Development of a Hip Abduction-Adduction Exoskeleton for Mediolateral Assistance

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***Abstract*—Lower limb exoskeletons are gaining prevalence to augment mobility of people with gait impairments. However, current exoskeletons using serial elastic actuators do not have the torque and bandwidth capabilities to assist in balance control in daily activities. Considering the critical role of mediolateral stability in balance control of individuals affected by neurological and age-related gait impairments, we propose an abduction-adduction exoskeleton for mediolateral assistance. The exoskeleton utilizes harmonic gear driven actuators with active torque feedback to ensure high bandwidth and admittance control capabilities, designed as an assistive device for enhanced balance. The exoskeleton is developed to be able to provide assistance up to a bandwidth of 5 Hz at the hip to individuals weighing up to 90 Kgs. Benchtop testing of the exoskeleton showed closed loop velocity bandwidth of more than 5 Hz while under loading with a user weighing 85 Kgs. Further, analysis of admittance controller using both static and dynamic testing showed that the developed controller can simulate stiffnesses up to 95 Nm/rad with an R^2 of over 99%. Pilot human testing individuals showed that the exoskeleton can modulate step width behavior of individuals while ensuring compliance with the users, facilitating seamless human robot interaction. The implication of the developed exoskeleton for balance control in elderly and neurologically impaired populations, and future avenues of research are discussed.**

***Index Terms*— Wearable Robotics, Admittance Control, Assistive Robotics, human robot interaction, Rehabilitation Robotics**

I. INTRODUCTION

EXOSKELETONS have been gaining prominence for use in industrial, military, and medical applications. Specifically, lower limb exoskeletons are increasingly being used in industry to prevent injuries during weight intensive operations [1] and in military applications to increase strength and endurance [2]. In the medical field, wearable lower limb exoskeleton systems have recently emerged as a potential solution for therapeutic training purpose for people with lower limb motor impairments [3,4]. However, their relevance as an assistive device, especially in community settings, has been limited [5,6].

Initial lower limb exoskeleton systems have been designed to enable upright walking for spinal cord injured patients. The control generate cyclic motions in lower limb joints to create gait patterns as a form of rehabilitation [7]. These devices are limited by the actuator technology, which made them bulky, had no torque feedback, and lacked any human-robot interaction needed for utilization by other populations who still have residual motor outputs (such as post-stroke individuals) [8]. Exoskeletons were developed then for assistance outside rehabilitation facilities, but these devices still used similar actuators and expected the users to use crutches and other support devices [9]. With the advent of serial elastic actuators [10], exoskeletons had the ability to control torque at the joints and ensure back drivability, expanding their utility. Several exoskeletons use serial elastic actuators to control interactive torque at the human robot joint, and thereby provide assistance for people with disabilities [11-15]. However, due to the complex relationship between the torque resolution, bandwidth, and impedance of these actuators, several of these exoskeletons cannot simultaneously provide high torque and bandwidth needed for balance and gait [16,17]. As a result, these devices have predominantly been used for reducing the energetic cost of walking by supplementing a part of human generated torque during activities [18-20]. Recently, soft exoskeletons have been developed to address the needs of people suffering from neurological disorders [21]. While these devices provide additional benefits due to the compact and compliant nature of the devices, they have mostly been used in improving energetics [22,23] or in rehabilitation applications through entrainment [24,25]. This is mainly due to the limited torque capabilities and bandwidth of these devices. While energetic efficiency offered by exoskeletons is important for people with gait impairments, diminished balance capabilities is also a major cause of concern and is not currently addressed.

Balance assistance requires exoskeletons with high torque to overcome effects of upper body inertia, agile enough to respond to balance perturbations, and be backdrivable to enable human robot interaction and safety[26]. However, current devices do not have the torque and bandwidth capabilities to enable human-like balance control [27]. Emulators have shown promise in balance control as they have both bandwidth and torque capabilities [28,29]. However, they are not portable as the actuators are too bulky to be packaged on to the robot. The limitations of existing lower limb exoskeletons constrains the use of these devices in community by people needing balance

