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Assistive Powered Hip Exoskeleton Improves Self-Selected Walking Speed in One Individual with Hemiparesis: A Case Study

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***Abstract*—Most individuals suffering a stroke have permanent weakness on one side of the body (hemiparesis) that reduces their ability to ambulate. Autonomous powered exoskeletons have been proposed as a possible solution to this problem. Studies with healthy subjects show that assistive powered exoskeletons have the potential to improve gait, for example, by reducing the metabolic cost of walking. However, only a handful of studies have been conducted with individuals with hemiparesis. Thus, the ability of autonomous exoskeletons to improve gait in this population remains largely unknown. In this study, we assess self-selected walking speed with and without an autonomous powered hip exoskeleton in one individual with hemiparesis walking on level ground. Results show that the proposed exoskeleton improves self-selected walking speed by ~30%. The biomechanical analysis suggest that the increased walking speed is the result of the powered hip exoskeleton enabling the subject to take longer strides on the hemiparetic side. This case study provides important information to inform future exoskeleton development and clinical study design.**

I. Introduction

Over thirty million Americans—about 1 in 10—have a disability that prevents them from independently carrying out daily activities such as self-care or attending work [1]. Most of these individuals have difficulties walking and climbing stairs [1]. These statistics include the 7 million stroke survivors currently living in the United States. Stroke is the leading cause of long-term disability in the US [2]. Approximately 80% of stroke survivors experience hemiparesis, a difficulty or inability to move one side of the body. Symptoms of hemiparesis include muscle weakness, abnormally low strength and early onset of fatigue, which can severely reduce walking speed, efficiency, and endurance [3][4]. Even with the best rehabilitation therapy, most of the 800,000 Americans who suffer a stroke each year have permanent impairments that reduce their ability to ambulate [5]. Beyond rehabilitation, these individuals could benefit from the use of assistive technologies that compensate for the weakness of the affected lower extremity [6].

Powered exoskeletons present a promising solution to this problem. Originally proposed to enhance the rehabilitation process within clinics [7]–[10], lightweight assistive exoskeletons have been more recently developed to improve ambulation at home and in the community [11]. Biomechanics studies conducted with healthy subjects show that, despite the negative effect of the exoskeleton mass on the user's effort [12]–[14], a net reduction of metabolic cost is obtained if the right amount of assistance is provided at the right time within the gait cycle [15]–[18]. Studies with healthy individuals also show that powered exoskeletons assisting the hip joints have the potential to provide greater metabolic improvements than exoskeletons assisting the knee or the ankle joint [11]. The observed differences may be due to their lightweight design [19], the more proximal location of the assistive device mass [13], or the ability to assist during both stance and swing, which is not possible with powered ankle exoskeletons.

Only a handful of exoskeleton studies have been conducted with hemiparetic subjects. A 2018 study showed metabolic improvements in hemiparetic subjects when they used a powered ankle exoskeleton, compared to using it unpowered [20]. In contrast, a 2019 study using a treadmill-based ankle exoskeleton showed no metabolic improvements in hemiparetic subjects compared to not wearing the exoskeleton, despite using a similar assistive approach focused on ankle pushoff and positive net-energy injection [21]. More recently, a 2020 study with hemiparetic subjects using a portable ankle exoskeleton showed faster self-selected speed (11.2%) but no metabolic rate improvements compared to not wearing an exoskeleton [22]. These studies show that lightweight powered ankle exoskeletons have the potential to improve ambulation in individuals with hemiparesis.

Powered hip exoskeletons have been shown effective in reducing the metabolic cost of walking in healthy subjects [11]. Used as a rehabilitation device and in combination with an intensive training regimen (i.e., three sessions/week, four weeks), a lightweight powered hip exoskeleton has also been shown to reduce metabolic cost of walking without an exoskeleton in hemiparetic subjects [23]. However, to the best of our knowledge, there have not been any studies using powered hip exoskeletons as assistive devices for individuals with hemiparesis.

