IMUs placed
on the thighs will eliminate cable issues. With the design of
the hip exoskeleton now validated, additional elderly people
and people with lower-limb impairments clinical validation can
conduct investigate clinical outcomes in the further [39].

VII. Conclusion

In this paper, a novel concept for actuator design, namely, a
series elastic actuator with two-motor variable speed transmis-
sion is introduced in the hip exoskeleton design. The reduction
ratio can be adjusted in real-time to meet the different require-
ments of torque-velocity characteristics for walking, running,
stand-to-sit, sit-to-stand, and climbing stairs. The design,
control, and experimental validation of a novel lightweight
hip exoskeleton for elderly individuals and people with lower-
limb impairments are presented in this study. The proposed
lightweight hip exoskeleton driven by SEA-with-two-motor-
variable-speed-transmission can application in elderly people
and people with lower-limb impairments, as well as the
able-bodied populations for regular activities.

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