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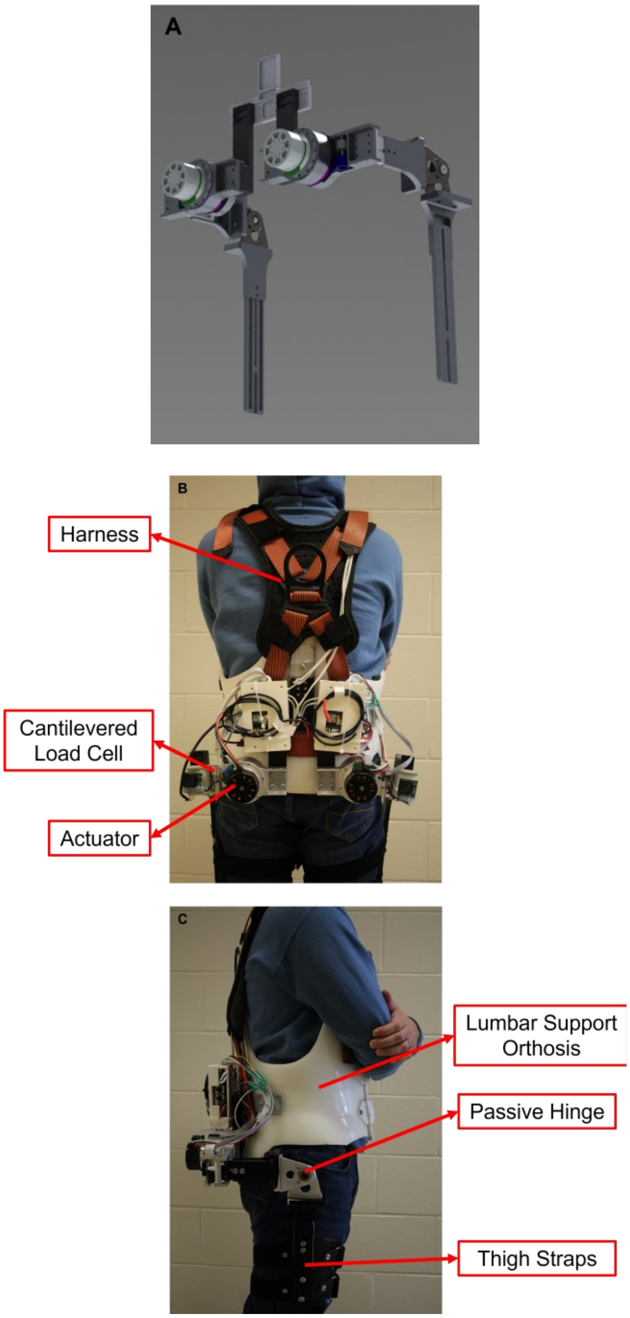

Fig. 1. A) Render of the exoskeleton; **B)** Back view of the exoskeleton showcasing the actuators, load cell and the harness; **C)** Side view of the exoskeleton showcasing the hinge, thigh straps and orthosis.

assistance [6]. In fact, one in three elderly individuals in the US experience a fall, resulting in serious injury or even death [30,31]. In addition, neurological disorders such as stroke[32], multiple sclerosis [33] and Parkinson's disease[34] further increased fall risks. Hence, we aimed to develop an exoskeleton that could provide high torque and bandwidth, while being backdrivable and portable to provide balance assistance.

Research has shown that compromised mediolateral stability affects balance and has a significant role in causing falls [35,36]. Mediolateral balance outcomes such as variability in gait behavior (e.g., step width variability) have been successfully shown to predict likelihood of falls [37,38]. falls in mediolateral direction, while not significantly higher than anterioposterior direction, result in injuries of greater significance such as hip fractures [39,40]. Despite the significance of mediolateral balance, the few exoskeletons focusing on balance have mostly focused on the sagittal plane with any frontal plane assistance being an addition for sagittal plane assistance [41,42].

Recognizing the need for robotic devices that can provide assistance to address balance deficits in the frontal plane, we have developed a mediolateral hip exoskeleton system that can provide assistance along the abduction-adduction motion. We specifically chose the hip joint due to the vital role it plays in balance control strategies. The main contributions of this research are: 1) We developed a mediolateral hip exoskeleton by using an innovative actuator with active interaction torque feedback addressing the bandwidth limitations of series elastic actuators [43] while ensuring a compact design, thereby making it possible to both torque and bandwidth necessary for balance. 2) we implemented an admittance controller to facilitate human-robot interaction necessary for the robot to understand user intent and provide necessary assistance, and 3) We demonstrated the ability of this exoskeleton in modulating mediolateral hip behavior through step width alterations in individuals, while being compliant enough to be overridden by users when needed.