In this case study, we assess self-selected walking speed with and without an autonomous unilateral powered hip exoskeleton, developed by our lab [24], in one individual with hemiparesis. We hypothesize that a powered hip exoskeleton can improve self-selected walking speed by assisting the hemiparetic hip to accelerate the leg into swing and to extend the stride length. To test this hypothesis, we developed an assistive controller that assists the wearer by providing torque to the hemiparetic-side hip in flexion direction only. The exoskeleton assistive flexion torque is timed to the wearer's stride so that it starts in late stance and continues throughout swing. To assess self-selected walking speed, we administered the 10-meter walking test (10MWT) for six times without the exoskeleton and for six times with the exoskeleton. Results of

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(a) (b) (c)

Fig. 1. Experimental setup. (a) Still frame of the participant performing the 10-meter walking test with the powered hip exoskeleton (b) A photos of the powered hip exoskeleton used for the study (c) Sectioned view of the exoskeleton actuator with callouts highlighting the location of the main components.

this case study will inform future control development and clinical study design.

II. Methods

A. Experimental Protocol and Data Analysis

One participant (Male, 61 y/o, 82 kg, 173 cm, 15 years post stroke, hemiparetic right side) was enrolled in the study. The experimental protocol was approved by the University of Utah's Institutional Review Board. Written informed consent was provided by the subject before the experiment took place. The subject also provided written consent for the use of photos and videos of the experiment.

After consenting to participate in the experiment, the subject wore a safety harness and performed the 10MWT (self-selected speed) six times without the exoskeleton. During the 10MWT, the subject was instructed to cross a 10 m walkway at a comfortable walking speed. Researchers started a timer when the subject crossed a 2-m mark and stopped the timer when the subject cross an 8-m mark. Then, with assistance from the researchers, the subject donned the exoskeleton and performed a tuning session, which lasted for about 30 minutes. The subject wore the powered hip exoskeleton in bilateral configuration (Fig. 1). However, assistance was provided solely to the right hip joint only (i.e., hemiparetic side) whereas the left hip exoskeleton joint was operated in zero-torque mode to promote backdrivability. The tuning session began with the subject walking with the exoskeleton in zero-torque mode on both sides. Starting with the exoskeleton in zero-torque mode, we tuned the controller based on the subjective feedback of the user and the experience of the experimenters. After the tuning session, the subject rested without the exoskeleton until he felt ready to start walking. After resting, the subject donned the exoskeleton and performed the 10MWT six times while receiving assistance on the impaired, right hip only.

B. Powered Hip Exoskeleton

In this study, we used an autonomous, lightweight, powered exoskeleton to assist the subject 's hemiparetic hip during walking, as shown in Fig. 1(a-b) [24]–[26]. This hip exoskeleton can assist the wearer's hip by generating torque in flexion and extension through an integrated electromechanical actuator, which is fully enclosed in the exoskeleton thigh frame (Fig. 1(c)). The exoskeleton allows for unconstrained motion of the wearer's hip joint in the frontal plane through a combination of passive abduction/adduction joints (Fig. 1(c)). Moreover, the exoskeleton uses a self-aligning mechanism to avoid spurious force and torques on the wearer's leg, increasing comfort and performance [27], [28]. The exoskeleton can be operated in unilateral and bilateral configuration.

The exoskeleton connects to the wearer around the pelvis and the thigh using custom orthoses (Fig. 1(b)). These orthoses are 3D-printed using materials with different strength and stiffness to create a custom fit around both the pelvis and the thigh. Specifically, the exoskeleton uses a flexible thermoplastic polyurethane (TPU) which directly interfaces the user's hip with the exoskeleton (Fig. 1(b)). Stiff, carbon fiber bars connect the compliant TPU pelvis interfaces to the powered hip joints. The stiff connecting bars can transmit assistive torque from the exoskeleton to the user. The rigid connecting bars also contain the electrical components. At the thigh, a TPU interface wrap around the leg to evenly distribute exoskeleton force on the limb (Fig. 1(b)). Both the pelvis and thigh orthoses are tightened to the wearer using BOA straps (Click Medical, CO, USA).

