# Design and Adaptive Compliance Control of a Wearable Walk Assist Device

Muhammad Arsalan
*Faculty of Mechanical Engineering*
*GIKI*
Swabi, Pakistan
m.arsalan@giki.edu.pk

Syed Humayoon Shah
*Dept. of Mechanical Engineering*
*NTUST*
Taipei, Taiwan
engrhumayoon@yahoo.com

Muhammad Shahab Alam
*Defense Technologies Institute*
*GTU*
Gebze/Kocaeli, Turkey
shahab@gtu.edu.tr

Izhar Ul Haq
*Dept. of Mechatronics Enigneering*
*UET*
Peshawar, Pakistan
izhar@uetpeshawar.edu.pk

Said G. Khan
*Dept. of Mechanical Engineering*
*UOB*
Isa Town, Bahrain
engr_ghani@hotmail.com

Jamshed Iqbal
*School of Computer Science and Engineering*
*UOH*
Hull, UK
j.iqbal@hull.ac.uk

***Abstract*—The ability to walk independently is a predominant feature that human beings are bestowed with by nature. People with moving disabilities face many challenges in day-to-day activities and they have to rely on others to perform their day-to-day activities. Robotic walk-assist technology has the ability to play an indispensable role in improving the mobility of people who are suffering from walking disabilities. However, there are several technical challenges, such as safe interaction of human and robotic walk-assist devices, and control of highly nonlinear dynamic systems. This paper proposes a preliminary design of an assistive device for elderly persons having poor mobility. An adaptive inertia-related controller is employed for the desired tracking control of hip and knee joints of the walk assist device. The mass estimation of both hip and knee links is estimated through the proposed adaptive controller, which plays an important role if people of different weights and sizes opt to use the same device. Moreover, the adaptive control scheme is coupled with a compliant spring-mass-damper reference model to realize a compliance control for the hip and knee joints of the exoskeleton wearable walk-assist robotic device. Simulation results validate the performance of the proposed controller for both hip and knee joints. Results demonstrate that proposed controller has the capability to estimate the weights of the links, and the uncertain parameters while changing the assistive device dynamics.**

***Index Terms*—adaptive control, wearable devices, lower limb exoskeleton**

## I. Introduction

Robotic technology has the potential to develop rehabilitation robots, artificial limbs/muscles [1]–[3], wearable assistive devices, and exoskeletons that can restore and further enhance human abilities [4]–[8]. A plethora of research is available on the exoskeleton technology, which emphasizes its potential in assisting human beings in daily life activities [9]–[17]; for instance, force augmentation (assists when needed) and physical rehabilitation [18]–[20]. The assistive device has to be made according to the nature of the patient's motor impairment(s).

Rehabilitation of the lower limbs aims at patients whose lower limbs are in an ill-functioning state due to bone deformities or impaired nerves. Diseases like Spinal Cord Injuries (SCIs), Cerebral Palsy (CP), Multiple Sclerosis (MS), Traumatic Brain Injuries (TBIs), etc, leave patients in the aforementioned state [21]–[23]. People with walking disabilities due to age or body structure (i.e., obesity) are excessively dependent on their family members for mobility. The traditional tools used for assisting people with walking disabilities include, walkers, crutches, canes, etc. These tools, however, are not an apt choice as they require high physical strength, and have poor stability and safety. Therefore, there is a dire need to have alternative and more advanced devices that can efficiently deal with walking disabilities [24].

Recent research demonstrates that lower limb exoskeletons have the capability to eliminate the dependency of elderly people (with walking disabilities) on younger population [25]–[28]. Thus, these cutting-edge devices will replace crutches and other traditional walking implements. However, the design and control (from safety's perspective) of assistive devices is still an intricate research task in the field of robotics [29].

The research presented in this paper deals with lower limb impairment in elderly people [30]–[32]. People with walking disabilities (fully or partially) depend on walk assistive devices for their mobility such as walker or wheelchair. Robotic Walk Assist Device (RWAD) is one of the important fields that is growing rapidly. The magnitude of walking disability varies depending on the type of cause. For instance, older people tend to have reduced walking capability due to weaker muscles and, therefore, the traditional walk-assistive devices, such as walkers and canes, prove sufficient for them. Moreover, other walking disabilities, due to stroke or other illnesses, are severe and tend to have long-term damage in muscles; therefore, need more advanced walk-assistive devices.