In this paper, we described the design considerations for the development of a mediolateral exoskeleton for balance enhancement control (Section IIA and IIB), discussed the mechanical and control design (Section IIC), and finally demonstrated its validity in modulating mediolateral gait behaviors in individuals (Section III and IV). The implications of the device in addressing balance deficits were discussed in Section V.

II. Design

A. Design Considerations

The design considerations were determined such that exoskeleton would be adaptable to a wide range of physical demographics, with the goal of being suitable for populations within 10th-90th percentile of the target population. The main considerations were that: (i) the device can apply torques to support an individual weighing up to 90 Kgs, (ii) have mechanical linkages that support the stress caused by the dynamics with a safety factor of 1.5, (iii) An abduction and adduction range of motion of 30 degrees, spanning 60 degrees in total, (iv) facilitate human-robot interaction and (v) have sufficient bandwidth to provide mediolateral balance assistance. Based on prior literature, the peak mediolateral torque observed in humans was 0.8 Nm/kg, which translates to 72 Nm for a person weighing 90 Kgs [44]. Further, a minimum bandwidth of 5 Hz would be sufficient to apply assistance in under 200 ms, which is the duration for active volitional response observed in individuals [45].

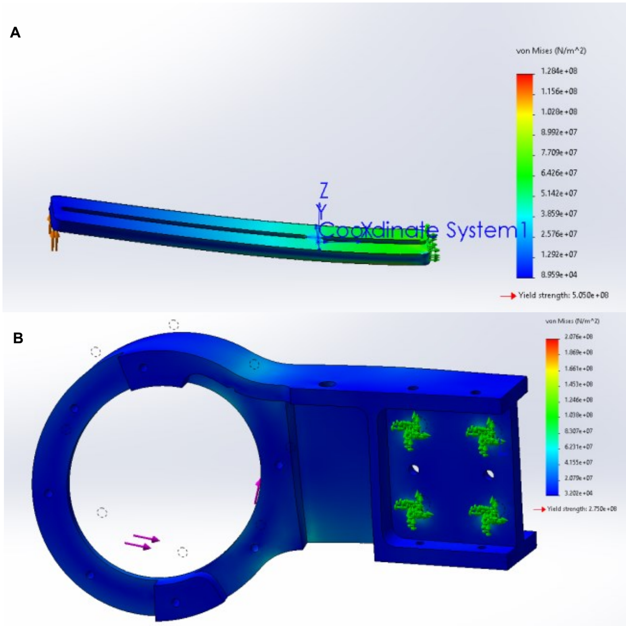

Fig. 2. Sample finite element analysis of **A)** thigh straps and **B)** actuator housing.

B. Mechanical Design

One of the main design goals for the exoskeleton is to be able to apply sufficient torque to users to provide mediolateral assistance. Further, the device should be able to apply the torques at the hip joint to minimize shear forces at the attachments to the user's body. In order to achieve that, the actuators were designed using a 100:1 harmonic gear (CSD-20-100-2A-GR-SP674, Harmonic Drive, MA, USA) attached to a Maxon EC-60 brushless motor to provide a moment at the hip and achieve high torque to weight ratio. The actuators were attached on the back such that the point of rotation of the actuators aligns with the hip joint axis along the mediolateral direction (Fig. 1B). A climbing harness was connected to a Thoracic Lumar Support Orthosis (Spinal Technology, MA) to act as the support shell for the actuators (Fig. 1C). The harness can be further adjusted to ensure alignment of the axes of rotation.

The actuators are attached to the orthosis through aluminum housings. The designed housings were evaluated using Finite Element Analysis to ensure that they can withhold the stresses applied by the actuators (Fig. 2). A safety factor of 1.5 was applied for the housings to ensure rigidity without adding too much additional material. The output of the actuator is connected to aluminum linkages that were then connected to the user's limbs. A cantilevered load cell is connected in parallel to the actuator to provide active feedback of the interaction torque between the device and the user that could be utilized in the control.

A major challenge in the development of abduction-adduction hip exoskeletons is to account for the flexion-extension motion. Most rigid flexion-extension exoskeletons arrest the abduction-adduction motion to simplify the designs[46]. This approach is not feasible for an abduction-adduction exoskeleton as the range of motion of flexion-extension motion is much higher and vital for gait and locomotion. In order to ensure minimal interference, we attached passive hinges between the actuators and the linkages that strap to the thighs of the user such that the axis of rotation coincides with the hip flexion-extension axis. This design was chosen to minimize the load on the passive hinges and ensure minimum complexity in design while having all the rotational axes to coincide. Benchtop testing was performed to ensure that the torque at the actuators was being transferred to the limbs despite the hinge being present between the actuator and the straps.