The exoskeleton's back structure hosts the control electronics and the power supply (6S Li-Ion battery). The control electronics use an embedded computer and a microcontroller to interface with all sensors and to perform all control routines. The control electronics contains two motor drivers allowing the exoskeleton to be used in bilateral

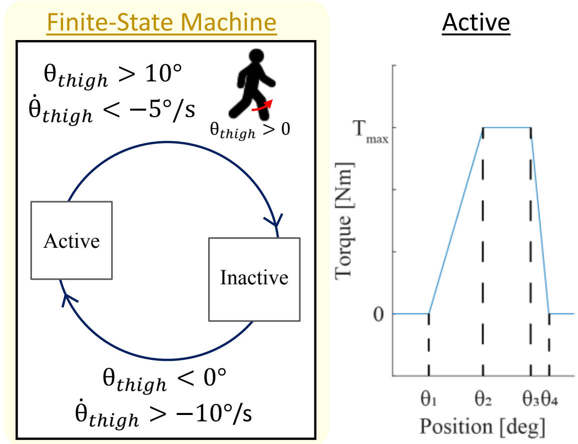

Fig. 2. Assistive controller and finite state machine. The finite state machine switches between active and transparent modes to prevent receiving position-based assistance when it is unwanted. A position-based assistance profile is defined by experimental tuning. The maximum assistance T_{max} and the shape of assistance θ_n are defined to maximize positive power from the exoskeleton.

configuration. The control electronics can communicate with a laptop via Wi-Fi for data visualization and assistance tuning.

Each hip exoskeleton actuator weighs 640 g, including the three wiring cables connecting the electrical sensors and motors to the control electronics. The thigh orthosis weighs 83 g. The hip orthosis, including both 3D printed pads, BOA straps, and the abduction and adduction passive degrees of freedom, weighs 866 g. The electronics box, including the controller and battery, weighs 388 g. The total weight of the exoskeleton, as used in the experiments, is 2700 g.

C. *Assistive Controller*

We implemented a hierarchical controller to provide synchronous assistance during walking. The high-level controller uses a simple finite-state machine to determine when the assistive torque is active during the gait cycle. The finite-state machine contains two states, *Active*, when the exoskeleton assists, and *Inactive*, when the exoskeleton is controlled to be in zero torque (also known as transparent mode). The finite-state machine transitions from *Active* to *Inactive* when the thigh position is above a specified threshold and the thigh angular velocity is below a specified threshold (10° and -5°/s, respectively). The finite-state machine transitions from the *Inactive* state to the *Active* state when the thigh position is below a specified threshold and the thigh velocity is above a specific threshold (0° and -10°/s, Fig. 2). The *Inactive* state of the finite-state machine prevents hip flexion torque during hip extension motion. Additionally, the finite-state machine is used to time the assistance to the wearer as well as to avoid the assistance being provided when the subject is shuffling without walking.

During the *Active* state, the exoskeleton generates a position-dependent, trapezoidal torque profile that assists flexion only, defined by Eq. (1), where θ is the orientation of the thigh:

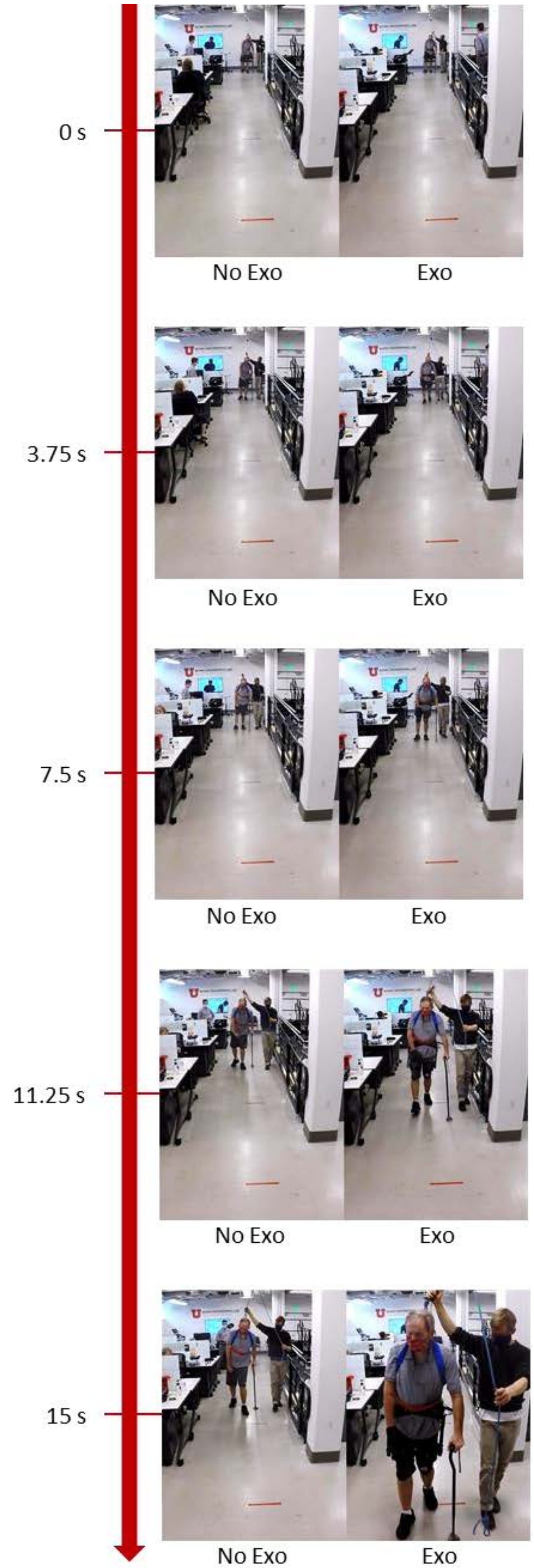

Fig. 3. Ten-meter walking test. Still frames from the supplementary videos show the visual difference between using the exoskeleton and not using the exoskeleton.

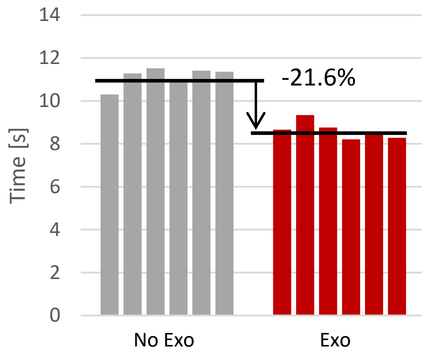

Fig. 4. Results of the 10-meter walking test (10MWT). The 10MWT was repeated six times without the exoskeleton (grey bars) and six times with the powered hip exoskeleton (red bars). The average time to complete the test with the powered hip exoskeleton was 21.6 % lower than without exoskeleton.

$$T(\theta) = \begin{cases} 0 & \theta < \theta_1 || \theta > \theta_4 \\ \frac{T_{max}}{\theta_2 - \theta_1}(\theta - \theta_1) & \theta_1 \le \theta < \theta_2 \\ T_{max} & \theta_2 \le \theta < \theta_3 \\ \frac{T_{max}}{\theta_4 - \theta_3}(\theta_4 - \theta) & \theta_3 \le \theta < \theta_4 \end{cases} \quad (1)$$

Based on this trapezoidal profile, the exoskeleton assistive torque increases proportionally to the thigh orientation until a first threshold is achieved (θ_2). The exoskeleton assistive torque remains constant until a second threshold is achieved (θ_3). As the thigh orientation increases past this second threshold, the flexion torque decreases proportionally, until it reaches zero at θ_4 (Fig. 2). The parameters (θ_1 , θ_2, θ_3, θ_4, T_{max}) were tuned to reliably trigger assistive torque at the transition from stance to swing and to prolong the assistive torques while maintaining user comfort.

III. Results

The powered hip exoskeleton reduced the time to complete the 10MWT by 21.6% (Fig. 3, Fig. 4). Specifically, the result of the 10MWT with the exoskeleton was 8.7 ± 0.37 s (average ± standard deviation) down from 11.1 ±0.41 s without the exoskeleton. Thus, the participant was 2.4 s faster with the powered hip exoskeleton than without it. Based on the results of the 10MWTs, we estimated that the powered hip exoskeleton increased the self-selected speed by 29.6% compared to walking without the exoskeleton. Specifically, the self-selected walking speed was 0.70 m/s with the exoskeleton and 0.54 m/s without the exoskeleton (Fig. 5(a)). The powered hip exoskeleton significantly increased the comfortable walking speed (two-tailed paired t-test, p= 1.4e-06).