The plausible potential of robotic walk assistive devices is not yet fully unlocked and utilized. However, recent advancements in the field of walk-assist technology, for instance, by HAL, Cyberdyne, and Hyundai envisage that robotics has a great aptitude to enable people, with walking disability, in retaining independent mobility for longer period of time. Based on the previous literature, robot-based assistive technologies have enormous unexploited potential and have many benefits for people with disabilities, such as empowering them with independent mobility. Presently, most of the available devices are expensive, heavy, and have several shortcoming (in terms safety). Moreover, these assistive technologies are envisaged to not only ameliorate human disabilities but also drive human capabilities beyond their inherent physiological levels. The aim of this work is to ensure safety by incorporating compliance control into walk assist device and to synchronize human-machine interaction.

The paper is organized in the following manner: Background and literature review is presented in Section II; a discussion on the control of the bionic leg is given in Section III; results are presented in Section IV; and finally a discussion on the conclusion and future work is presented in Section V.

## II. Background and Literature Review

The gradual increase in the percentage of senior citizens in the global population, along with the unhealthy food and lifestyle choices by certain sections of the younger generations, has led to an increase in patients affected with some form of lower-extremity sensory impairment. In such cases, the person suffers from reduced joint excursion, subpar reflex responses, and insufficient forward propulsion, which leads to a halting, asymmetrical gait. To compensate for this, the affected patients tend to use inefficient methods such as raising the pelvic joint at an abnormal elevation while taking a step. The resulting awkward gait leads to increased social dependence for performing the day-to-day activities. The rising age gap in society, along with the new family structure becoming more widespread in scope, has led to a lack of young people supporting their elders either physically or financially.

The aforementioned challenges necessitate research into the development of wearable walk-assist devices by various research institutions across the world. An exoskeleton is wearable walk-assist device that can assist the motion of patients with weak lower limbs. It can be controlled by the exertion of force from the muscular system of the wearer to enhance the strength of their lower limbs, which can assist in the completion of various movements done by the patient. The human gait, being a highly sophisticated process, is one of the most actively researched areas in human-machine interaction in the present day.

A plethora of such devices have been proposed in the recent years. Lamers et. al. [33] proposed a novel mechanical structure with body-weight support based on the human hinge model and human kinesiology analysis. The paper also proposed a control method based on the foot plantar pressure and crotch contact force. Experiments conducted on the prototype indicated success in assisted walking due to the reduction of pressure on the user's knees and ankles. The prototype does not restrict the user's movements and is suitable for people of differing heights and weights. The research conducted by Susko et. al. [34] led to the proposal of a robot walking helper incorporated with both passive and active control modes for guidance. Keeping the user's safety in mind, the passive mode works by adopting a braking control law to differentially steer the vehicle. The active control mode works in environments when the external forces acting on the human body need to be taken into consideration when just the user-applied forces are inadequate for guidance. The theory of differential flatness and the theory of model predictive control have been integrated within the proposed control scheme. The simulation and experimental results of the prototype demonstrated successful guidance of the user up a slope effectively.

A novel robot-aided assist-as-needed gait training paradigm was developed by Krebs et. al. [35]. Based on previous studies conducted on the assist-as-needed robot-aided gait training (RAGT) – which demonstrated improvement in treadmill-walking performance post-stroke, the study examines the effects of the assist-as-needed RAGT on over-ground walking pattern post-stroke. Clinical evaluations and gait training were carried out on 9 stroke subjects before, immediately after and post a 6-month training period. The results obtained showed great improvements in the selected parameters – over-ground walking, Dynamic gait index, Timed up and Go, peak knee flexion angle during swing phase and total hip joint excursion over the whole gait cycle for the affected leg. Milad D. Farahani et. al. [36] presented a concept of a walking assist robot for assisting the elder and/or overweight population. The proposed design possesses 6 DOF, which ensures no inhibition in the user's natural gait. The 2 active joints are prismatic, while the others are passive, resulting in reduced power consumption. The robot's architecture allows it to be operated by users of different builds. Another design can be seen in the research done by Masaru Higachi et. al. [37], which proposes a formation of a walking assist machine using crutches (WAMC). The research studied the connection between walking stability and walking motion parameters through dynamic simulations. The determined parameter results were then conveyed to an experimental setup of the WAMC via inbuilt sensors and switches.