C. Controller Design

The control architecture of the exoskeleton is developed as a two-level hierarchical control structure (Fig. 3). The low-level controller is a closed loop PID velocity controller that was implemented in the individual BLDC motor controllers (ELMO Gold solo twitter) for each actuator. These controllers operate at a voltage of 24 V and can provide up to 40 Amps of current to apply mediolateral torques at the hip joints. An admittance controller that commands velocities to the low-level controller based on the interaction torque from the load cell to simulate second order mechanical system behavior based on the specified stiffness (K), damping (B), and Inertia (M) parameters based on the relationship described in (1) was developed as the high-level controller. The admittance controller was implemented on a realtime TwinCAT system operating at a frequency of 1 KHz and would facilitate human robot interaction. While the higher-level control was implemented in a single control system, the admittance loops for each actuator are independent of each other enabling the exoskeleton to simulate different characteristics on each limb. The admittance

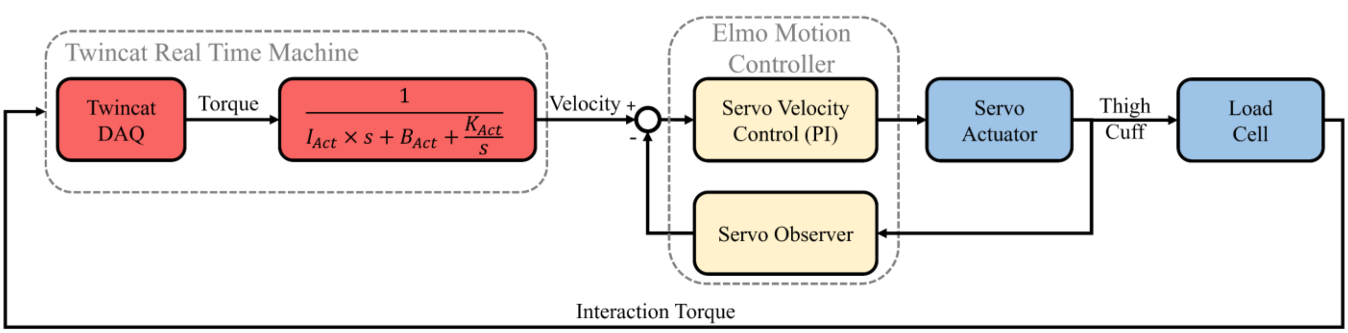

Fig. 3. Control Architecture of the 2-level controller developed for each actuator of the exoskeleton.

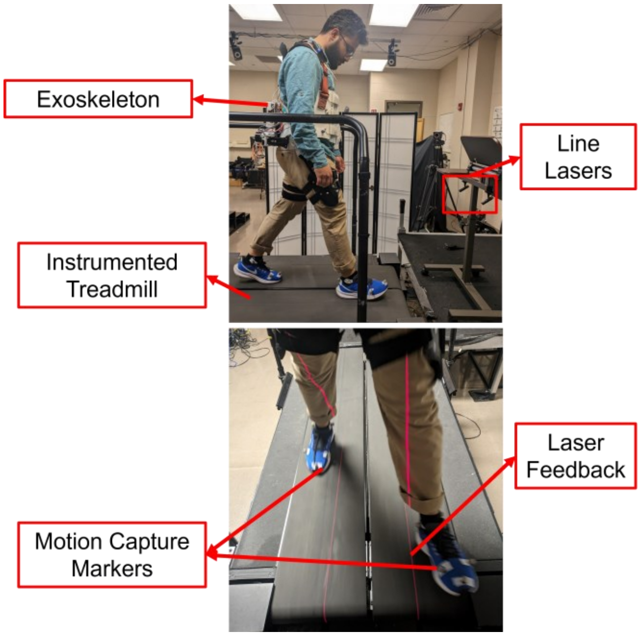

Fig. 4. Experimental Setup for the pilot human testing trials. **Top:** The subject performing treadmill walking trials while using feedback from line lasers while the exoskeleton applies assistance, **Bottom:** The laser feedback to aid subjects in modulating their step width.

parameters can be altered at the operating frequency of 1 KHz to affect the exoskeleton behavior thereby providing assistance or resistance torques based on the application. A UDP communication was set up for the high-level controller to facilitate integration with learning based systems or remote adjustments of the admittance parameters.

$$T(s) = (Ms^2 + Bs + K)\theta(s) \tag{1}$$

III. Validation

In order to ensure that the developed exoskeleton meets the design considerations and is safe for use by target populations, validations including benchtop testing and pilot human trials involving three non-disabled individuals were performed.