The exoskeleton affected cadence and stride length. There was a modest, 3.8% increase in self-selected cadence with the powered hip exoskeleton. The average cadence with the exoskeleton was 84.9 steps/min up from 81.7 steps/min without the exoskeleton (Fig. 5(b)). Interestingly, on average, the participant took 12 strides to complete the 10MWT without the powered hip exoskeleton. In comparison, he took 10 strides with the exoskeleton (Fig. 5(c)). Thus, the cadence was about

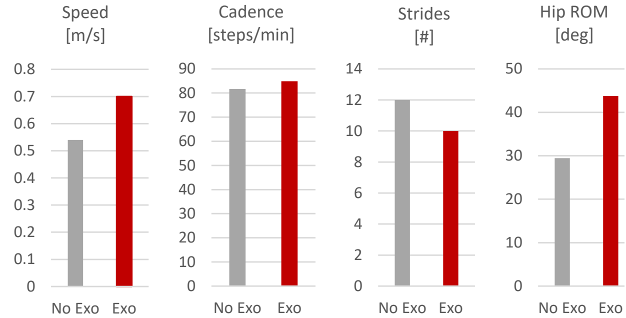

Fig. 5. Secondary outcomes of the 10-meter walking test. Walking speed, cadence, number of strides, and hip range of motion during the 10-meter walking test with (red) and without (grey) the exoskeleton.

the same, but the stride length increased substantially with the powered hip exoskeleton.

Kinematic analysis provides further insights into the effects of the powered hip exoskeleton. On average, the powered hip exoskeleton increased the range of motion of the hip joint on the affected side by 48.6% (Fig. 5(d)). Specifically, the range of motion of the affected hip increased from 29.5° without the exoskeleton to 43.8° with the exoskeleton. Data shows that the observed increase in range of motion is primarily due to the increase in hip flexion angle. Interestingly the range of motion of the affected side with the powered hip exoskeleton (solid red line, Fig. 6(a)) is similar to that of healthy control subjects (dashed black line, Fig. 6(a)), although the hip angle profiles are noticeably different between 50% and 100% of the gait cycle (i.e., late stance to heel strike). Coherent with the observed increased in range of motion, the peak hip velocity was 43.5% higher with the exoskeleton compared to not wearing the exoskeleton. Specifically, the absolute peak of joint velocity increased from

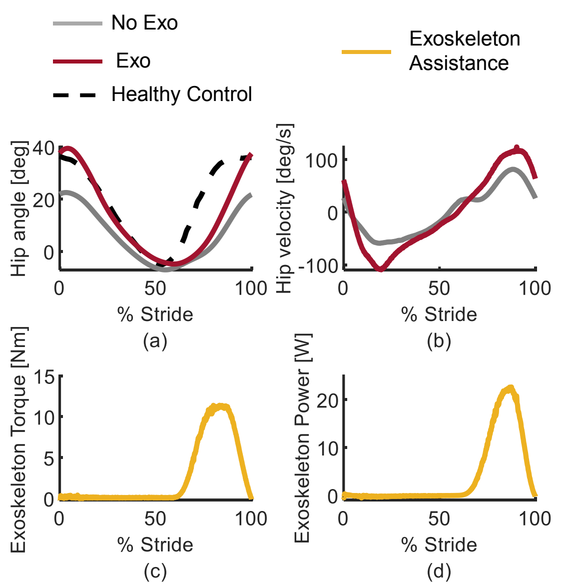

Fig. 6. Kinematics and Exoskeleton assistance. (a) Average hip angle and velocity trajectories as a function of the normalized stride time (% Stride). (b) Average trajectories of the assistive torque and power generated by the hip exoskeleton as a function of normalized stride time (% Stride).

80.5°/s without the exoskeleton to 115.5°/s with the exoskeleton (Fig. 6(b)). Thus, the powered exoskeleton had a substantial effect on the kinematics of the affected hip.

The assistive controller provided torque in synchrony with the movements of the affected hip joint. Assistive torque was provided in flexion direction only, from about 50% of stride to about 100% of stride (Fig. 6(c-d)). The peak of the assistive torque was about 12 Nm and happened at 85% of stride completion (mid-swing phase). The mechanical power output of the exoskeleton roughly matches the timing of the assistive torque profile, peaking in mid-swing at about 23 W. Thus, the exoskeleton assistance primarily targeted swing phase.