The work proposed by M.Munih et. al. [38] introduces a design termed the exoskeletal power assistive system – a wearable robot made to help human body motion. Keeping in view the robot's limitations caused by its excessive weight and volume, the paper proposes a tendon-driven exoskeletal power assistive device, exoskeleton for patients and the old by the Sogang University (EXPOS) as an alternate solution. The caster walker supports heavy equipment including motors, drivers, controllers, and batteries so that the weight and volume of the wearable exoskeleton are minimized. The motors and pulleys connected to the user's hip and knee (via tendons) generate assistive power as per the user's requirements. The research conducted by E.Burdet et. al. [39] put forwards the design and implementation of a unique control system featuring a unique human-machine interface that allows the user to control the proposed electro-mechanical therapeutic system just by moving or rotating his/her body. In a similar work, a proposal laid out in A.M.Barbosa et. al. [40] outlines the design and implementation of a distinctive manipulatory procedure governed by a human-laptop interface that makes it possible for the human to instinctively manage the procedure simply via relocation or rotation of his/her physique.

For an exoskeleton, controlling the interaction force between the user and the actuators is of paramount importance, as it directly governs the accuracy of the realized impedance. Addressing the aforementioned problem, G.Orekhov et. al. [41] proposes an approach, named the model-inverse time delay control, which is attained by infusing a virtual reference predicted by the inverse of model dynamics in time delay control (TDC). Performance of force control was significantly improved with the proposed method. Keeping a similar bearing, K.I.Sherwani et. al. [42] put forwards a multi-modal control technique for exoskeletons used for rehabilitation. The controller incorporates three control modes – the robot-assisted mode enables the user to voluntarily exert control over the mechanism within the desired region, the robot-dominated mode corrects movement outside the region, and the safety-stop mode stops the robot when the exerted force exceeds the safety margin. The proposed controller achieves the "assist-as-needed" paradigm by utilizing the regional position and force feedback.

## III. Model of the Proposed Lower Limb Exoskeleton

Human walking comprises of repetitive movement of lower limbs that results in motion. Understanding of human gait cycle is important for ensuring stability of the exoskeleton. The gait cycle mainly consists of the stance phase and swing phase. During the stance phase, the human foot remains in contact with the ground. The stance phase further involves five events namely: (i) heel-strike (HS), (ii) foot-flat (FF), (iii) mid-stance (MS), (iv) heel-off (HO), and (v) toe-off (TO). In the later stages of the stance phase, the body drives forward. In the second phase of the gait cycle, i.e., the swing phase, the foot does not remain in contact with the ground. The human gait cycle is described in percentages due to the time-independency of the sequences that occur in the cycle. The overall gait cycle are generally divided into eight sub-phases namely: (i) initial contact, (ii) loading response, (iii) mid-stance, (iv) terminal stance, (v) pre-swing, (vi) initial swing, (vii) mid-swing, and (viii) terminal swing, as shown in Fig 1.

Modeling the human lower limb is crucial for designing a lower limb walk assistive device that is capable of a safe and effective interaction with human, i.e., human-robot (walk assist device) interaction. Conceptually, a simple walking model can be represented by an inverted pendulum. A more complex model of the human lower limb can be modeled as an open chain of links consisting of cascaded bones (links), pelvis, femur, tibia, fibula, and articulations (joints). For instance, the hip, knee, and ankle, are actuated by muscles (motor/actuators). This work is focused on flexion and extension, a simple movement, during walking, which occurs, commonly, in the sagittal plane. The complexity of design increases by adding other movements of hip and ankle joints, for instance, adduction/abduction and inversion/eversion movements.