A. Benchtop Testing

The goal of the benchtop testing was to analyze the bandwidth capabilities and verify the ability of the system to simulate admittance responses through the actuators. In order to analyze the bandwidth capabilities, a sinusoidal sweep signal having frequencies ranging from 1-100 Hz with a maximum current of 50% motor rating was applied. In order to simulate realistic loading, the exoskeleton was attached to a non-disabled under weighing 85 Kgs and the input signals were applied while the user was in a quiet standing position. The frequency responses of the output velocities were analyzed to quantify the bandwidth of the system.

In order to verify the admittance characteristics, two experiments have been conducted: (i) Static trials and (ii) dynamic trials. During the static trials, force is applied to the thigh straps while the exoskeleton simulated different stiffnesses using an instrumented spring weight scale. 4 different stiffnesses (20, 40, 60 and 80 Nm/rad) were used while forces were applied to obtain similar angles of deflection. Once the steady state is reached, the deflection of the actuator is noted. The linear relationship between the deflection angle and the force applied as well as the slope of the linear relationship is estimated.

In order to estimate the dynamic behavior, the step response of the physical admittance controller was compared to the simulated step response of a second order system having the same admittance parameters. These comparisons are performed across 3 different stiffness values (12, 48 and 95.04 Nm/rad) and corresponding damping values that could simulate damping ratios of 0.6, 0.8, 1, 1.2 using the relationships from (3) to recreate (1) as a second order system (2). This validation ensures that a wide range of behaviors ranging from underdamped to overdamped systems are analyzed. Additionally, the ability of the system to simulate different natural frequencies was also analyzed.

$$T(s) = (s^2 + 2\zeta\,\omega_n s + \omega_n^2)\theta(s) \tag{2}$$

$$\omega_n = \sqrt{\frac{k}{m}},\ \zeta = \sqrt{\frac{b^2}{4mk}} \tag{3}$$

The ability of the system to simulate theoretical behavior was estimated using R^2.

B. Pilot Human trials

Three individuals (Age: 28-34, Height: 167-172 cm, Weight: 72-85 Kg) with no prior neurological or musculoskeletal diseases have been recruited for the study. Informed consent was obtained from all the subjects prior to the study. The purpose of the study was to verify (i) if the exoskeleton can influence the step width behavior in individuals and (ii) if the exoskeleton can be volitionally overridden by users to facilitate safe human-robot interaction. In order to perform the verification, the users were instructed to walk on an instrumented treadmill at their preferred speed for a total of 5 trials, each of a duration of 2 min. The step width of the users was tracked using 6 reflective markers attached to each foot of the user that is then tracked by a motion capture system (VICON, Oxford, U.K.).

The trials were divided into two visual feedback trials and three non-visual feedback trials. During the non-visual feedback trials, subjects were instructed to walk normally at their preferred speed on the treadmill while the exoskeleton simulated a transparent mode with minimal impedance, an abduction admittance mode where the equilibrium angle was set to 15 degrees of hip abduction user and an adduction assistance mode where the equilibrium angle was set to 15 degrees of adduction. A stiffness of 40 Nm/rad was simulated by the exoskeleton during the abduction and adduction admittance modes. The equilibrium angles and stiffnesses were chosen as the midpoints of both stiffness and range of motion capabilities of the exoskeleton. For the visual feedback trials, two lasers that would project lines along the treadmill belts were used. Subjects were instructed to walk on the treadmill