IV. Discussion

A. *Significance*

Millions of individuals face reduced mobility, independence, and quality of life after suffering a stroke. Even with the best rehabilitation therapies, many stroke survivors have permanent weakness on one side of the body (hemiparesis) that reduce their ability to ambulate. Assistive powered exoskeletons can theoretically address this problem by compensating for the permanent weakness in the affected lower limb with onboard actuators and control. However, designing lightweight, effective exoskeletons is an open challenge and substantial research effort is still spent to improve the performance of powered exoskeletons. Moreover, most human experiments are still performed with young, healthy individuals who do not need an assistive device to walk independently. Only a handful of studies have included persons with hemiparesis, obtaining promising but mixed results [20]-[22]. Therefore, the effects of powered exoskeletons on individuals with hemiparesis is largely unknown. This case study suggests that a lightweight, unilateral powered hip exoskeleton has the potential to improve ambulation ability by increasing self-selected walking speed in individuals with hemiparesis.

Self-selected walking speed is a good predictor of mobility in the community [29], [30]. Studies have shown that the capability to increase walking speed in individuals with hemiparesis is limited by impaired hip and ankle power generation [3]. Moreover, the ankle joint has been shown to be the main contributor to forward propulsion in healthy individuals [31]. This observation has motivated the development of several assistive ankle and hip exoskeletons. Both ankle and hip exoskeletons have shown successful results in assisting gait in healthy individuals [15]–[17]. More recently, one ankle exoskeleton has also shown 11.2% increase in walking speed in individuals with hemiparesis [22]. In contrast, hip exoskeletons have been primarily used to enhance the outcomes of rehabilitation therapy after stroke, with no demonstration of their effectiveness as an assistive device [7] [23] . Our case study suggests that a powered hip exoskeleton used as an assistive device can effectively increase self-selected walking speed. The 29.6% increase in self-selected walking speed observed in the study participant is substantial. Thus, if confirmed in a broader population, the observed increase in walking speed could have considerable positive impact on the mobility of individuals with hemiparesis.

Walking speed is the byproduct of stride length and the gait cadence. Thus, an exoskeleton can improve walking speed by increasing either stride length or cadence. Our results show that the proposed powered hip exoskeleton and related assistive controller primarily affect walking speed by increasing stride length on the affected side (Fig. 5). Kinematic analysis suggests that the increased stride length is due to a substantial increase in the range of motion of the affected hip (48.6%). The kinematic analysis also shows a small increase in gait cadence (3.8%). Thus, this study suggests that increasing stride length is an effective way to improve self-selected walking speed in individuals with hemiparesis.

Most assistive controllers for powered exoskeletons target forward propulsion by injecting positive net energy in stance phase when the foot is on the ground [20]-[22]. In contrast, the proposed assistive strategy aims to increase the stride length, acting primarily in swing (Fig. 6). The assistive power analysis shows that the exoskeleton injects substantial net-positive energy into the gait cycle and that the exoskeleton only provides positive power (Fig. 6). However, this energy is injected in swing phase, when the foot is off the ground. Interestingly, biomechanical experiments [32] and simulations [33] have shown that there is an interplay between the ankle plantarflexion torque and the hip flexion torque in late stance. Thus, it is possible that the hip assistance provided by the exoskeleton in late stance partly compensated for the limited ankle strength. Further investigation is necessary to assess the effect of ankle and hip assistance in individuals with hemiparesis.

B. *Limitations*

Despite the promising results of this case study, there are important limitations to consider. Like in all case studies, the findings may not generalize to a broader population. This limitation is particularly important given wide variability observed in individuals with hemiparesis. Additionally, the lack of randomization of appearance of exoskeleton condition may introduce bias. The proposed exoskeleton controller was designed to target swing and stride length by assisting the hemiparetic hip in the flexion direction only. However, previous studies in healthy individuals have shown that providing hip extension assistance during early stance is an effective way for improving body propulsion [18]. Therefore, future control developments should implement both flexion and extension assistance. The mechanisms underlining the observed improvement in walking speed are not entirely clear. Future studies should include electromyography, inverse dynamic analysis, along with randomization of experimental conditions to assess the effect of the exoskeleton assistance on motor control pathway reorganization, muscle effort, and joint loading. An analysis of stability and balance should be conducted to assess whether the faster self-selected walking speed has a negative or a positive effect on these outcomes.

V. Conclusion

This case study shows that a lightweight autonomous powered hip exoskeleton has the potential to increase self-selected walking speed in individual with hemiparesis—a major predictor of community ambulation. By improving walking speed, exoskeletons may have considerable positive impact in the mobility and quality of life of millions of stroke survivors. The results of this case study provide important information to design future clinical trials with appropriate statistical power.

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