Assistive devices are deemed as one of the cutting-edge solutions for augmentation of walking and lifting heavy objects. The fundamental design parameters for consideration in the design of walk assistive devices are low-cost, lightweight, ease of use, and most importantly safety (since such devices have direct contact with humans). The assistive device proposed in this work is composed of four main parts: (1) waist support, (2) hip link, (3) knee link, and (4) toe support. Complete assembly of the 3D CAD model of the assistive device is shown in Fig 2.

The waist support part of the assistive device makes a firm bond between human and the walk assist device using a belt. The inner surface of the waist support component is supposed to be covered with soft material for enhanced user-comfort. Shank (knee link) is fused with hip and toe support components. Triangular and circular perforations are incorporated in the design of hip and knee links for weight optimization.

The proposed assist device is in direct contact with the human lower limb. One of the most challenging task in the

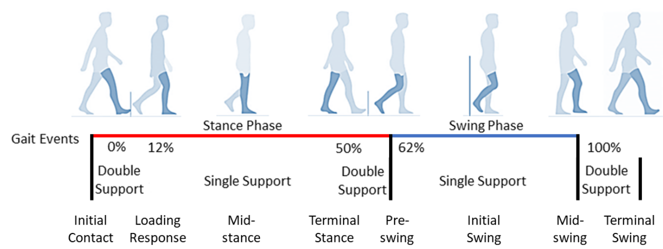


Fig. 1. Human gait cycle. [43]

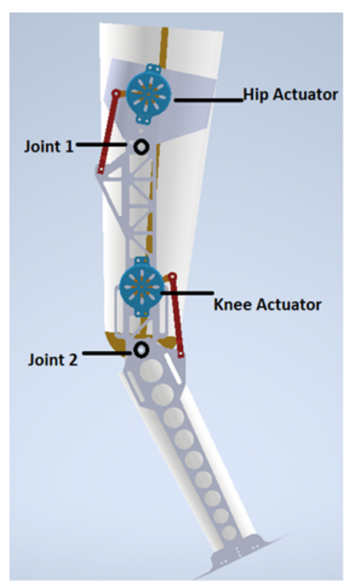


Fig. 2. 3D CAD model of the walk assistive device

exoskeleton is the synchronization of human and robot control systems. Both systems are operated by two different control schemes, i.e, human functions controlled by the brain (human controller), and robot functions controlled by made human controller (embedded/computer controller).

## IV. Adaptive inertia-related control for RWAD (Robotic Walk Assist Device)

Adaptive control presents the idea of estimating the system's uncertain parameters and controller online [44], [45]. For instance, in our case (RWAD), masses of the links may not be known accurately because people with different leg sizes and weights will use it. In such a scenario, other conventional control techniques may not track the desired performance. The adaptive controller works better in situations where the systems dynamics are unknown and changing, as compared to other controllers (such as PID). A comprehensive explanation of the adaptive controller can be found in work done by Slotine [46] and Lewis [47]. The controller's key objective is to have a desirable performance to deal with a dynamic environment and uncertainties in the system dynamics. The complete control law of the proposed controller can be expressed as follows:

$$\tau = Y(\cdot)\hat{\phi} + k\dot{e} + k\pi e, \tag{1}$$

where $\tau$ represents the joint (actuator) torque. The term $k$ denotes derivative gain (spring stiffness), $\dot{e}(\dot{\theta}_d - \dot{\theta})$ is joint velocity error and $e(\theta_d - \theta)$ is joint position error, respectively. The diagonal matrix $\pi$ (pronounced as Pi) is positive definite. The product of the regression matrix $Y(\cdot)$ and the computed vector $\hat{\phi}$ are the crucial parts of the presented control scheme.

$$Y(\cdot)\hat{\phi} = \hat{H}(\ddot{\theta}_d + \pi\dot{e}) + \hat{C}(\dot{\theta}_d + \pi e) + \hat{G}, \tag{2}$$

where $\hat{H}$ refers to inertia matrix estimation, $\hat{C}$ denotes centripetal torque calculation, and $\hat{G}$ represents computation of gravitational torque. The block diagram of adaptive inertia-related control for the proposed lower limb exoskeleton is depicted in Fig 3.