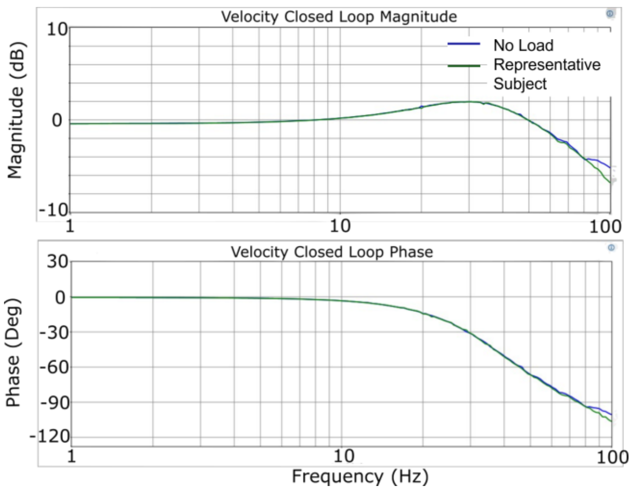

Fig. 5. Bandwidth analysis of the velocity controller

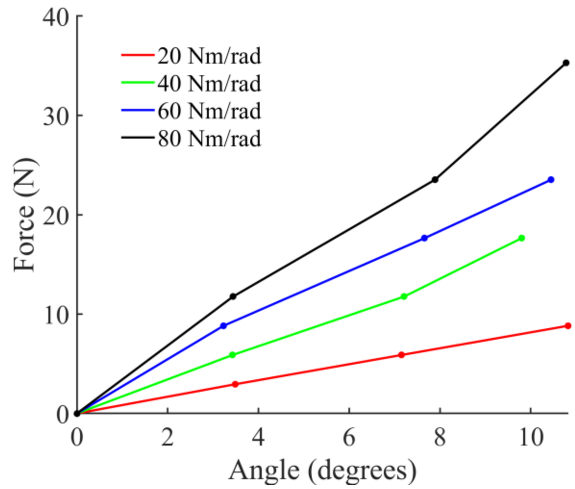

Fig. 6. Static analysis plots showing the relationship between applied force and observed deflection.

with their feet landing between the laser lines while the robot applied abduction torque. Similarly, they were asked to walk with a wider stance so that their feet were outside the laser lines while the hip exoskeleton applied adduction torque. The step width of each subject is evaluated across the five trials and compared.

IV. Results

A. Bandwidth Analysis

Observing the frequency response of the closed loop velocity control as shown in the bode plot (Fig. 5), the controller can replicate input signals without any phase lag up to 5 Hz. The behavior is similar in the frequencies of 1-5 Hz and under both no load and while being worn by a subject of weight 85 Kg. Hence, the exoskeleton would be able to perform at a bandwidth of 5 Hz across users of different body weights.

B. Static and Dynamic Admittance Control Analysis

The static analysis showed a linear response across all the stiffnesses as shown in Fig. 6, where the applied forces were plotted against the deflection. Additionally, linear regression analysis showed that the relationship is linear with a minimum R^2 of 99.4% with the slope being within the bounds of stiffness with a maximum error of 2.5%. Finally, the dynamic analysis trials showed that the exoskeleton actuator response was similar to the expected theoretical step response across stiffnesses and damping ratios. The representative comparisons are shown in Fig. 7 and the R^2 of each trial is listed in Table I.

C. Pilot Human Trials

Pilot human testing analysis showed that all three subjects increased their step width on abduction assistance and decreased their step width on adduction assistance (Fig. 8). More importantly, subjects were able to decrease step width during abduction assistance with visual feedback and increase step width during adduction assistance with visual feedback by overriding exoskeleton assistance. All subjects showed significantly different mean step widths during assistance trials compared to the transparent mode trials simulating zero impedance. Subjects 2 and 3 showed significant difference mean step widths across all trials, while subject 1 showed no significant difference between no visual feedback adduction assistance and abduction assistance with visual feedback. These results show that the exoskeleton can influence step width but can act with compliance and its behavior can be influenced by human behavior to ensure human robot interaction.

V. Discussion

The goal of this research was to develop a robotic hip exoskeleton to provide assistance along the mediolateral direction to aid in balance. Hence the design considerations included the ability to provide sufficient torque for a wide demographic range of users, have sufficient bandwidth to suit assistive applications, and have a controller that facilitates human robot interaction. The developed exoskeleton has been validated using both benchtop testing and pilot human subject testing. The observations and implications of the results are discussed below.

A. Benchtop Testing

Benchtop testing was performed to analyze the performance on both the low-level and high-level controllers. The low-level controller analysis showed that the device can accurately replicate input velocity signals up to a frequency of 5 Hz even under loading caused by users. This high bandwidth could enable the system to be used in assist as needed conditions where the device can respond immediately to perturbations while allowing the users to function without assistance during functions of daily living [47]. Such approaches are vital for populations including older people who have high functionality but are at risk of falls.