The parameters estimate vector $\hat{\phi}$ for the two links proposed lower limb assist device can be written as,

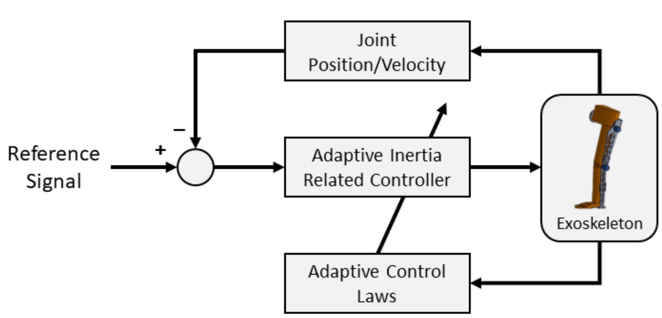


Fig. 3. Inertia-related adaptive control for walk assist device

$$\hat{\phi} = \begin{vmatrix} \hat{m_1} \\ \hat{m_2} \end{vmatrix}, \tag{3}$$

where $\hat{m_1}$ represents the mass of the hip link, and $\hat{m_2}$ represents the mass of the knee link. The updated law for parameter estimation is given by

$$\hat{\dot{\phi}} = Y\int_0^t \Gamma Y^T(\cdot)(\pi e + \dot{e}), \tag{4}$$

The term $(\pi e + \dot{e})$ is known as filter tracking error, and matrix $\Gamma$ is diagonal positive definite. The regression matrix $Y(\cdot)$ is given by

$$Y(\ddot{\theta}_d, \dot{\theta}_d, \theta_d, \theta, \dot{\theta}) = \begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix}, \tag{5}$$

where

$$Y_{11} = \frac{1}{3}l_1^2(\ddot{\theta}_{d1} + \pi_1\dot{e}_1) + \frac{1}{2}l_1 gsin(\theta_1), \tag{6}$$

$$\begin{aligned} Y_{12} = (&\frac{1}{3}l_2^2 + l_1 l_2 cos(\theta_2) + l_1^2 + \frac{1}{4}{R_2}^2)(\ddot{\theta}_{d1} + \lambda_1\dot{e}_1) \\ &+(\frac{1}{3}l_2^2 + \frac{1}{2}l_1 l_2 cos(\theta_2) + \frac{1}{4}{R_2}^2)(\ddot{\theta}_{d2} + \lambda_2\dot{e}_2) \\ +l_1 gsin(\theta_1) &- \frac{1}{2}l_1 l_2 sin(\theta_2)(\dot{\theta}_{d2} + \lambda_1 e_2) - l_1 l_2 sin(\theta_2)(\dot{\theta}_{d1} \\ &+\lambda_1\dot{e}_1)(\dot{\theta}_{d2} + \lambda_2 e_2) + \frac{1}{2}l_2 gsin(\theta_{12}) + l_1 gsin(\theta_1), \end{aligned} \tag{7}$$

$$Y_{21} = 0, \tag{8}$$

$$\begin{aligned} Y_{21} = (&\frac{1}{2}l_1 l_2 cos(\theta_2) + \frac{1}{3}l_2^2\frac{1}{4}{R_2}^2)(\ddot{\theta}_{d1} + \lambda_1\dot{e}_1) \\ +(&\frac{1}{3}l_2^2 + \frac{1}{4}{R_2}^2)(\ddot{\theta}_{d2} + \lambda_2\dot{e}_2) - \frac{1}{2}l_1 l_2 sin(\theta_2)(\dot{\theta}_{d1} \\ &+\lambda_1 e_1)^2 + l_2 gsin(\theta_{12}), \end{aligned} \tag{9}$$

The approach presented by Lyapunov can be employed to develop a law for updating estimates for Eq 4. Furthermore, for driving parameters estimation update law and stability proof, Lyapunov energy function can be employed, as given in Eq 10.

$$V_{Lyap} = \frac{1}{2}(\pi)^T H(\theta)\pi + \frac{1}{2}\tilde{\phi}^T\Gamma^{-1}\tilde{\phi}, \tag{10}$$

## Results and Discussion

A 2-DOF lower exoskeleton is modeled in MATLAB/SimMechanics. The aforementioned control scheme is used as the controller for the motor force/torque control which is provided to assistive device. Figures 4 and 5 show the controller's tracking performance with the changing dynamics of the assistive device. Both the hip and knee link masses are estimated and demonstrated in Fig 6. It is evident from the figure that the computed link masses converge to the actual values (10kg) in simulation. A real application may not converge to the real values if the persistency of the excitation condition is not fully met. However, the tracking performance will not be adversely affected if the link masses are not converged to the real values. A healthy adult's normal human gait pattern is employed as a position demand for the walk assist device. For instance, knee flexion of the gait pattern is shown in Fig 7 [48]. The standard phases (states) of the human gait cycle are initial stance (it usually lasts for the first 18 to 20% of the gait cycle), mid-stance (stays till 40%), terminal stance and pre-swing (40 to 60%), and swing (the remaining 40%). A similar pattern exists for the Hip joint. In Fig 8, simulation results for hip and knee position tracking are shown. The demand trajectory of the hip and knee is based on the real human walking pattern, based on the work of David Winter [49].

To demonstrate the compliance of the controller, simulation is carried out as shown in Figures 9 - 11. During the initial 10 seconds, human leg do not apply any torque, therefore the RWAD tracks the desired trajectory ($qr$). However, during the 11 to 16 seconds interval, the lower limb of the human applies torque (shown in Fig 9 (bottom). Thus, compliance control play its role and adjust the desired trajectory to $qd$, according to the torque/force obtained from the human lower limb. The same description applies to Fig 10. It is noteworthy that although unlike conventional dynamic model-based controllers, an adaptive controller does not need any complete knowledge of the model's dynamics or the link masses of robotic walk assist device. Yet, the tracking performance is better, which shows the feasibility of this controller for RWAD. The error signal is shown in Fig 11 bottom. However, a short-coming of model-free controllers is that such controllers are energy inefficient, as evident from the control signal illustrated in Fig 11 top.

## V. Conclusion

Design and control of a non-linear system is a highly challenging task, particularly when the system has direct contact with human beings. A walk assistive device for lower limb impaired patients should be lightweight, user-friendly and economical. In this work, a preliminary design and a partially model-based adaptive control scheme for a walk assistive device is proposed and simulated. The study focuses on people having walking disability due to weak legs. Static finite