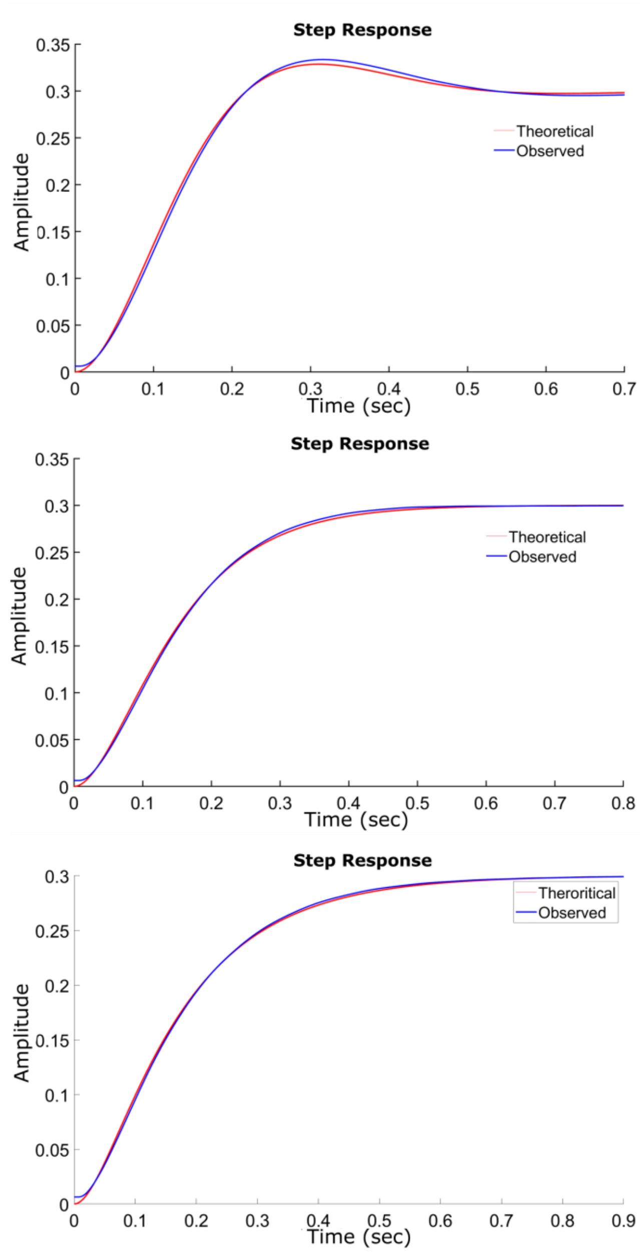

Fig. 7. Representative theoretical step response comparisons for an underdamped, critically damped and overdamped condition.

TABLE I
R^2 ACROSS DYNAMIC RESPONSE TRIALS

Stiffness	**Damping Ratio**			
(Nm/rad)	**0.6**	**0.8**	**1**	**1.2**
12	99.51	99.83	99.57	99.91
48	99.59	99.94	99.64	99.96
95.04	98.46	99.61	99.78	99.60

Admittance controllers are ideal to facilitate human-robot interaction due to the inherent compliance and feedback through interaction torque sensing [48]. The measured interaction torque between the user and the device can also be utilized in intent characterization of the user. Both static and dynamic trials show that the exoskeleton can successfully simulate admittance control through a wide range of stiffnesses and damping ratios.