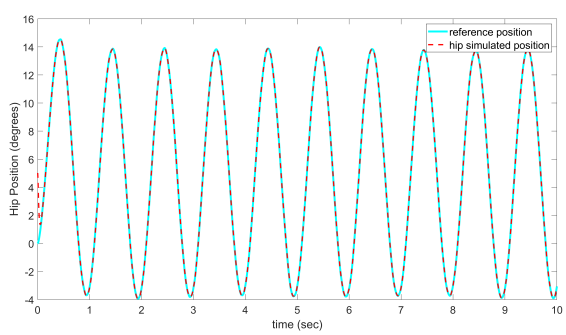


Fig. 4. Desired tracking of the hip and knee joints

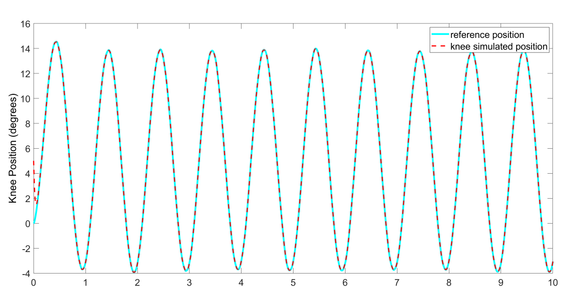


Fig. 5. Desired tracking of the hip and knee joints

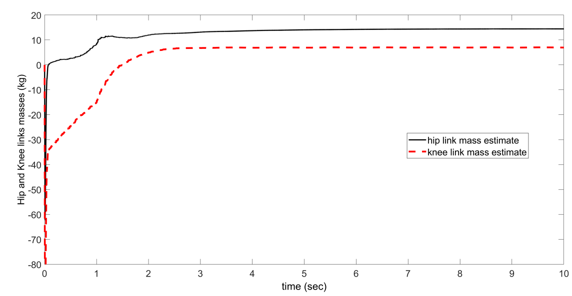


Fig. 6. Mass estimation of hip and knee links

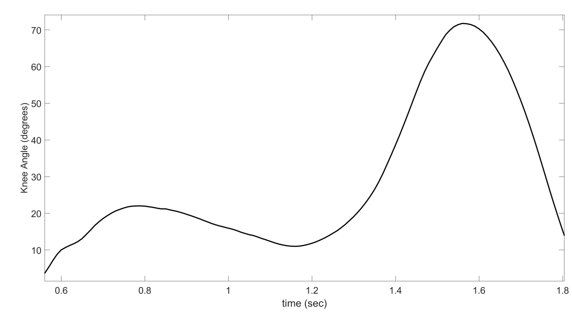


Fig. 7. Knee angle phases with normal gait cycle [48]

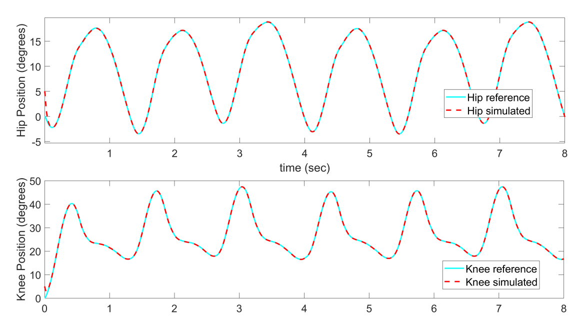


Fig. 8. Knee and hip tracking using a human-like trajectory

element analysis (FEA) of the proposed design is performed for validating the design feasibility. An adaptive controller is suitable for efficient performance tracking without requiring any prior knowledge of the dynamics of the assistive device. In addition, model-free or partially model-based adaptive controllers are more suitable for assistive devices as the same device can be used by different impaired patients having varying leg sizes and weights. The proposed adaptive inertia-related controller is able to estimate the weight of the links, and has the ability to deal with the assistive device's parametric uncertainties in case of changing dynamics. Moreover, for compliance and safety of the assistive device, a compliance control is incorporated. The future work aims at the development and application of the proposed design and control scheme on a prototype walk assistive device.

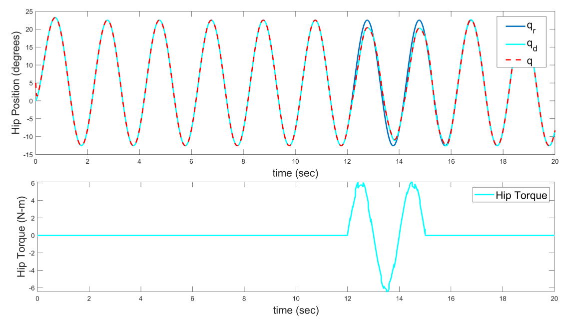


Fig. 9. Compliance control simulation result of hip joint

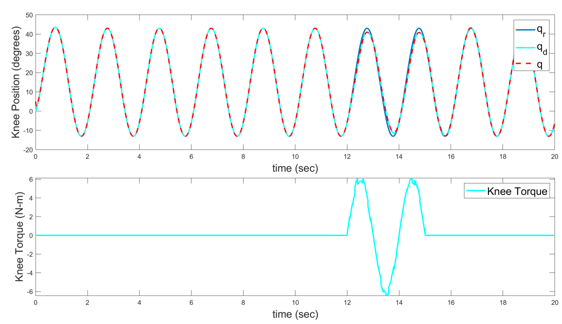


Fig. 10. Compliance control simulation result of knee joint

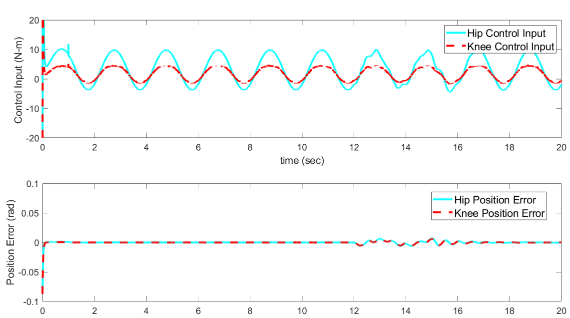


Fig. 11. Control inputs (above) and hip and knee position errors

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