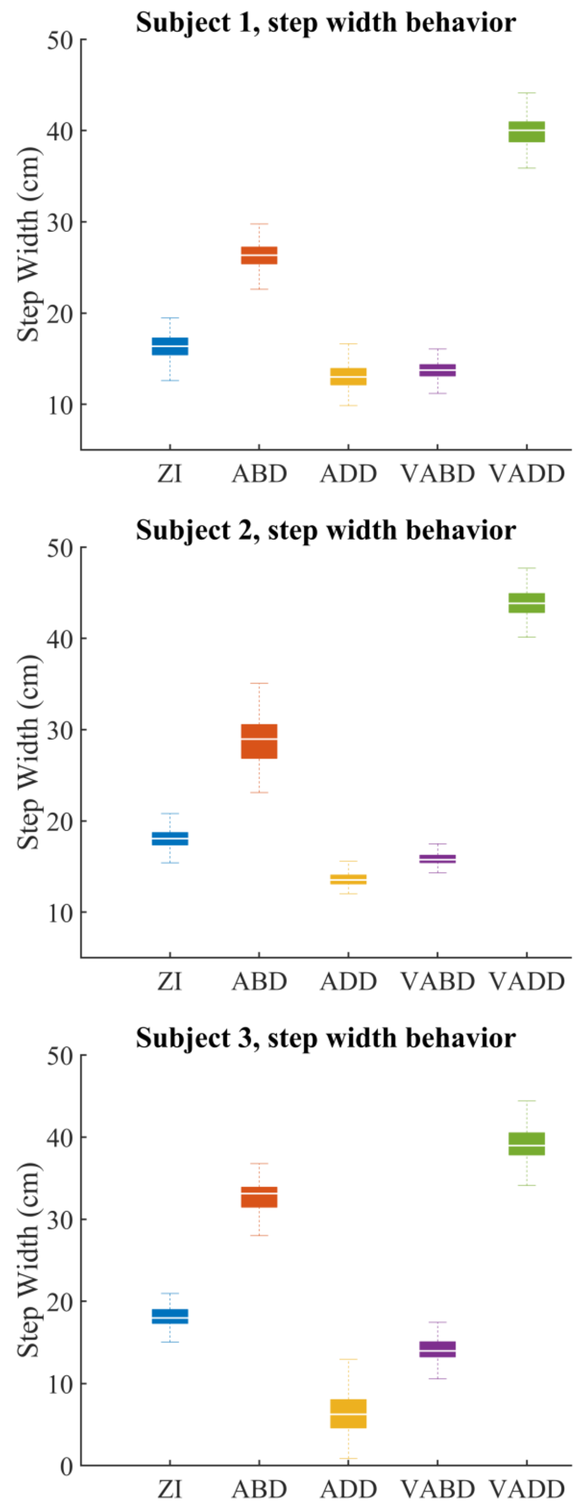

Fig. 8. Observed step width behaviors across transparent mode trial (ZI), non-visual feedback abduction (ABD) and adduction (ADD) trials, and visual feedback abduction (VABD) and adduction (VADD) trials.

B. Pilot Human Trial Analysis

While the exoskeleton was validated through benchtop testing, it is vital that the applied torques from the exoskeleton could change user step width behavior. Comparing the non-visual feedback trials, it is observed that all subjects exhibited a significant change in their mean step width when compared to the transparent mode. More importantly, users should be able to perform tasks and change exoskeleton behavior through volitional control, which is observed through the visual feedback trials. These behaviors can be leveraged in rehabilitation, to strengthen abduction-adduction motions by applying assistance and using visual feedback. Further, this behavior would be ideal for people suffering from neurological disorders as they can utilize the robot for assistance while still having control over mediolateral movements.

C. Limitations and Future Scope

This research showed that the developed exoskeleton satisfied all design considerations and is able to modulate the step width of individuals using admittance control modulation. While the results show promise, there are a few limitations that need to be addressed before the device can be implemented in community settings. Due to conservative design choices, the weight of the device is 6.2 Kgs, which makes the current iteration impractical for use by people with lower limb disabilities. Further, the control was implemented on EtherCAT, which needs a tethered connection at all times compromising the portability. However, since these limitations are engineering problems, they could be addressed in future iterations.

The validated device has a wide range of applications in assistive and rehabilitative fields and our goal is to explore the different applications of the developed device. Since the current study shows that the device can modulate step width, the relationship between the admittance parameters and step width could be studied across various populations. This information could provide insights into the neuromuscular mechanisms of different populations, which could be vital in development of suitable rehabilitation protocols or development of interventions to prevent falls. Further, this information could be leveraged in the development of controllers that could accurately modulate step width during functional tasks to ensure balance.

The ability of the device to simulate different admittance properties can also be leveraged in rehabilitation. The device can provide resistance which could be integrated with visual feedback to provide safe and effective rehabilitation protocols. The relationship between different simulated resistances, the corresponding muscle activities and neuromuscular responses would need to be analyzed to develop effective protocols. Such protocols would be a drastic improvement over current manual physical therapeutic protocol.

VI. Conclusion

In this study, we designed a hip exoskeleton that could assist in the mediolateral direction that is capable of providing high torque, backdrivability and sufficient bandwidth necessary for balance assistance. The developed exoskeleton addresses a major need in assistive and rehabilitative robotics through its capabilities in providing assistance along the frontal plane. The performance of the robot and its unique capabilities could improve understanding of balance mechanisms and impact clinical outcomes for people at risk of falls.

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